Holoscan SDK User Guide

Release 3.1.0

NVIDIA Corporation

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INTRODUCTION

CHAPTER

ONE

OVERVIEW

NVIDIA Holoscan is the AI sensor processing platform that combines hardware systems for low-latency sensor and network connectivity, optimized libraries for data processing and AI, and core microservices to run streaming, imaging, and other applications, from embedded to edge to cloud. It can be used to build streaming AI pipelines for a variety of domains, including medical devices, high-performance computing at the edge, industrial inspection, and more.

The Holoscan SDK assists developers by providing:

1. **Various installation strategies**

From containers, to Python wheels, to source, and from development to deployment environments, the Holoscan SDK comes in many packaging flavors to adapt to different needs. Find more information in the *sdk installation* section.

2. **C++ and Python APIs**

These APIs are now the recommended interface for the creation of application pipelines in the Holoscan SDK. See the *Using the SDK* section to learn how to leverage those APIs, or the Doxygen pages (C++/Python) for specific API documentation.

3. **Built-in Operators**

The units of work in Holoscan applications are implemented within Operators, as described in the *core concepts* of the SDK. The operators included in the SDK provide domain-agnostic functionalities such as IO, machine learning inference, processing, and visualization, optimized for AI streaming pipelines, relying on a set of *Core Technologies*. This guide provides more information on the operators provided within the SDK *here*.

4. **Minimal Examples**

The Holoscan SDK provides a list of examples to illustrate specific capabilities of the SDK. Their source code can be found in the GitHub repository. The *Holoscan by Example* section provides step-by-step analysis of some of these examples to illustrate the inner workings of the Holoscan SDK.

5. **Repository of Operators and Applications**

HoloHub is a central repository for users and developers to share reusable operators and sample applications with the Holoscan community. Being open-source, these operators and applications can also be used as reference implementations to complete the built-in operators and examples available in the SDK.

6. **Tooling to Package and Deploy Applications**

Packaging and deploying applications is a complex problem that can require large amount of efforts. The *Holoscan CLI* is a command-line interface included in the Holoscan SDK that provides commands to *package and run applications* in OCI-compliant containers that could be used for production.

7. **Performance tools**

As highlighted in the relevant technologies section, the soul of the Holoscan project is to achieve peak performance by leveraging hardware and software developed at NVIDIA or provided by third parties. To validate this, Holoscan provides performance tools to help users and developers track their application performance. They currently include:

- the *Data Flow Tracking* feature to profile your application and analyze the data flow between operators in its graph.

8. **Documentation**

The Holoscan SDK documentation is composed of:

- This user guide, in a webpage or PDF format
- Build and run instructions specific to each *installation strategy*
- Release notes on Github

Note: In previous releases, the prefix `Clara` was used to define Holoscan as a platform designed initially for medical devices. Starting with version 0.4.0, the Holoscan SDK is built to be domain-agnostic and can be used to build sensor AI applications in multiple domains. Domain specific content will be hosted on the HoloHub repository.

CHAPTER

TWO

RELEVANT TECHNOLOGIES

Holoscan accelerates streaming AI applications by leveraging both hardware and software. The Holoscan SDK relies on multiple core technologies to achieve low latency and high throughput:

- *Rivermax and GPUDirect RDMA*
- *Graph Execution Framework*
- *TensorRT Optimized Inference*
- *Interoperability between CUDA and rendering frameworks*
- *Accelerated image transformations*
- *Unified Communications X*

2.1 Rivermax and GPUDirect RDMA

The NVIDIA Developer Kits equipped with a ConnectX network adapter can be used along with the NVIDIA Rivermax SDK to provide an extremely efficient network connection that is further optimized for GPU workloads by using GPUDirect for RDMA. This technology avoids unnecessary memory copies and CPU overhead by copying data directly to or from pinned GPU memory, and supports both the integrated GPU or the discrete GPU.

Note: NVIDIA is committed to supporting hardware vendors enabling RDMA within their own drivers, an example of which is provided by the *AJA Video Systems*, as part of a partnership with NVIDIA for the Holoscan SDK. The `AJASource` operator is an example of how the SDK can leverage RDMA.

For more information about GPUDirect RDMA, see the following:

- GPUDirect RDMA Documentation
- Minimal GPUDirect RDMA Demonstration source code, which provides a real hardware example of using RDMA and includes both kernel drivers and user space applications for the RHS Research PicoEVB and HiTech Global HTG-K800 FPGA boards.

2.2 Graph Execution Framework

The Graph Execution Framework (GXF) is a core component of the Holoscan SDK that provides features to execute pipelines of various independent tasks with high performance by minimizing or removing the need to copy data across each block of work, and providing ways to optimize memory allocation.

GXF will be mentioned in many places across this user guide, including a *dedicated section* which provides more details.

2.3 TensorRT Optimized Inference

NVIDIA TensorRT is a deep learning inference framework based on CUDA that provided the highest optimizations to run on NVIDIA GPUs, including the NVIDIA Developer Kits.

The *inference module* leverages TensorRT among other backends, and provides the ability to execute multiple inferences in parallel.

2.4 Interoperability between CUDA and rendering frameworks

Vulkan is commonly used for real-time visualization and, like CUDA, is executed on the GPU. This provides an opportunity for efficient sharing of resources between CUDA and this rendering framework.

The *Holoviz* module uses the external resource interoperability functions of the low-level CUDA driver application programming interface, the Vulkan external memory and external semaphore extensions.

2.5 Accelerated image transformations

Streaming image processing often requires common 2D operations like resizing, converting bit widths, and changing color formats. NVIDIA has built the CUDA accelerated NVIDIA Performance Primitive Library (NPP) that can help with many of these common transformations. NPP is extensively showcased in the Format Converter operator of the Holoscan SDK.

2.6 Unified Communications X

The Unified Communications X (UCX) framework is an open-source communication framework developed as a collaboration between industry and academia. It provides high-performance point-to-point communication for data-centric applications. Holoscan SDK uses UCX to send data between fragments in distributed applications. UCX's high level protocols attempt to automatically select an optimal transport layer depending on the hardware available. For example technologies such as TCP, CUDA memory copy, CUDA IPC and GPUDirect RDMA are supported.

CHAPTER

THREE

GETTING STARTED WITH HOLOSCAN

As described in the *Overview*, the Holoscan SDK provides many components and capabilities. The goal of this section is to provide a recommended path to getting started with the SDK.

3.1 1. Choose your platform

The Holoscan SDK is optimized and compatible with multiple hardware platforms, including NVIDIA Developer Kits (aarch64) and x86_64 workstations. Learn more on the developer page to help you decide what hardware you should target.

3.2 2. Setup the SDK and your platform

Start with *installing the SDK*. If you have a need for it, you can go through additional *recommended setups* to achieve peak performance, or *setup additional sensors* from NVIDIA's partners.

3.3 3. Learn the framework

1. Start with the *Core Concepts* to understand the technical terms used in this guide, and the overall behavior of the framework.
2. Learn how to use the SDK in one of two ways (or both), based on your preference: a. Going through the *Holoscan by Example* tutorial which will build your knowledge step-by-step by going over concrete minimal examples in the SDK. You can refer to each example source code and run instructions to inspect them and run them as you go. b. Going through the condensed documentation that should cover all capabilities of the SDK using minimal mock code snippets, including *creating an application*, *creating a distributed application*, and *creating operators*.

3.4 4. Understand the reusable capabilities of the SDK

The Holoscan SDK does not only provide a framework to build and run applications, but also a set of reusable operators to facilitate implementing applications for streaming, AI, and other general domains.

The list of existing operators is available *here*, which points to the C++ or Python API documentation for more details. Specific documentation is available for the *visualization* (codename: HoloViz) and *inference* (codename: HoloInfer) operators.

Additionally, HoloHub is a central repository for users and developers to share reusable operators and sample applications with the Holoscan community, extending the capabilities of the SDK:

- Just like the SDK operators, the HoloHub operators can be used in your own Holoscan applications.
- The HoloHub sample applications can be used as reference implementations to complete the examples available in the SDK.

Take a glance at HoloHub to find components you might want to leverage in your application, improve upon existing work, or contribute your own additions to the Holoscan platform.

3.5 5. Write and run your own application

The steps above cover what is required to write your own application and run it. For facilitating packaging and distributing, the Holoscan SDK includes utilities to *package and run your Holoscan application* in an OCI-compliant container image.

3.6 6. Master the details

- Expand your understanding of the framework with details on the *logging utility* or the *data flow tracking* benchmarking tool and *job statistics* measurements.
- Learn more details on the configurable components that control the execution of your application, like [Schedulers], [Conditions], and [Resources]. (Advanced) These components are part on the GXF execution backend, hence the **Graph Execution Framework** section at the bottom of this guide if deep understanding of the application execution is needed.

CHAPTER

FOUR

SDK INSTALLATION

The section below refers to the installation of the Holoscan SDK referred to as the **development stack**, designed for NVIDIA Developer Kits (arm64), and for x86_64 Linux compute platforms, ideal for development and testing of the SDK.

Note: or Holoscan Developer Kits such as the IGX Orin Developer Kit, an alternative option is the *deployment stack*, based on OpenEmbedded (Yocto build system) instead of Ubuntu. This is recommended to limit your stack to the software components strictly required to run your Holoscan application. The runtime Board Support Package (BSP) can be optimized with respect to memory usage, speed, security and power requirements.

4.1 Prerequisites

NVIDIA Developer Kits

Setup your developer kit:

Developer Kit	User Guide	OS	GPU Mode
NVIDIA IGX Orin	Guide	IGX Software 1.1 Production Release	iGPU **or*** dGPU
NVIDIA Jetson AGX Orin and Orin Nano	Guide	JetPack 6.1	iGPU
NVIDIA Clara AGX*Only supporting the NGC container*	Guide	HoloPack 1.2*Upgrade to 535+ drivers required*	dGPU

** iGPU and dGPU can be used concurrently on a single developer kit in dGPU mode. See* details here.

NVIDIA SuperChips

This version of the Holoscan SDK was tested on the Grace-Hopper SuperChip (GH200) with Ubuntu 22.04. Follow setup instructions here.

Attention: Display is not supported on SBSA/superchips. You can however do headless rendering with *HoloViz* for example.

x86_64 Workstations

Supported x86_64 distributions:

OS	NGC Container	Debian/RPM package	Python wheel	Build from source
Ubuntu 22.04	Yes	Yes	Yes	Yes
RHEL 9.x	Yes	No	No	No[1]
Other Linux distros	No[2]	No	No[3]	No[1]

[1] Not formally tested or supported, but expected to work if building bare metal with the adequate dependencies. [2] Not formally tested or supported, but expected to work if supported by the NVIDIA container-toolkit. [3] Not formally tested or supported, but expected to work if the glibc version of the distribution is 2.35 or above.

NVIDIA discrete GPU (dGPU) requirements:

- Ampere or above recommended for best performance
- Quadro/NVIDIA RTX necessary for GPUDirect RDMA support
- Tested with NVIDIA Quadro RTX 6000 and NVIDIA RTX A6000
- NVIDIA dGPU drivers: 535 or above
- For RDMA Support, follow the instructions in the *Enabling RDMA* section.
- Additional software dependencies might be needed based on how you choose to install the SDK (see section below).
- Refer to the *Additional Setup* and *Third-Party Hardware Setup* sections for additional prerequisites.

4.2 Install the SDK

We provide multiple ways to install and run the Holoscan SDK:

4.2.1 Instructions

NGC Container

- **dGPU** (x86_64, IGX Orin dGPU, Clara AGX dGPU, GH200)

```
docker pull nvcr.io/nvidia/clara-holoscan/holoscan:v3.1.0-dgpu
```

- **iGPU** (Jetson, IGX Orin iGPU, Clara AGX iGPU)

```
docker pull nvcr.io/nvidia/clara-holoscan/holoscan:v3.1.0-igpu
```

See details and usage instructions on NGC.

Debian package

Try the following to install the holoscan SDK:

```
sudo apt update
sudo apt install holoscan
```

Attention: This will not install dependencies needed for the Torch nor ONNXRuntime inference backends. To do so, install transitive dependencies by adding the `--install-suggests` flag to `apt install holoscan`, and refer to the support matrix below for links to install libtorch and onnxruntime.

Troubleshooting

If `holoscan` is not found with apt:

```
E: Unable to locate package holoscan
```

Try the following before repeating the installation steps above:

- **IGX Orin**: Ensure the compute stack is properly installed which should configure the L4T repository source. If you still cannot install the Holoscan SDK, use the `arm64-sbsa` installer from the CUDA repository.
- **Jetson**: Ensure JetPack is properly installed which should configure the L4T repository source. If you still cannot install the Holoscan SDK, use the `aarch64-jetson` installer from the CUDA repository.
- **GH200**: Use the `arm64-sbsa` installer from the CUDA repository.
- **x86_64**: Use the `x86_64` installer from the CUDA repository.

If you get missing CUDA libraries at runtime like below:

```
ImportError: libcudart.so.12: cannot open shared object file: No such file or directory
```

This could happen if your system has multiple CUDA Toolkit component versions installed. Find the path of the missing CUDA library (`libcudart.so.12` here) using `find /usr/local/cuda* -name libcudart.so.12` and select that path in `sudo update-alternatives --config cuda`. If that library is not found, or other cuda toolkit libraries become missing afterwards, you could try a clean reinstall of the full CUDA Toolkit:

```
sudo apt update && sudo apt install -y cuda-toolkit-12-6
```

If you get missing CUDA headers at compile time like below:

```
the link interface contains: CUDA::nppidei but the target was not found. [...] fatal␣
↪error: npp.h: No such file or directory
```

Generally the same issue as above due from mixing CUDA Toolkit component versions in your environment. Confirm the path of the missing CUDA header (`npp.h` here) with `find /usr/local/cuda-* -name npp.h` and follow the same instructions as above.

If you get missing TensorRT libraries at runtime like below:

```
Error: libnvinfer.so.8: cannot open shared object file: No such file or directory
...
Error: libnvonnxparser.so.8: cannot open shared object file: No such file or directory
```

This could happen if your system has a different major version installed than version 8. Try to reinstall TensorRT 8 with:

```
sudo apt update && sudo apt install -y libnvinfer-bin="8.6.*"
```

If you cannot import the holoscan Python module:

```
ModuleNotFoundError: No module named 'holoscan'
```

To leverage the python module included in the debian package (instead of installing the python wheel), include the path below to your python path:

```
export PYTHONPATH="/opt/nvidia/holoscan/python/lib"
```

Python wheel

```
pip install holoscan
```

See details and troubleshooting on PyPI.

Note: For x86_64, ensure that the CUDA Toolkit is installed.

4.2.2 Not sure what to choose?

- The **Holoscan container image on NGC** it the safest way to ensure all the dependencies are present with the expected versions (including Torch and ONNX Runtime), and should work on most Linux distributions. It is the simplest way to run the embedded examples, while still allowing you to create your own C++ and Python Holoscan application on top of it. These benefits come at a cost:
  - large image size from the numerous (some of them optional) dependencies. If you need a lean runtime image, see *section below*.
  - standard inconvenience that exist when using Docker, such as more complex run instructions for proper configuration.
- If you are confident in your ability to manage dependencies on your own in your host environment, the **Holoscan Debian package** should provide all the capabilities needed to use the Holoscan SDK, assuming you are on Ubuntu 22.04.
- If you are not interested in the C++ API but just need to work in Python, or want to use a different version than Python 3.10, you can use the **Holoscan python wheels** on PyPI. While they are the easiest solution to install the SDK, it might require the most work to setup your environment with extra dependencies based on your needs. Finally, they are only formally supported on Ubuntu 22.04, though should support other linux distributions with glibc 2.35 or above.

	NGC dev Container	Debian Package	Python Wheels
Runtime libraries	**Included**	**Included**	**Included**
Python module	3.10	3.10	**3.9 to 3.12**
C++ headers andC-Make config	**Included**	**Included**	N/A
Examples (+ source)	**Included**	**Included**	retrieve fromGitHub
Sample datasets	**Included**	retrieve fromNGC	retrieve fromNGC
CUDA runtime[1]	**Included**	automatically[2]installed	require manualinstallation
NPP support[3]	**Included**	automatically[Page 11, 2]installed	require manualinstallation
TensorRT support[4]	**Included**	automatically[Page 11, 2]installed	require manualinstallation
Vulkan support[5]	**Included**	automatically[Page 11, 2]installed	require manualinstallation
V4L2 support[6]	**Included**	automatically[Page 11, 2]installed	require manualinstallation
Torch support[7]	**Included**	require manual[8]installation	require manual[Page 11, 8]installation
ONNX Runtime support[9]	**Included**	require manual[10]installation	require manual[Page 11, 10]installation
MOFED support[11]	**User space included** Install kernel drivers on the host	require manual installation	require manual installation
CLI support	*require manual installation*	*require manual installation*	*require manual installation*

[1] CUDA 12 is required. Already installed on NVIDIA developer kits with IGX Software and JetPack.

[2] Debian installation on x86_64 requires the latest cuda-keyring package to automatically install all dependencies.

[3] NPP 12 needed for the FormatConverter and BayerDemosaic operators. Already installed on NVIDIA developer kits with IGX Software and JetPack.

[4] TensorRT 10.3+ needed for the Inference operator. Already installed on NVIDIA developer kits with IGX Software and JetPack.

[5] Vulkan 1.3.204+ loader needed for the HoloViz operator (+ libegl1 for headless rendering). Already installed on NVIDIA developer kits with IGX Software and JetPack.

[6] V4L2 1.22+ needed for the V4L2 operator. Already installed on NVIDIA developer kits with IGX Software and JetPack. V4L2 also requires libjpeg.

[7] Torch support requires LibTorch 2.5+, TorchVision 0.20+, OpenBLAS 0.3.20+, OpenMPI v4.1.7a1+, UCC 1.4+, MKL 2021.1.1 (x86_64 only), NVIDIA Performance Libraries (aarch64 dGPU only), libpng, and libjpeg. Note that container builds use OpenMPI and UCC originating from the NVIDIA HPC-X package bundle.

[8] To install LibTorch and TorchVision, either build them from source, download our pre-built packages, or copy them from the holoscan container (in `/opt`).

[9] ONNXRuntime 1.18.1+ needed for the Inference operator. Note that ONNX models are also supported through the TensorRT backend of the Inference Operator.

[10] To install ONNXRuntime, either build it from source, download our pre-built package with CUDA 12 and TensoRT execution provider support, or copy it from the holoscan container (in `/opt/onnxruntime`).

[11] Tested with MOFED 24.07

4.2.3 Need more control over the SDK?

The Holoscan SDK source repository is **open-source** and provides reference implementations, as well as infrastructure, for building the SDK yourself.

Attention: We only recommend building the SDK from source if you need to build it with debug symbols or other options not used as part of the published packages. If you want to write your own operator or application, you can use the SDK as a dependency (and contribute to HoloHub). If you need to make other modifications to the SDK, file a feature or bug request.

4.2.4 Looking for a light runtime container image?

The current Holoscan container on NGC has a large size due to including all the dependencies for each of the built-in operators, but also because of the development tools and libraries that are included. Follow the instructions on GitHub to build a runtime container without these development packages. This page also includes detailed documentation to assist you in only including runtime dependencies your Holoscan application might need.

CHAPTER

FIVE

ADDITIONAL SETUP

In addition to the required steps to *install the Holoscan SDK*, the steps below will help you achieve peak performance:

5.1 Enabling RDMA

Note: Learn more about RDMA in the *technology overview* section.

There are two parts to enabling RDMA for Holoscan:

- *Enabling RDMA on the ConnectX SmartNIC*
- *Enabling GPUDirect RDMA*

5.1.1 Enabling RDMA on the ConnectX SmartNIC

Skip to the next section if you do not plan to leverage a ConnectX SmartNIC.

The NVIDIA IGX Orin developer kit comes with an embedded ConnectX Ethernet adapter to offer advanced hardware offloads and accelerations. You can also purchase an individual ConnectX adapter and install it on other systems, such as x86_64 workstations.

The following steps are required to ensure your ConnectX can be used for RDMA over Converged Ethernet (RoCE):

1. Install MOFED drivers

Ensure the Mellanox OFED drivers version 23.10 or above are installed:

```
cat /sys/module/mlx5_core/version
```

If not installed, or an older version is installed, you should install the appropriate version from the MLNX_OFED download page, or use the script below:

```
# You can choose different versions/OS or download directly from the
# Download Center in the webpage linked above
MOFED_VERSION="24.07-0.6.1.0"
OS="ubuntu22.04"
MOFED_PACKAGE="MLNX_OFED_LINUX-${MOFED_VERSION}-${OS}-$(uname -m)"
wget --progress=dot:giga https://www.mellanox.com/downloads/ofed/MLNX_OFED-${MOFED_
↪VERSION}/${MOFED_PACKAGE}.tgz
```

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```
tar xf ${MOFED_PACKAGE}.tgz
sudo ./${MOFED_PACKAGE}/mlnxofedinstall
# add the --force flag to force uninstallation if necessary:
# sudo ./${MOFED_PACKAGE}/mlnxofedinstall --force
rm -r ${MOFED_PACKAGE}*
```

2. Load MOFED drivers

Ensure the drivers are loaded:

```
sudo lsmod | grep ib_core
```

If nothing appears, run the following command:

```
sudo /etc/init.d/openibd restart
```

3. Switch the board Link Layer to Ethernet

The ConnectX SmartNIC can function in two separate modes (called link layer):

- Ethernet (ETH)
- Infiniband (IB)

Holoscan does not support IB at this time (as it is not tested), so the ConnectX will need to use the ETH link layer.

To identify the current mode, run `ibstat` or `ibv_devinfo` and look for the `Link Layer` value. In the example below, the `mlx5_0` interface is in Ethernet mode, while the `mlx5_1` interface is in Infiniband mode. Do not pay attention to the `transport` value which is always `InfiniBand`.

```
$ ibstat
CA 'mlx5_0'
        CA type: MT4129
        Number of ports: 1
        Firmware version: 28.37.0190
        Hardware version: 0
        Node GUID: 0x48b02d0300ee7a04
        System image GUID: 0x48b02d0300ee7a04
        Port 1:
                State: Down
                Physical state: Disabled
                Rate: 40
                Base lid: 0
                LMC: 0
                SM lid: 0
                Capability mask: 0x00010000
                Port GUID: 0x4ab02dfffeee7a04
                Link layer: Ethernet
CA 'mlx5_1'
        CA type: MT4129
        Number of ports: 1
```

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```
        Firmware version: 28.37.0190
        Hardware version: 0
        Node GUID: 0x48b02d0300ee7a05
        System image GUID: 0x48b02d0300ee7a04
        Port 1:
                State: Active
                Physical state: LinkUp
                Rate: 100
                Base lid: 0
                LMC: 0
                SM lid: 0
                Capability mask: 0x00010000
                Port GUID: 0x4ab02dfffeee7a05
                Link layer: InfiniBand
```

If no results appear after `ibstat` and `sudo lsmod | grep ib_core` returns a result like this:

```
ib_core               425984  1 ib_uverbs
```

Consider running the following command or rebooting:

```
sudo /etc/init.d/openibd restart
```

To switch the link layer mode, there are two possible options:

1. On IGX Orin developer kits, you can switch that setting through the BIOS: see IGX Orin documentation.
2. On any system with a ConnectX (including IGX Orin developer kits), you can run the command below from a terminal (this will require a reboot). `sudo ibdev2netdev -v` is used to identify the PCI address of the ConnectX (any of the two interfaces is fine to use), and `mlxconfig` is used to apply the changes.

   ```
   mlx_pci=$(sudo ibdev2netdev -v | awk '{print $1}' | head -n1)
   sudo mlxconfig -d $mlx_pci set LINK_TYPE_P1=ETH LINK_TYPE_P2=ETH
   ```

   Note: `LINK_TYPE_P1` and `LINK_TYPE_P2` are for `mlx5_0` and `mlx5_1` respectively. You can choose to only set one of them. You can pass `ETH` or `2` for Ethernet mode, and `IB` or `1` for InfiniBand.

   This is the output of the command above:

   ```
   Device #1:
   ----------

   Device type:    ConnectX7
   Name:           P3740-B0-QSFP_Ax
   Description:    NVIDIA Prometheus P3740 ConnectX-7 VPI PCIe Switch Motherboard;␣
   ↪400Gb/s; dual-port QSFP; PCIe switch5.0 X8 SLOT0 ;X16 SLOT2; secure boot;
   Device:         0005:03:00.0

   Configurations:                                      Next Boot       New
         LINK_TYPE_P1                                ETH(2)          ETH(2)
         LINK_TYPE_P2                                IB(1)           ETH(2)

   Apply new Configuration? (y/n) [n] :
   ```

Next Boot is the current value that was expected to be used at the next reboot, while New is the value you're about to set to override Next Boot.

Apply with y and reboot afterwards:

```
Applying... Done!
-I- Please reboot machine to load new configurations.
```

4. Configure the IP addresses of the Ethernet interfaces

First, identify the logical names of your ConnectX interfaces. Connecting a cable in just one of the interfaces on the ConnectX will help you identify which port is which (in the example below, only mlx5_1 – i.e., eth3 – is connected):

```
$ sudo ibdev2netdev
mlx5_0 port 1 ==> eth2 (Down)
mlx5_1 port 1 ==> eth3 (Up)
```

Tip: For IGX Orin Developer Kits with no live source to connect to the ConnectX QSFP ports, adding -v can show you which logical name is mapped to each specific port:

- 0005:03.00.0 is the QSFP port closer to the PCI slots
- 0005:03.00.1 is the QSFP port closer to the RJ45 ethernet ports

```
$ sudo ibdev2netdev -v
0005:03:00.0 mlx5_0 (MT4129 - P3740-0002 ) NVIDIA IGX, P3740-0002, 2-port QSFP up to␣
↪400G, InfiniBand and Ethernet, PCIe5                                                  ␣
↪                                                        fw 28.37.0190 port 1 (DOWN  ) ==>
↪ eth2 (Down)
0005:03:00.1 mlx5_1 (MT4129 - P3740-0002 ) NVIDIA IGX, P3740-0002, 2-port QSFP up to␣
↪400G, InfiniBand and Ethernet, PCIe5                                                  ␣
↪                                                        fw 28.37.0190 port 1 (DOWN  ) ==>
↪ eth2 (Down)
```

If you have a cable connected but it does not show Up/Down in the output of ibdev2netdev, you can try to parse the output of dmesg instead. The example below shows that 0005:03:00.1 is plugged, and that it is associated with eth3:

```
$ sudo dmesg | grep -w mlx5_core
...
[   11.512808] mlx5_core 0005:03:00.0 eth2: Link down
[   11.640670] mlx5_core 0005:03:00.1 eth3: Link down
...
[ 3712.267103] mlx5_core 0005:03:00.1: Port module event: module 1, Cable plugged
```

The next step is to set a static IP on the interface you'd like to use so you can refer to it in your Holoscan applications (e.g., *Emergent cameras*, *distributed applications*. . .).

First, check if you already have an address setup. We'll use the eth3 interface in this example for mlx5_1:

```
ip -f inet addr show eth3
```

If nothing appears, or you'd like to change the address, you can set an IP and MTU (Maximum Transmission Unit) through the Network Manager user interface, CLI (`nmcli`), or other IP configuration tools. In the example below, we use `ip` (`ifconfig` is legacy) to configure the `eth3` interface with an address of `192.168.1.1/24` and a MTU of `9000` (i.e., "jumbo frame") to send Ethernet frames with a payload greater than the standard size of 1500 bytes:

```
sudo ip link set dev eth3 down
sudo ip addr add 192.168.1.1/24 dev eth3
sudo ip link set dev eth3 mtu 9000
sudo ip link set dev eth3 up
```

Note: If you are connecting the ConnectX to another ConnectX with a LinkX interconnect, do the same on the other system with an IP address on the same network segment.

For example, to communicate with `192.168.1.1/24` above (`/24 -> 255.255.255.0` submask), setup your other system with an IP between `192.168.1.2` and `192.168.1.254`, and the same `/24` submask.

5.1.2 Enabling GPUDirect RDMA

Note: Only supported on NVIDIA's Quadro/workstation GPUs (not GeForce).

Follow the instructions below to enable GPUDirect RDMA:

dGPU

On dGPU, the GPUDirect RDMA drivers are named `nvidia-peermem`, and are installed with the rest of the NVIDIA dGPU drivers.

Attention: To enable the use of GPUDirect RDMA with a ConnectX SmartNIC (section above), the following steps are required if the MOFED drivers were installed after the peermem drivers:

```
nv_driver_version=$(modinfo nvidia | awk '/^version:/ {print $2}' | cut -d. -f1)
sudo dpkg-reconfigure nvidia-dkms-$nv_driver_version # or nvidia-dkms-${nv_driver_
↪version}-server
```

Load the peermem kernel module manually:

```
sudo modprobe nvidia-peermem
```

Run the following to load it automatically during boot:

```
echo nvidia-peermem | sudo tee -a /etc/modules
```

iGPU

Warning: At this time, the IGX SW 1.0 DP and JetPack 6.0 DP are missing the `nvidia-p2p` kernel for support for GPU Direct RDMA support. They're planned in the respective GA releases. The instructions below are to load the kernel module once it is packaged in the GA releases.

On iGPU, the GPUDirect RDMA drivers are named `nvidia-p2p`. Run the following to load the kernel module manually:

```
sudo modprobe nvidia-p2p
```

Run the following to load it automatically during boot:

```
echo nvidia-p2p | sudo tee -a /etc/modules
```

5.1.3 Testing with Rivermax

The instructions below describe the steps to test GPUDirect using the Rivermax SDK. The test applications used by these instructions, `generic_sender` and `generic_receiver`, can then be used as samples in order to develop custom applications that use the Rivermax SDK to optimize data transfers.

Note: The Linux default path where Rivermax expects to find the license file is `/opt/mellanox/rivermax/rivermax.lic`, or you can specify the full path and file name for the environment variable `RIVERMAX_LICENSE_PATH`.

Note: If manually installing the Rivermax SDK from the link above, please note there is no need to follow the steps for installing MLNX_OFED/MLNX_EN in the Rivermax documentation.

Running the Rivermax sample applications requires two systems, a sender and a receiver, connected via ConnectX network adapters. If two Developer Kits are used, then the onboard ConnectX can be used on each system. However, if only one Developer Kit is available, then it is expected that another system with an add-in ConnectX network adapter will need to be used. Rivermax supports a wide array of platforms, including both Linux and Windows, but these instructions assume that another Linux based platform will be used as the sender device while the Developer Kit is used as the receiver.

Note: The `$rivermax_sdk` variable referenced below corresponds to the path where the Rivermax SDK package is installed. If the Rivermax SDK was installed via SDK Manager, this path will be:

```
rivermax_sdk=$HOME/Documents/Rivermax/1.31.10
```

If the Rivermax SDK was installed via a manual download, make sure to export your path to the SDK:

```
rivermax_sdk=$DOWNLOAD_PATH/1.31.10
```

The install path might differ in future versions of Rivermax.

1. Determine the logical name for the ConnectX devices that are used by each system. This can be done by using the `lshw -class network` command, finding the `product:` entry for the ConnectX device, and making note of the `logical name:` that corresponds to that device. For example, this output on a Developer Kit shows

the onboard ConnectX device using the `enp9s0f01` logical name (`lshw` output shortened for demonstration purposes).

```
$ sudo lshw -class network
*-network:0
     description: Ethernet interface
     product: MT28908 Family [ConnectX-6]
     vendor: Mellanox Technologies
     physical id: 0
     bus info: pci@0000:09:00.0
     <b>logical name: enp9s0f0</b>
     version: 00
     serial: 48:b0:2d:13:9b:6b
     capacity: 10Gbit/s
     width: 64 bits
     clock: 33MHz
     capabilities: pciexpress vpd msix pm bus_master cap_list ethernet physical␣
↪1000bt-fd 10000bt-fd autonegotiation
     configuration: autonegotiation=on broadcast=yes driver=mlx5_core␣
↪driverversion=5.4-1.0.3 duplex=full firmware=20.27.4006 (NVD0000000001) ip=10.0.0.
↪2 latency=0 link=yes multicast=yes
     resources: iomemory:180-17f irq:33 memory:1818000000-1819ffffff
```

The instructions that follow will use the `enp9s0f0` logical name for `ifconfig` commands, but these names should be replaced with the corresponding logical names as determined by this step.

2. Run the `generic_sender` application on the sending system.

   a. Bring up the network:

```
$ sudo ifconfig enp9s0f0 up 10.0.0.1
```

   b. Build the sample apps:

```
$ cd ${rivermax_sdk}/apps
$ make
```

   e. Launch the `generic_sender` application:

```
$ sudo ./generic_sender -l 10.0.0.1 -d 10.0.0.2 -p 5001 -y 1462 -k 8192 -z 500 -v
```

   which gives

```
+#############################################
| Sender index: 0
| Thread ID: 0x7fa1ffb1c0
| CPU core affinity: -1
| Number of streams in this thread: 1
| Memory address: 0x7f986e3010
| Memory length: 59883520[B]
| Memory key: 40308
+#############################################
| Stream index: 0
| Source IP: 10.0.0.1
| Destination IP: 10.0.0.2
```

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```
| Destination port: 5001
| Number of flows: 1
| Rate limit bps: 0
| Rate limit max burst in packets: 0
| Memory address: 0x7f986e3010
| Memory length: 59883520[B]
| Memory key: 40308
| Number of user requested chunks: 1
| Number of application chunks: 5
| Number of packets in chunk: 8192
| Packet's payload size: 1462
+**********************************************
```

3. Run the generic_receiver application on the receiving system.

   a. Bring up the network:

```
$ sudo ifconfig enp9s0f0 up 10.0.0.2
```

   b. Build the generic_receiver app with GPUDirect support from the Rivermax GitHub Repo. Before following the instructions to build with CUDA Toolkit support, apply the changes to the file generic_receiver/generic_receiver.cpp in this PR. This was tested on the NVIDIA IGX Orin Developer Kit with Rivermax 1.31.10.

   c. Launch the generic_receiver application from the build directory:

```
$ sudo ./generic_receiver -i 10.0.0.2 -m 10.0.0.2 -s 10.0.0.1 -p 5001 -g 0
...
Attached flow 1 to stream.
Running main receive loop...
Got 5877704 GPU packets | 68.75 Gbps during 1.00 sec
Got 5878240 GPU packets | 68.75 Gbps during 1.00 sec
Got 5878240 GPU packets | 68.75 Gbps during 1.00 sec
Got 5877704 GPU packets | 68.75 Gbps during 1.00 sec
Got 5878240 GPU packets | 68.75 Gbps during 1.00 sec
...
```

With both the generic_sender and generic_receiver processes active, the receiver will continue to print out received packet statistics every second. Both processes can then be terminated with <ctrl-c>.

5.2 Enabling G-SYNC

For better performance and to keep up with the high refresh rate of Holoscan applications, we recommend the use of a G-SYNC display.

Tip: Holoscan has been tested with these two G-SYNC displays:

- Asus ROG Swift PG279QM
- Asus ROG Swift 360 Hz PG259QNR

Follow these steps to ensure G-SYNC is enabled on your display:

1. Open the "NVIDIA Settings" Graphics application (`nvidia-settings` in Terminal).
2. Click on `X Server Display Configuration` then the `Advanced` button. This will show the `Allow G-SYNC on monitor not validated as G-SYNC compatible` option. Enable the option and click `Apply`:
3. To show the refresh rate and G-SYNC label on the display window, click on `OpenGL Settings` for the selected display. Now click `Allow G-SYNC/G-SYNC Compatible` and `Enable G-SYNC/G-SYNC Compatible Visual Indicator` options, then click `Quit`. This step is shown in the image below. The `Gsync` indicator is at the top right of the screen once the application is running.

5.3 Disabling Variable Backlight

Various monitors have a Variable Backlight feature. That setting can add up to a frame of latency when enabled. Refer to your monitor's manufacturer instructions to disable it.

Tip: To disable variable backlight on the ASUS ROG Swift monitors mentioned above, use the joystick button at the back of the display, go to the `image` tag, select `variable backlight`, then switch that setting to `OFF`.

5.4 Enabling Exclusive Display Mode

By default, applications use a borderless full screen window managed by the window manager. Because the window manager also manages other applications, applications may suffer a performance hit. To improve performance, exclusive display mode can be used with Holoscan's new visualization module (Holoviz), allowing the application to bypass the window manager and render directly to the display. Refer to the *Holoviz documentation* for details.

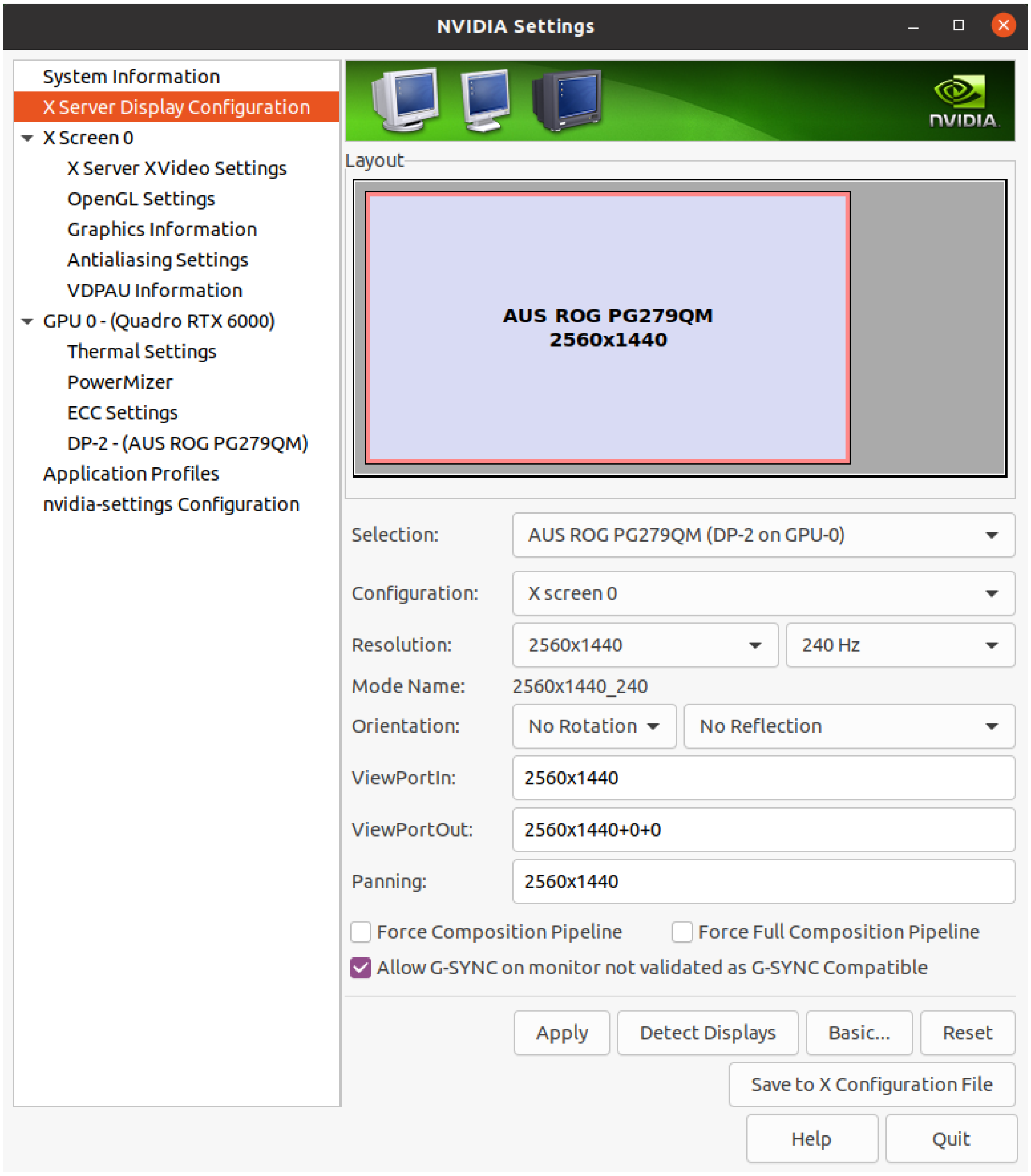
5.5 Use both Integrated and Discrete GPUs on NVIDIA Developer Kits

NVIDIA Developer Kits like the NVIDIA IGX Orin or the NVIDIA Clara AGX have both a discrete GPU (dGPU - optional on IGX Orin) and an integrated GPU (iGPU - Tegra SoC).

As of this release, when these developer kits are flashed to leverage the dGPU, there are two limiting factors preventing the use of the iGPU:

1. Conflict between the dGPU kernel mode driver and the iGPU display kernel driver (both named `nvidia.ko`). This conflict is not addressable at this time, meaning that **the iGPU cannot be used for display while the dGPU is enabled**.
2. Conflicts between the user mode driver libraries (ex: `libcuda.so`) and the compute stack (ex: `libcuda_rt.so`) for dGPU and iGPU.

We provide utilities to work around the second conflict:



NVIDIA Settings

- System Information
- X Server Display Configuration
- X Screen 0
  - X Server XVideo Settings
  - OpenGL Settings
  - Graphics Information
  - Antialiasing Settings
  - VDPAU Information
- GPU 0 - (Quadro RTX 6000)
  - Thermal Settings
  - PowerMizer
  - ECC Settings
  - DP-2 - (AUS ROG PG279QM)
- Application Profiles
- nvidia-settings Configuration

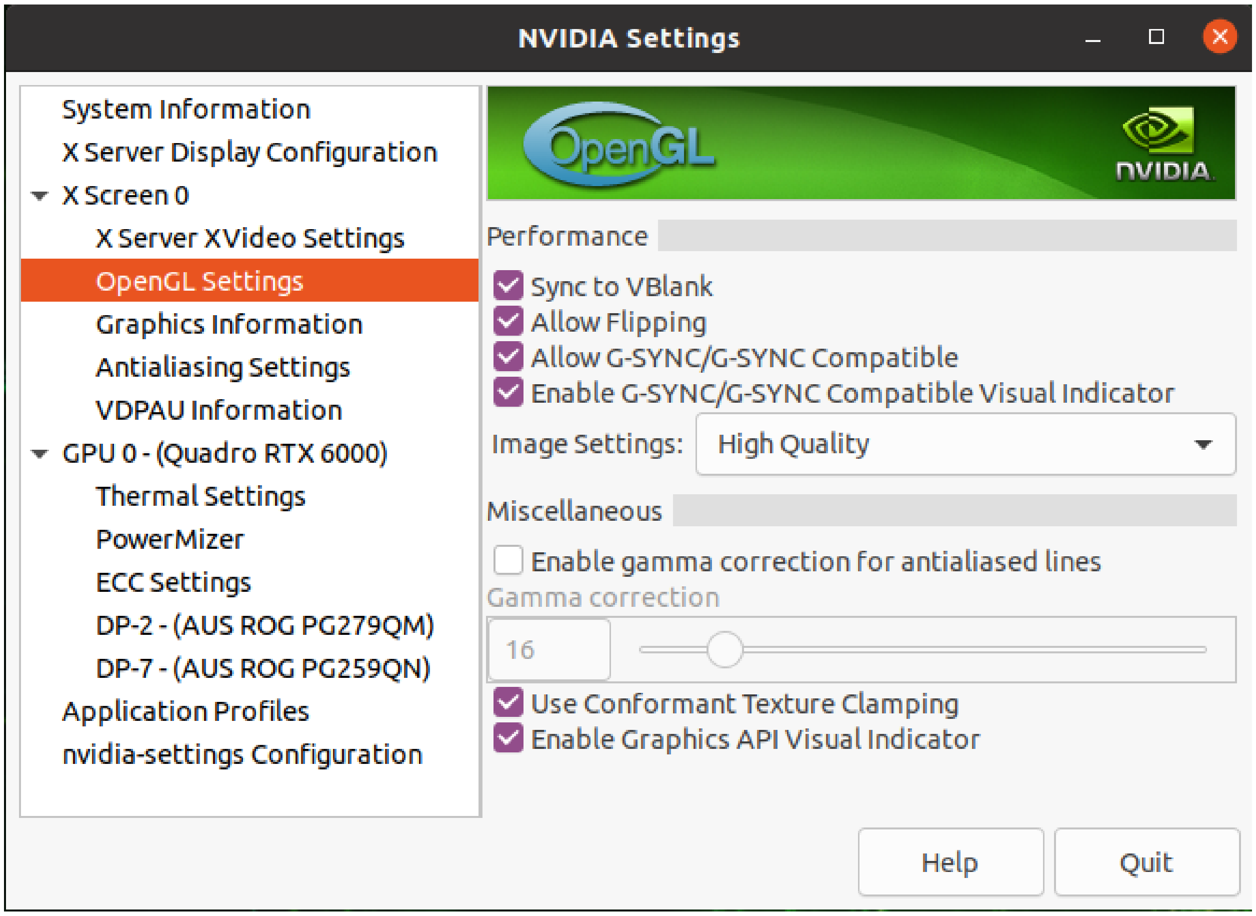
Layout

AUS ROG PG279QM
2560x1440

Selection: AUS ROG PG279QM (DP-2 on GPU-0)
Configuration: X screen 0
Resolution: 2560x1440 240 Hz
Mode Name: 2560x1440_240
Orientation: No Rotation No Reflection
ViewPortIn: 2560x1440
ViewPortOut: 2560x1440+0+0
Panning: 2560x1440

☐ Force Composition Pipeline ☐ Force Full Composition Pipeline
☑ Allow G-SYNC on monitor not validated as G-SYNC Compatible

Fig. 5.1: Enable G-SYNC for the current display



Performance

- [✓] Sync to VBlank
- [✓] Allow Flipping
- [✓] Allow G-SYNC/G-SYNC Compatible
- [✓] Enable G-SYNC/G-SYNC Compatible Visual Indicator

Image Settings: High Quality

Miscellaneous

- [ ] Enable gamma correction for antialiased lines

Gamma correction: 16

- [✓] Use Conformant Texture Clamping
- [✓] Enable Graphics API Visual Indicator

Fig. 5.2: Enable Visual Indicator for the current display

IGX SW 1.0

1. From an IGX developer kit flashed for dGPU, run the following command to enable iGPU container support:

```
sudo /opt/nvidia/l4t-igpu-container-on-dgpu-host-config/l4t-igpu-container-on-dgpu-
↪host-config.sh configure
```

Refer to the IGX user guide for details.

2. To leverage both GPUs in Holoscan, you can either:

   1. create separate Holoscan applications running concurrently, where the iGPU application must run in the Holoscan iGPU container, and the dGPU application can run bare metal or in the Holoscan dGPU container. Refer to the IGX user guide for details on how to launch a Holoscan container using the iGPU.

   2. create a single distributed application that leverages both the iGPU and dGPU by executing separate fragments on the iGPU and on the dGPU.

The example below shows the ping distributed application between the iGPU and dGPU using Holoscan containers:

```
COMMON_DOCKER_FLAGS="--rm -i --init --net=host
--runtime=nvidia -e NVIDIA_DRIVER_CAPABILITIES=all
--cap-add CAP_SYS_PTRACE --ipc=host --ulimit memlock=-1 --ulimit stack=67108864
"
HOLOSCAN_VERSION=3.1.0
HOLOSCAN_IMG="nvcr.io/nvidia/clara-holoscan/holoscan:v$HOLOSCAN_VERSION"
HOLOSCAN_DGPU_IMG="$HOLOSCAN_IMG-dgpu"
HOLOSCAN_IGPU_IMG="$HOLOSCAN_IMG-igpu"

# Pull images
docker pull $HOLOSCAN_DGPU_IMG
docker pull $HOLOSCAN_IGPU_IMG

# Run ping distributed (python) in dGPU container
# - Making this one the `driver`, but could be igpu too
# - Using & to not block the terminal to run igpu afterwards. Could run igpu in separate␣
↪terminal instead.
docker run \
  $COMMON_DOCKER_FLAGS \
  $HOLOSCAN_DGPU_IMG \
  bash -c "python3 ./examples/ping_distributed/python/ping_distributed.py --gpu --worker␣
↪--driver" &

# Run ping distributed (c++) in iGPU container
docker run \
  $COMMON_DOCKER_FLAGS \
  -e NVIDIA_VISIBLE_DEVICES=nvidia.com/igpu=0 \
  $HOLOSCAN_IGPU_IMG \
  bash -c "./examples/ping_distributed/cpp/ping_distributed --gpu --worker"
```

HoloPack 1.2+

The L4T Compute Assist is a container on NGC which isolates the iGPU stack by containing the L4T BSP packages in order to enable iGPU compute on the developer kits configured for dGPU. Other applications can run concurrently on the dGPU, natively or in another container.

Attention: These utilities enable using the iGPU for capabilities other than **display** only, since they do not address the first conflict listed above.

5.6 Deployment Software Stack

NVIDIA Holoscan accelerates deployment of production-quality applications by providing a set of **OpenEmbedded** build recipes and reference configurations that can be leveraged to customize and build Holoscan-compatible Linux4Tegra (L4T) embedded board support packages (BSP) on the NVIDIA IGX Developer Kits.

Holoscan OpenEmbedded/Yocto recipes add OpenEmbedded recipes and sample build configurations to build BSPs for the NVIDIA IGX Developer Kit that feature support for discrete GPUs (dGPU), AJA Video Systems I/O boards, and the Holoscan SDK. These BSPs are built on a developer's host machine and are then flashed onto the NVIDIA IGX Developer Kit using provided scripts.

There are two options available to set up a build environment and start building Holoscan BSP images using OpenEmbedded.

1. The first sets up a local build environment in which all dependencies are fetched and installed manually by the developer directly on their host machine. Please refer to the Holoscan OpenEmbedded/Yocto recipes README for more information on how to use the local build environment.
2. The second uses a Holoscan OpenEmbedded/Yocto Build Container that is provided by NVIDIA on NGC, which contains all of the dependencies and configuration scripts so the entire process of building and flashing a BSP can be done with just a few simple commands.

CHAPTER

SIX

THIRD PARTY HARDWARE SETUP

GPU compute performance is a key component of the Holoscan hardware platforms, and in order to optimize GPU-based video processing applications and provide lowest possible latency, the Holoscan SDK now supports AJA Video Systems capture cards and Emergent Vision Technologies high-speed cameras. The following sections will provide more information on how to setup the system with these technologies.

6.1 AJA Video Systems

AJA provides a wide range of proven, professional video I/O devices, and thanks to a partnership between NVIDIA and AJA, Holoscan provides ongoing support for the AJA NTV2 SDK and device drivers.

The AJA drivers and SDK offer RDMA support for NVIDIA GPUs. This feature allows video data to be captured directly from the AJA card to GPU memory, which significantly reduces latency and system PCI bandwidth for GPU video processing applications as sysmem to GPU copies are eliminated from the processing pipeline.

The following instructions describe the steps required to setup and use an AJA device with RDMA support on NVIDIA Developer Kits with a PCIe slot. Note that the AJA NTV2 SDK support for Holoscan includes all of the AJA Developer Products, though the following instructions have only been verified for the Corvid 44 12G BNC, *KONA XM*, and KONA HDMI products, specifically.

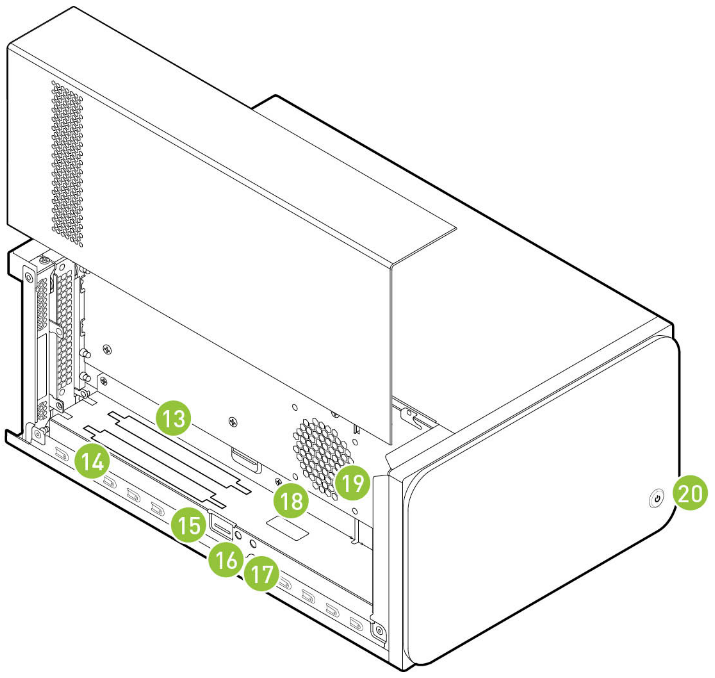
Note: The addition of an AJA device to a NVIDIA Developer Kit is optional. The Holoscan SDK has elements that can be run with an AJA device with the additional features mentioned above, but those elements can also run without AJA. For example, there are Holoscan sample applications that have an AJA live input component, however they can also take in video replay as input. Similarly, the latency measurement tool can measure the latency of the video I/O subsystem with or without an AJA device available.

6.1.1 Installing the AJA Hardware

This section describes how to install the AJA hardware on the Clara AGX Developer Kit. Note that the AJA Hardware is also compatible with the NVIDIA IGX Orin Developer Kit.

To install an AJA Video Systems device into the Clara AGX Developer Kit, remove the side access panel by removing two screws on the back of the Clara AGX. This provides access to the two available PCIe slots, labelled 13 and 14 in the Clara AGX Developer Kit User Guide:

While these slots are physically identical PCIe x16 slots, they are connected to the Clara AGX via different PCIe bridges. Only slot 14 shares the same PCIe bridge as the RTX6000 dGPU, and so the AJA device must be installed into slot 14 for RDMA support to be available. The following image shows a Corvid 44 12G BNC card installed into slot 14 as needed to enable RDMA support.


13
14
15
16
17
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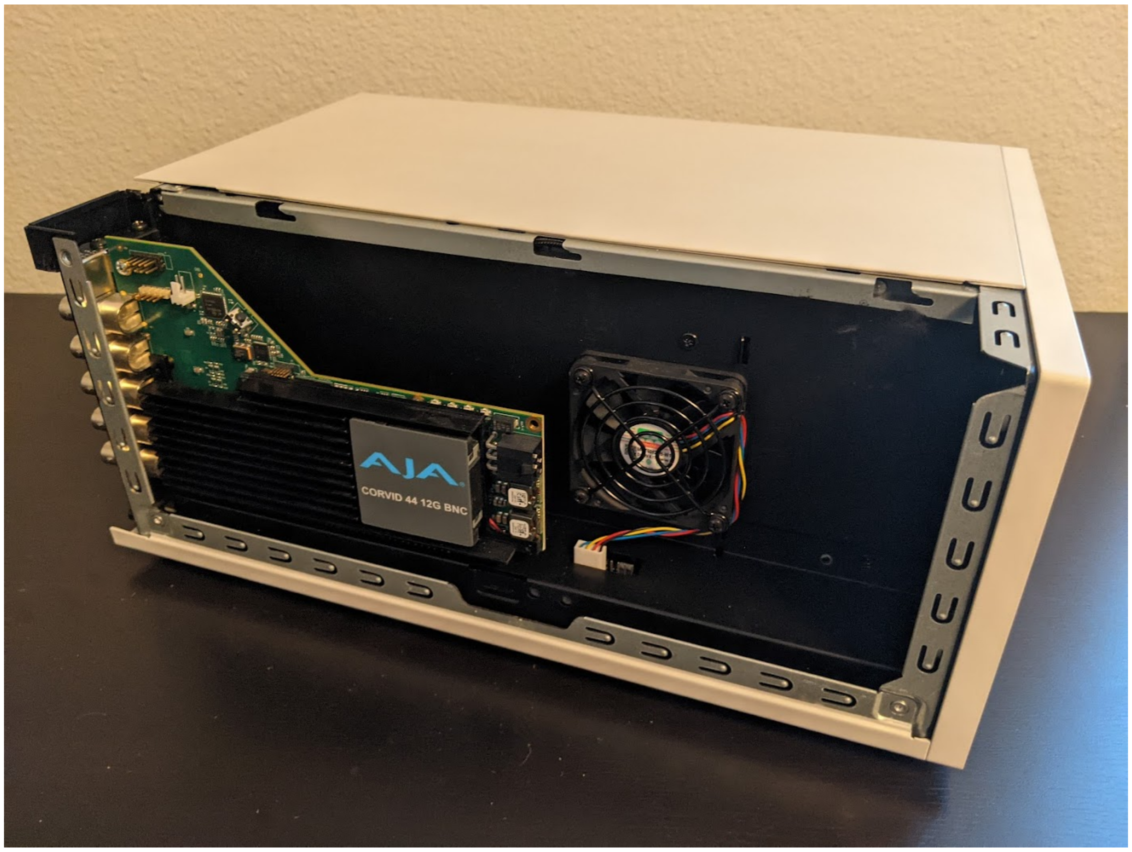
20


AJA
CORVID 44 12G BNC

6.1.2 Installing the AJA Software

The AJA NTV2 SDK includes both the drivers (kernel module) that are required in order to enable an AJA device, as well as the SDK (headers and libraries) that are used to access an AJA device from an application.

The drivers must be loaded every time the system is rebooted, and they must be loaded natively on the host system (i.e. not inside a container). The drivers must be loaded regardless of whether applications will be run natively or inside a container (see *Using AJA Devices in Containers*).

The SDK only needs to be installed on the native host and/or container that will be used to compile applications with AJA support. The Holoscan SDK containers already have the NTV2 SDK installed, and so no additional steps are required to build AJA-enabled applications (such as the reference Holoscan applications) within these containers. However, installing the NTV2 SDK and utilities natively on the host is useful for the initial setup and testing of the AJA device, so the following instructions cover this native installation.

Note: To summarize, the steps in this section must be performed on the native host, outside of a container, with the following steps **required once**:

- *Downloading the AJA NTV2 SDK Source*
- *Building the AJA NTV2 Drivers*

The following steps **required after every reboot**:

- *Loading the AJA NTV2 Drivers*

And the following steps are **optional** (but recommended during the initial setup):

- *Building and Installing the AJA NTV2 SDK*
- *Testing the AJA Device*

Using the AJA NTV2 Driver and SDK Build Script

Included in the *scripts* directory is the *aja_build.sh* script which can be used to download the AJA NTV2 source, build the drivers and SDK, load the drivers, and run the *ntv2enumerateboards* utility to list the AJA boards that are connected to the system. To download and build the drivers and SDK, simply run the script:

```
$ ./scripts/aja_build.sh
```

To optionally have the script load the drivers and list the connected devices once the build is complete, add the *–load-driver* flag:

```
$ ./scripts/aja_build.sh --load-driver
```

Note: The remainder of the steps in this documentation describe how to manually build and load the AJA NTV2 drivers and SDK, and are not needed when using the build script. However, it will still be required to reload the drivers after rebooting the system by running the *load_ajantv2* command as described in *Loading the AJA NTV2 Drivers*.

Downloading the AJA NTV2 SDK Source

Navigate to a directory where you would like the source code to be downloaded, then perform the following to clone the NTV2 SDK source code.

```
$ git clone https://github.com/nvidia-holoscan/libajantv2.git
$ export NTV2=$(pwd)/libajantv2
```

Note: These instructions use a fork of the official AJA NTV2 Repository that is maintained by NVIDIA and may contain additional changes that are required for Holoscan SDK support. These changes will be pushed to the official AJA NTV2 repository whenever possible with the goal to minimize or eliminate divergence between the two repositories.

Installing the NVIDIA Open Kernel Modules for RDMA Support

If the AJA NTV2 drivers are going to be built with RDMA support, the open-source NVIDIA kernel modules must be installed instead of the default proprietary drivers. If the drivers were installed from an NVIDIA driver installer package then follow the directions on the NVIDIA Open GPU Kernel Module Source GitHub page. If the NVIDIA drivers were installed using an Ubuntu package via *apt*, then replace the installed *nvidia-kernel-source* package with the corresponding *nvidia-kernel-open* package. For example, the following shows that the *545* version drivers are installed:

```
S dpkg --list | grep nvidia-kernel-source
ii  nvidia-kernel-source-545    545.23.08-0ubuntu1    amd64    NVIDIA kernel␣
↪source package
```

And the following will replace those with the corresponding *nvidia-kernel-open* drivers:

```
S sudo apt install -y nvidia-kernel-open-545
$ sudo dpkg-reconfigure nvidia-dkms-545
```

The system must then be rebooted to load the new open kernel modules.

Building the AJA NTV2 Drivers

The following will build the AJA NTV2 drivers with RDMA support enabled. Once built, the kernel module (**ajantv2.ko**) and load/unload scripts (**load_ajantv2** and **unload_ajantv2**) will be output to the `${NTV2}/driver/bin` directory.

```
$ export AJA_RDMA=1 # Or unset AJA_RDMA to disable RDMA support
$ unset AJA_IGPU # Or export AJA_IGPU=1 to run on the integrated GPU of the␣
↪IGX Orin Devkit (L4T >= 35.4)
$ make -j --directory ${NTV2}/driver/linux
```

Loading the AJA NTV2 Drivers

Running any application that uses an AJA device requires the AJA kernel drivers to be loaded, even if the application is being run from within a container.

Note: To enable RDMA with AJA, ensure the *NVIDIA GPUDirect RDMA kernel module is loaded* before the AJA NTV2 drivers.

The AJA drivers must be manually loaded every time the machine is rebooted using the **load_ajantv2** script:

```
$ sudo sh ${NTV2}/driver/bin/load_ajantv2
loaded ajantv2 driver module
```

Note: The `NTV2` environment variable must point to the NTV2 SDK path where the drivers were previously built as described in *Building the AJA NTV2 Drivers*.

Secure boot must be disabled in order to load unsigned module. If any errors occur while loading the module refer to the *Troubleshooting* section, below.

Building and Installing the AJA NTV2 SDK

Since the AJA NTV2 SDK is already loaded into the Holoscan containers, this step is not strictly required in order to build or run any Holoscan applications. However, this builds and installs various tools that can be useful for testing the operation of the AJA hardware outside of Holoscan containers, and is required for the steps provided in *Testing the AJA Device*.

```
$ sudo apt-get install -y cmake
$ mkdir ${NTV2}/cmake-build
$ cd ${NTV2}/cmake-build
$ export PATH=/usr/local/cuda/bin:${PATH}
$ cmake ..
$ make -j
$ sudo make install
```

Testing the AJA Device

The following steps depend on tools that were built and installed by the previous step, *Building and Installing the AJA NTV2 SDK*. If any errors occur, see the *Troubleshooting* section, below.

1. To ensure that an AJA device has been installed correctly, the `ntv2enumerateboards` utility can be used:

```
$ ntv2enumerateboards
AJA NTV2 SDK version 16.2.0 build 3 built on Wed Feb 02 21:58:01 UTC 2022
1 AJA device(s) found:
AJA device 0 is called 'KonaHDMI - 0'

This device has a deviceID of 0x10767400
This device has 0 SDI Input(s)
This device has 0 SDI Output(s)
This device has 4 HDMI Input(s)
```

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```
This device has 0 HDMI Output(s)
This device has 0 Analog Input(s)
This device has 0 Analog Output(s)

47 video format(s):
    1080i50, 1080i59.94, 1080i60, 720p59.94, 720p60, 1080p29.97, 1080p30,
    1080p25, 1080p23.98, 1080p24, 2Kp23.98, 2Kp24, 720p50, 1080p50b,
    1080p59.94b, 1080p60b, 1080p50a, 1080p59.94a, 1080p60a, 2Kp25, 525i59.94,
    625i50, UHDp23.98, UHDp24, UHDp25, 4Kp23.98, 4Kp24, 4Kp25, UHDp29.97,
    UHDp30, 4Kp29.97, 4Kp30, UHDp50, UHDp59.94, UHDp60, 4Kp50, 4Kp59.94,
    4Kp60, 4Kp47.95, 4Kp48, 2Kp60a, 2Kp59.94a, 2Kp29.97, 2Kp30, 2Kp50a,
    2Kp47.95a, 2Kp48a
```

2. To ensure that RDMA support has been compiled into the AJA driver and is functioning correctly, the `rdmawhacker` utility can be used (use <*ctrl-c*> to terminate):

```
$ rdmawhacker

DMA engine 1 WRITE 8388608 bytes  rate: 3975.63 MB/sec  496.95 xfers/sec
Max rate: 4010.03 MB/sec
Min rate: 3301.69 MB/sec
Avg rate: 3923.94 MB/sec
```

6.1.3 Using AJA Devices in Containers

Accessing an AJA device from a container requires the drivers to be loaded natively on the host (see *Loading the AJA NTV2 Drivers*), then the device that is created by the **load_ajantv2** script must be shared with the container using the `--device` docker argument, such as *–device /dev/ajantv20:/dev/ajantv20*.

6.1.4 Troubleshooting

1. **Problem:** The `sudo sh ${NTV2}/driver/bin/load_ajantv2` command returns an error.

   Solutions:

   a. Make sure the AJA card is properly installed and powered (see 2.a below)

   b. Check if SecureBoot validation is disabled:

   ```
   $ sudo mokutil --sb-state
     SecureBoot enabled
     SecureBoot validation is disabled in shim
   ```

   If SecureBoot validation is enabled, disable it with the following procedure:

   ```
   $ sudo mokutil --disable-validation
   ```

   - Enter a temporary password and reboot the system.
   - Upon reboot press any key when you see the blue screen MOK Management
   - Select Change Secure Boot state
   - Enter the password your selected

- Select Yes to disable Secure Book in shim-signed
- After reboot you can verify again that SecureBoot validation is disabled in shim.

2. **Problem:** The `ntv2enumerateboards` command does not find any devices.

   Solutions:

   a. Make sure that the AJA device is installed properly and detected by the system (see *Installing the AJA Hardware*):

   ```
   $ lspci
   0000:00:00.0 PCI bridge: NVIDIA Corporation Device 1ad0 (rev a1)
   0000:05:00.0 Multimedia video controller: AJA Video Device eb25 (rev 01)
   0000:06:00.0 PCI bridge: Mellanox Technologies Device 1976
   0000:07:00.0 PCI bridge: Mellanox Technologies Device 1976
   0000:08:00.0 VGA compatible controller: NVIDIA Corporation Device 1e30 (rev a1)
   ```

   b. Make sure that the AJA drivers are loaded properly (see *Loading the AJA NTV2 Drivers*):

   ```
   $ lsmod
   Module                  Size  Used by
   ajantv2               610066  0
   nvidia_drm             54950  4
   mlx5_ib               170091  0
   nvidia_modeset       1250361  8 nvidia_drm
   ib_core               211721  1 mlx5_ib
   nvidia              34655210  315 nvidia_modeset
   ```

3. **Problem:** The `rdmawhacker` command outputs the following error:

   ```
   ## ERROR: GPU buffer lock failed
   ```

   Solution: The AJA drivers need to be compiled with RDMA support enabled. Follow the instructions in *Building the AJA NTV2 Drivers*, making sure not to skip the `export AJA_RDMA=1` when building the drivers.

6.2 Emergent Vision Technologies (EVT)

Thanks to a collaboration with Emergent Vision Technologies, the Holoscan SDK now supports EVT high-speed cameras on NVIDIA Developer Kits equipped with a ConnectX NIC using the Rivermax SDK.

6.2.1 Installing EVT Hardware

The EVT cameras can be connected to NVIDIA Developer Kits through a Mellanox ConnectX SmartNIC, with the most simple connection method being a single cable between a camera and the devkit. For 25 GigE cameras that use the SFP28 interface, this can be achieved by using SFP28 cable with QSFP28 to SFP28 adaptor.

Note: The Holoscan SDK application has been tested using a SFP28 copper cable of 2M or less. Longer copper cables or optical cables and optical modules can be used but these have not been tested as a part of this development.

Refer to the NVIDIA IGX Orin Developer Kit User Guide for the location of the QSFP28 connector on the device.

For EVT camera setup, refer to Hardware Installation in EVT Camera User's Manual. Users need to log in to find be able to download Camera User's Manual.

Tip: The EVT cameras require the user to buy the lens. Based on the application of camera, the lens can be bought from any online store.

6.2.2 Installing EVT Software

The Emergent SDK needs to be installed in order to compile and run the Clara Holoscan applications with EVT camera. The latest tested version of the Emergent SDK is `eSDK 2.37.05 Linux Ubuntu 20.04.04 Kernel 5.10.65 JP 5.0 HP` and can be downloaded from here. The Emergent SDK comes with headers, libraries and examples. To install the SDK refer to the Software Installation section of EVT Camera User's Manual. Users need to log in to find be able to download Camera User's Manual.

Note: The Emergent SDK depends on Rivermax SDK and the Mellanox OFED Network Drivers. If they're already installed on your system, use the following command when installing the Emergent SDK to avoid duplicate installation:

```
sudo ./install_eSdk.sh no_mellanox
```

Ensure the *ConnectX is properly configured* to use it with the Emergent SDK.

6.2.3 Testing the EVT Camera

To test if the EVT camera and SDK was installed correctly, run the `eCapture` application with `sudo` privileges. First, ensure that a valid Rivermax license file is under `/opt/mellanox/rivermax/rivermax.lic`, then follow the instructions under the eCapture section of EVT Camera User's Manual.

6.2.4 Troubleshooting

1. **Problem:** The application fails to find the EVT camera.

   Solution:

   - Make sure that the MLNX ConnectX SmartNIC is configured with the correct IP address. Follow section *Configure the ConnectX SmartNIC*

2. **Problem:** The application fails to open the EVT camera.

   Solutions:

   - Make sure that the application was run with `sudo` privileges.
   - Make sure a valid Rivermax license file is located at `/opt/mellanox/rivermax/rivermax.lic`.

3. **Problem:** Fail to find `eCapture` application in the home window.

   Solution:

   - Open the terminal and find it under `/opt/EVT/eCapture`. The applications needs to be run with `sudo` privileges.

4. **Problem:** The `eCapture` application fails to connect to the EVT camera with error message "GVCP ack error".

   Solutions: It could be an issue with the HR12 power connection to the camera. Disconnect the HR12 power connector from the camera and try reconnecting it.

5. **Problem:** The IP address of the Emergent camera is reset even after setting up with the above steps.

Solutions: Check whether the NIC settings in Ubuntu is set to "Connect automatically". Go to `Settings->Network->NIC for the Camera` and then unselect "Connect automatically" and in the IPv6 tab, select `Disable`.

CHAPTER

SEVEN

HOLOSCAN CORE CONCEPTS

Note: In its early days, the Holoscan SDK was tightly linked to the *GXF core concepts*. While the Holoscan SDK still relies on GXF as a backend to execute applications, it now offers its own interface, including a C++ API (0.3), a Python API (0.4), and the ability to write native operators (0.4) without requiring to wrap a GXF extension. Read the *Holoscan and GXF* section for additional details.

An `Application` is composed of `Fragments`, each of which runs a graph of `Operators`. The implementation of that graph is sometimes referred to as a pipeline, or workflow, which can be visualized below:

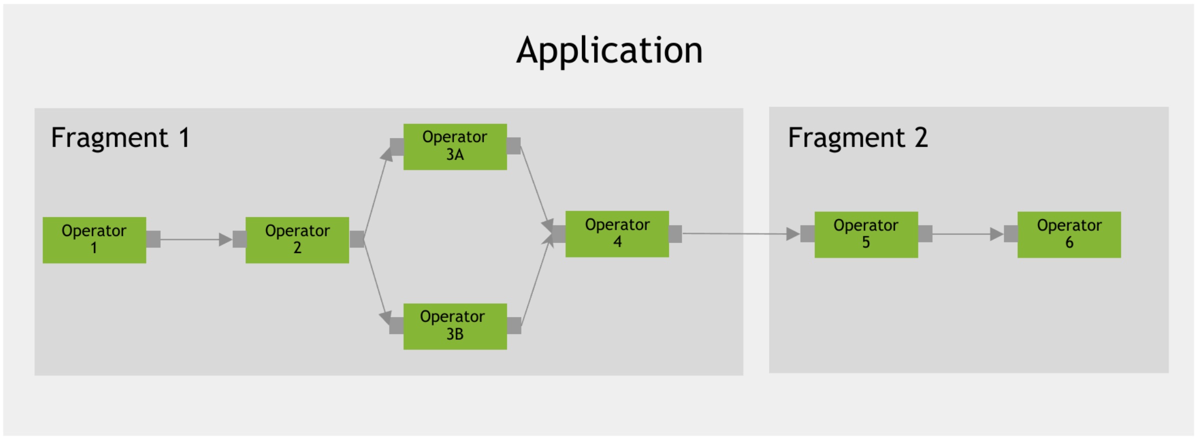

Fig. 7.1: Core concepts: Application

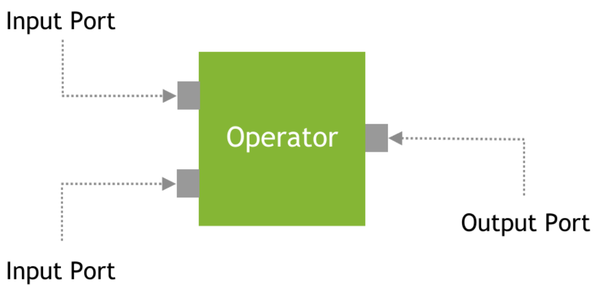

Fig. 7.2: Core concepts: Port

The core concepts of the Holoscan API are:

- **Application**: An application acquires and processes streaming data. An application is a collection of fragments where each fragment can be allocated to execute on a physical node of a Holoscan cluster.
- **Fragment**: A fragment is a building block of the application. It is a directed graph of operators. A fragment can be assigned to a physical node of a Holoscan cluster during execution. The runtime execution manages communication across fragments. In a fragment, Operators (Graph Nodes) are connected to each other by flows (Graph Edges).
- **Operator**: An operator is the most basic unit of work in this framework. An operator receives streaming data at an input port, processes it, and publishes it to one of its output ports. A *Codelet* in GXF would be replaced by an `Operator` in the Holoscan SDK. An `Operator` encapsulates `Receiver`s and `Transmitter`s of a GXF *Entity* as Input/Output `Port`s of the `Operator`.
- **(Operator) Resource**: Resources such as system memory or a GPU memory pool that an operator needs to perform its job. Resources are allocated during the initialization phase of the application. This matches the semantics of GXF's Memory `Allocator` or any other components derived from the `Component` class in GXF.
- **Condition**: A condition is a predicate that can be evaluated at runtime to determine if an operator should execute. This matches the semantics of GXF's *Scheduling Term*.
- **Port**: A port is an interaction point between two operators. Operators ingest data at Input ports and publish data at Output ports. `Receiver`, `Transmitter`, and `MessageRouter` in GXF would be replaced with the concept of Input/Output `Port` of the `Operator` and the `Flow` (Edge) of the Application Workflow (DAG) in the Framework.
- **Message**: A message is a generic data object used by operators to communicate information.
- **Executor**: An executor that manages the execution of a fragment on a physical node. The framework provides a default executor that uses a GXF *Scheduler* to execute an application.

CHAPTER

EIGHT

HOLOSCAN BY EXAMPLE

In this section, we demonstrate how to use the Holoscan SDK to build applications through a series of examples. The concepts needed to build your own Holoscan applications will be covered as we go through each example.

Note: Example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.1 Hello World

For our first example, we look at how to create a Hello World example using the Holoscan SDK.

In this example we'll cover:

- How to define your application class.
- How to define a one-operator workflow.
- How to use a `CountCondition` to limit the number of times an operator is executed.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.1.1 Defining the HelloWorldApp class

For more details, see the Defining an Application Class *section.*

We define the `HelloWorldApp` class that inherits from holoscan's `Application` base class. An instance of the application is created in `main`. The `run()` method will then start the application.

C++

```cpp
class HelloWorldApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the operators, allowing the hello operator to execute once
    auto hello = make_operator<ops::HelloWorldOp>("hello", make_condition<CountCondition>
↪(1));

    // Define the workflow by adding operator into the graph
    add_operator(hello);
  }
};

int main(int argc, char** argv) {
  auto app = holoscan::make_application<HelloWorldApp>();
  app->run();

  return 0;
}
```

Python

```python
class HelloWorldApp(Application):
    def compose(self):
        # Define the operators
        hello = HelloWorldOp(self, CountCondition(self, 1), name="hello")

        # Define the one-operator workflow
        self.add_operator(hello)

def main():
    app = HelloWorldApp()
    app.run()

if __name__ == "__main__":
    main()
```

8.1.2 Defining the HelloWorldApp workflow

For more details, see the Application Workflows *section.*

When defining your application class, the primary task is to define the operators used in your application, and the interconnectivity between them to define the application workflow. The `HelloWorldApp` uses the simplest form of a workflow which consists of a single operator: `HelloWorldOp`.

For the sake of this first example, we will ignore the details of defining a custom operator to focus on the highlighted information below: when this operator runs (`compute`), it will print out `Hello World!` to the standard output:

C++

```cpp
class HelloWorldOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(HelloWorldOp)

  HelloWorldOp() = default;

  void setup(OperatorSpec& spec) override {
  }

  void compute(InputContext& op_input, OutputContext& op_output,
               ExecutionContext& context) override {
    std::cout << std::endl;
    std::cout << "Hello World!" << std::endl;
    std::cout << std::endl;
  }
};
```

Python

```python
class HelloWorldOp(Operator):
    """Simple hello world operator.

    This operator has no ports.

    On each tick, this operator prints out hello world.
    """

    def setup(self, spec: OperatorSpec):
        pass

    def compute(self, op_input, op_output, context):
        print("")
        print("Hello World!")
        print("")
```

Defining the application workflow occurs within the application's `compose()` method. In there, we first create an instance of the `HelloWorldOp` operator defined above, then add it to our simple workflow using `add_operator()`.

C++

```cpp
class HelloWorldApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the operators, allowing the hello operator to execute once
    auto hello = make_operator<ops::HelloWorldOp>("hello", make_condition<CountCondition>
↪(1));
```

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```

    // Define the workflow by adding operator into the graph
    add_operator(hello);
  }
};
```

Python

```python
class HelloWorldApp(Application):
    def compose(self):
        # Define the operators
        hello = HelloWorldOp(self, CountCondition(self, 1), name="hello")

        # Define the one-operator workflow
        self.add_operator(hello)
```

Holoscan applications deal with streaming data, so an operator's `compute()` method will be called continuously until some situation arises that causes the operator to stop. For our Hello World example, we want to execute the operator only once. We can impose such a condition by passing a `CountCondition` object as an argument to the operator's constructor.

For more details, see the Configuring operator conditions *section.*

8.1.3 Running the Application

Running the application should give you the following output in your terminal:

```
Hello World!
```

Congratulations! You have successfully run your first Holoscan SDK application!

8.2 Ping Simple

Most applications will require more than one operator. In this example, we will create two operators where one operator will produce and send data while the other operator will receive and print the data. The code in this example makes use of the built-in **PingTxOp** and **PingRxOp** operators that are defined in the `holoscan::ops` namespace.

In this example we'll cover:

- How to use built-in operators.
- How to use `add_flow()` to connect operators together.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.2.1 Operators and Workflow

Here is an example workflow involving two operators that are connected linearly.

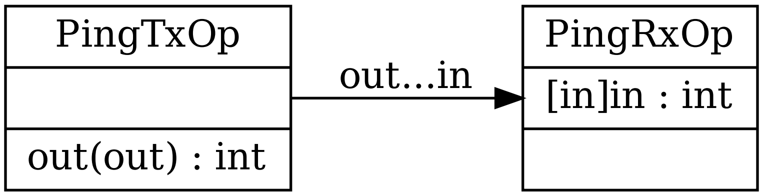

Fig. 8.1: A linear workflow

In this example, the source operator **PingTxOp** produces integers from 1 to 10 and passes it to the sink operator **PingRxOp** which prints the integers to standard output.

8.2.2 Connecting Operators

We can connect two operators by calling `add_flow()` (`C++`/`Python`) in the application's `compose()` method.

The `add_flow()` method (`C++`/`Python`) takes the source operator, the destination operator, and the optional port name pairs. The port name pair is used to connect the output port of the source operator to the input port of the destination operator. The first element of the pair is the output port name of the upstream operator and the second element is the input port name of the downstream operator. An empty port name ("") can be used for specifying a port name if the operator has only one input/output port. If there is only one output port in the upstream operator and only one input port in the downstream operator, the port pairs can be omitted.

The following code shows how to define a linear workflow in the `compose()` method for our example. Note that when an operator appears in an `add_flow()` statement, it doesn't need to be added into the workflow separately using `add_operator()`.

C++

```cpp
#include <holoscan/holoscan.hpp>
#include <holoscan/operators/ping_tx/ping_tx.hpp>
#include <holoscan/operators/ping_rx/ping_rx.hpp>

class MyPingApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;
    // Create the tx and rx operators
    auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
    auto rx = make_operator<ops::PingRxOp>("rx");

    // Connect the operators into the workflow:  tx -> rx
```

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```
14      add_flow(tx, rx);
15    }
16  };
17
18  int main(int argc, char** argv) {
19    auto app = holoscan::make_application<MyPingApp>();
20    app->run();
21
22    return 0;
23  }
```

- The header files that define **PingTxOp** and **PingRxOp** are included on lines 2 and 3 respectively.
- We create an instance of the **PingTxOp** using the `make_operator()` function (line 10) with the name "tx" and constrain its `compute()` method to execute 10 times.
- We create an instance of the **PingRxOp** using the `make_operator()` function (line 11) with the name "rx."
- The tx and rx operators are connected using `add_flow()` (line 14).

Python

```
1   from holoscan.conditions import CountCondition
2   from holoscan.core import Application
3   from holoscan.operators import PingRxOp, PingTxOp
4
5   class MyPingApp(Application):
6       def compose(self):
7           # Create the tx and rx operators
8           tx = PingTxOp(self, CountCondition(self, 10), name="tx")
9           rx = PingRxOp(self, name="rx")
10
11          # Connect the operators into the workflow:  tx -> rx
12          self.add_flow(tx, rx)
13
14
15  def main():
16      app = MyPingApp()
17      app.run()
18
19
20  if __name__ == "__main__":
21      main()
```

- The built-in holoscan operators, **PingRxOp** and **PingTxOp**, are imported on line 3.
- We create an instance of the **PingTxOp** operator with the name "tx" and constrain its `compute()` method to execute 10 times (line 8).
- We create an instance of the **PingRxOp** operator with the name "rx" (line 9).
- The tx and rx operators are connected using `add_flow()` which defines this application's workflow (line 12).

8.2.3 Running the Application

Running the application should give you the following output in your terminal:

```
Rx message value: 1
Rx message value: 2
Rx message value: 3
Rx message value: 4
Rx message value: 5
Rx message value: 6
Rx message value: 7
Rx message value: 8
Rx message value: 9
Rx message value: 10
```

8.3 Ping Custom Op

In this section, we will modify the previous `ping_simple` example to add a custom operator into the workflow. We've already seen a custom operator defined in the `hello_world` example but skipped over some of the details.

In this example we will cover:

- The details of creating your own custom operator class.
- How to add input and output ports to your operator.
- How to add parameters to your operator.
- The data type of the messages being passed between operators.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.3.1 Operators and Workflow

Here is the diagram of the operators and workflow used in this example.

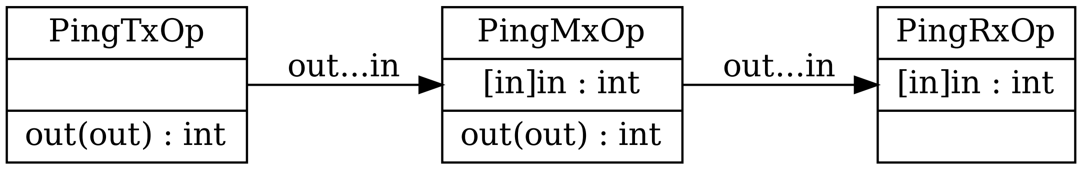

Fig. 8.2: A linear workflow with new custom operator

Compared to the previous example, we are adding a new **PingMxOp** operator between the **PingTxOp** and **PingRxOp** operators. This new operator takes as input an integer, multiplies it by a constant factor, and then sends the new value to **PingRxOp**. You can think of this custom operator as doing some data processing on an input stream before sending the result to downstream operators.

8.3.2 Configuring Operator Input and Output Ports

Our custom operator needs 1 input and 1 output port and can be added by calling `spec.input()` and `spec.output()` methods within the operator's `setup()` method. This requires providing the data type and name of the port as arguments (for C++ API), or just the port name (for Python API). We will see an example of this in the code snippet below. For more details, see *Specifying operator inputs and outputs (C++)* or *Specifying operator inputs and outputs (Python)*.

8.3.3 Configuring Operator Parameters

Operators can be made more reusable by customizing their parameters during initialization. The custom parameters can be provided either directly as arguments or accessed from the application's YAML configuration file. We will show how to use the former in this example to customize the "multiplier" factor of our **PingMxOp** custom operator. Configuring operators using a YAML configuration file will be shown in a subsequent *example*. For more details, see *Configuring operator parameters*.

The code snippet below shows how to define the **PingMxOp** class.

C++

```
#include <holoscan/holoscan.hpp>
#include <holoscan/operators/ping_tx/ping_tx.hpp>
#include <holoscan/operators/ping_rx/ping_rx.hpp>

namespace holoscan::ops {

class PingMxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingMxOp)

  PingMxOp() = default;

  void setup(OperatorSpec& spec) override {
    spec.input<int>("in");
    spec.output<int>("out");
    spec.param(multiplier_, "multiplier", "Multiplier", "Multiply the input by this value
↪", 2);
  }

  void compute(InputContext& op_input, OutputContext& op_output, ExecutionContext&)␣
↪override {
    auto value = op_input.receive<int>("in");

    std::cout << "Middle message value: " << value << std::endl;

    // Multiply the value by the multiplier parameter
    value *= multiplier_;

    op_output.emit(value);
```

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```
28    };
29
30   private:
31    Parameter<int> multiplier_;
32  };
33
34  }  // namespace holoscan::ops
```

- The `PingMxOp` class inherits from the `Operator` base class (line 7).
- The `HOLOSCAN_OPERATOR_FORWARD_ARGS` macro (line 9) is syntactic sugar to help forward an operator's constructor arguments to the `Operator` base class, and is a convenient shorthand to avoid having to manually define constructors for your operator with the necessary parameters.
- Input/output ports with the names "in"/"out" are added to the operator spec on lines 14 and 15 respectively. The port type of both ports are `int` as indicated by the template argument `<int>`.
- We add a "multiplier" parameter to the operator spec (line 16) with a default value of 2. This parameter is tied to the private "multiplier_" data member.
- In the `compute()` method, we receive the integer data from the operator's "in" port (line 20), print its value, multiply its value by the multiplicative factor, and send the new value downstream (line 27).
- On line 20, note that the data being passed between the operators has the type `int`.
- The call to `op_output.emit(value)` on line 27 is equivalent to `op_output.emit(value, "out")` since this operator has only 1 output port. If the operator has more than 1 output port, then the port name is required.

Python

```python
from holoscan.conditions import CountCondition
from holoscan.core import Application, Operator, OperatorSpec
from holoscan.operators import PingRxOp, PingTxOp

class PingMxOp(Operator):
    """Example of an operator modifying data.

    This operator has 1 input and 1 output port:
        input:  "in"
        output: "out"

    The data from the input is multiplied by the "multiplier" parameter

    """

    def setup(self, spec: OperatorSpec):
        spec.input("in")
        spec.output("out")
        spec.param("multiplier", 2)

    def compute(self, op_input, op_output, context):
        value = op_input.receive("in")
        print(f"Middle message value: {value}")

```

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```python
25         # Multiply the values by the multiplier parameter
26         value *= self.multiplier
27 
28         op_output.emit(value, "out")
```

- The `PingMxOp` class inherits from the `Operator` base class (line 5).
- Input/output ports with the names "in"/"out" are added to the operator spec on lines 17 and 18, respectively.
- We add a "multiplier" parameter to the operator spec with a default value of 2 (line 19).
- In the `compute()` method, we receive the integer data from the operator's "in" port (line 22), print its value, multiply its value by the multiplicative factor, and send the new value downstream (line 28).

Now that the custom operator has been defined, we create the application, operators, and define the workflow.

C++

```cpp
1  class MyPingApp : public holoscan::Application {
2   public:
3    void compose() override {
4      using namespace holoscan;
5      // Define the tx, mx, rx operators, allowing tx operator to execute 10 times
6      auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
7      auto mx = make_operator<ops::PingMxOp>("mx", Arg("multiplier", 3));
8      auto rx = make_operator<ops::PingRxOp>("rx");
9  
10     // Define the workflow:  tx -> mx -> rx
11     add_flow(tx, mx);
12     add_flow(mx, rx);
13   }
14 };
15 
16 int main(int argc, char** argv) {
17   auto app = holoscan::make_application<MyPingApp>();
18   app->run();
19 
20   return 0;
21 }
```

- The tx, mx, and rx operators are created in the `compose()` method on lines 6-8.
- The custom mx operator is created in exactly the same way with `make_operator()` (line 7) as the built-in operators, and configured with a "multiplier" parameter initialized to 3 which overrides the parameter's default value of 2 (in the `setup()` method).
- The workflow is defined by connecting tx to mx, and mx to rx using `add_flow()` on lines 11-12.

Python

```python
1  class MyPingApp(Application):
2      def compose(self):
3          # Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
4          tx = PingTxOp(self, CountCondition(self, 10), name="tx")
5          mx = PingMxOp(self, name="mx", multiplier=3)
6          rx = PingRxOp(self, name="rx")
7  
8          # Define the workflow:  tx -> mx -> rx
9          self.add_flow(tx, mx)
10         self.add_flow(mx, rx)
11 
12 
13 def main():
14     app = MyPingApp()
15     app.run()
16 
17 
18 if __name__ == "__main__":
19     main()
```

- The tx, mx, and rx operators are created in the `compose()` method on lines `4-6`.
- The custom mx operator is created in exactly the same way as the built-in operators (line `5`), and configured with a “multiplier” parameter initialized to 3 which overrides the parameter’s default value of 2 (in the `setup()` method).
- The workflow is defined by connecting tx to mx, and mx to rx using `add_flow()` on lines `9-10`.

8.3.4 Message Data Types

For the C++ API, the messages that are passed between the operators are the objects of the data type at the inputs and outputs, so the `value` variable from lines 20 and 25 of the example above has the type `int`. For the Python API, the messages passed between operators can be arbitrary Python objects so no special consideration is needed since it is not restricted to the stricter parameter typing used for C++ API operators.

Let’s look at the code snippet for the built-in **PingTxOp** class and see if this helps to make it clearer.

C++

```cpp
#include "holoscan/operators/ping_tx/ping_tx.hpp"

namespace holoscan::ops {

void PingTxOp::setup(OperatorSpec& spec) {
  spec.output<int>("out");
}

void PingTxOp::compute(InputContext&, OutputContext& op_output, ExecutionContext&) {
  auto value = index_++;
  op_output.emit(value, "out");
```

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```
12  }
13
14  }  // namespace holoscan::ops
```

- The "out" port of the **PingTxOp** has the type `int` (line 6).
- An integer is published to the "out" port when calling `emit()` (line 11).
- The message received by the downstream **PingMxOp** operator when it calls `op_input.receive<int>()` has the type `int`.

Python

```
1   class PingTxOp(Operator):
2       """Simple transmitter operator.
3
4       This operator has a single output port:
5           output: "out"
6
7       On each tick, it transmits an integer to the "out" port.
8       """
9
10      def setup(self, spec: OperatorSpec):
11          spec.output("out")
12
13      def compute(self, op_input, op_output, context):
14          op_output.emit(self.index, "out")
15          self.index += 1
```

- No special consideration is necessary for the Python version, we simply call `emit()` and pass the integer object (line 14).

Attention: For advanced use cases, e.g., when writing C++ applications where you need interoperability between C++ native and GXF operators, you will need to use the `holoscan::TensorMap` type instead. See *Interoperability between GXF and native C++ operators* for more details. If you are writing a Python application which needs a mixture of Python wrapped C++ operators and native Python operators, see *Interoperability between wrapped and native Python operators*.

8.3.5 Running the Application

Running the application should give you the following output in your terminal:

```
Middle message value: 1
Rx message value: 3
Middle message value: 2
Rx message value: 6
Middle message value: 3
Rx message value: 9
Middle message value: 4
Rx message value: 12
```

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```
Middle message value: 5
Rx message value: 15
Middle message value: 6
Rx message value: 18
Middle message value: 7
Rx message value: 21
Middle message value: 8
Rx message value: 24
Middle message value: 9
Rx message value: 27
Middle message value: 10
Rx message value: 30
```

8.4 Ping Multi Port

In this section, we look at how to create an application with a more complex workflow where operators may have multiple input/output ports that send/receive a user-defined data type.

In this example we will cover:

- How to send/receive messages with a custom data type.
- How to add a port that can receive any number of inputs.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.4.1 Operators and Workflow

Here is the diagram of the operators and workflow used in this example.

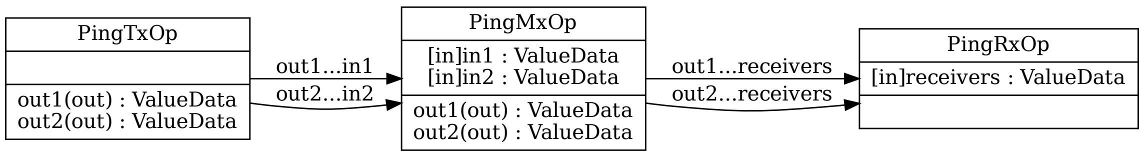

Fig. 8.3: A workflow with multiple inputs and outputs

In this example, `PingTxOp` sends a stream of odd integers to the `out1` port, and even integers to the `out2` port. `PingMxOp` receives these values using `in1` and `in2` ports, multiplies them by a constant factor, then forwards them to a single port - `receivers` - on `PingRxOp`.

8.4.2 User Defined Data Types

In the previous `ping` examples, the port types for our operators were integers, but the Holoscan SDK can send any arbitrary data type. In this example, we'll see how to configure operators for our user-defined `ValueData` class.

C++

```cpp
 1  #include "holoscan/holoscan.hpp"
 2
 3  class ValueData {
 4   public:
 5    ValueData() = default;
 6    explicit ValueData(int value) : data_(value) {
 7      HOLOSCAN_LOG_TRACE("ValueData::ValueData(): {}", data_);
 8    }
 9    ~ValueData() { HOLOSCAN_LOG_TRACE("ValueData::~ValueData(): {}", data_); }
10
11    void data(int value) { data_ = value; }
12
13    int data() const { return data_; }
14
15   private:
16    int data_;
17  };
```

The `ValueData` class wraps a simple integer (line 6, 16), but could have been arbitrarily complex.

Note: The `HOLOSCAN_LOG_<LEVEL>()` macros can be used for logging with fmtlib syntax (lines 7, 9 above) as demonstrated across this example. See the *Logging* section for more details.

Python

```python
from holoscan.conditions import CountCondition
from holoscan.core import Application, IOSpec, Operator, OperatorSpec

class ValueData:
    """Example of a custom Python class"""

    def __init__(self, value):
        self.data = value

    def __repr__(self):
        return f"ValueData({self.data})"

    def __eq__(self, other):
        return self.data == other.data

    def __hash__(self):
        return hash(self.data)
```

The `ValueData` class is a simple wrapper, but could have been arbitrarily complex.

8.4.3 Defining an Explicit Number of Inputs and Outputs

After defining our custom `ValueData` class, we configure our operators' ports to send/receive messages of this type, similarly to the *previous example*.

This is the first operator - `PingTxOp` - sending `ValueData` objects on two ports, `out1` and `out2`:

C++

```cpp
1  namespace holoscan::ops {
2
3  class PingTxOp : public Operator {
4   public:
5    HOLOSCAN_OPERATOR_FORWARD_ARGS(PingTxOp)
6
7    PingTxOp() = default;
8
9    void setup(OperatorSpec& spec) override {
10     spec.output<std::shared_ptr<ValueData>>("out1");
11     spec.output<std::shared_ptr<ValueData>>("out2");
12   }
13
14   void compute(InputContext&, OutputContext& op_output, ExecutionContext&) override {
15     auto value1 = std::make_shared<ValueData>(index_++);
16     op_output.emit(value1, "out1");
17
18     auto value2 = std::make_shared<ValueData>(index_++);
19     op_output.emit(value2, "out2");
20   };
21   int index_ = 1;
22 };
```

- We configure the output ports with the `ValueData` type on lines 10 and 11 using `spec.output<std::shared_ptr<ValueData>>()`. Therefore, the data type for the output ports is an object to a shared pointer to a `ValueData` object.
- The values are then sent out using `op_output.emit()` on lines 16 and 19. The port name is required since there is more than one port on this operator.

Note: Data types of the output ports are shared pointers (`std::shared_ptr`), hence the call to `std::make_shared<ValueData>(...)` on lines 15 and 18.

Python

```python
class PingTxOp(Operator):
    """Simple transmitter operator.

    This operator has:
        outputs: "out1", "out2"

    On each tick, it transmits a `ValueData` object at each port. The
```

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```
 8      transmitted values are even on port1 and odd on port2 and increment with
 9      each call to compute.
10      """
11
12      def __init__(self, fragment, *args, **kwargs):
13          self.index = 1
14          # Need to call the base class constructor last
15          super().__init__(fragment, *args, **kwargs)
16
17      def setup(self, spec: OperatorSpec):
18          spec.output("out1")
19          spec.output("out2")
20
21      def compute(self, op_input, op_output, context):
22          value1 = ValueData(self.index)
23          self.index += 1
24          op_output.emit(value1, "out1")
25
26          value2 = ValueData(self.index)
27          self.index += 1
28          op_output.emit(value2, "out2")
```

- We configure the output ports on lines 18 and 19 using `spec.output()`. There is no need to reference the type (`ValueData`) in Python.
- The values are then sent out using `op_output.emit()` on lines 24 and 28.

We then configure the middle operator - `PingMxOp` - to receive that data on ports `in1` and `in2`:

C++

```
class PingMxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingMxOp)

  PingMxOp() = default;

  void setup(OperatorSpec& spec) override {
    spec.input<std::shared_ptr<ValueData>>("in1");
    spec.input<std::shared_ptr<ValueData>>("in2");
    spec.output<std::shared_ptr<ValueData>>("out1");
    spec.output<std::shared_ptr<ValueData>>("out2");
    spec.param(multiplier_, "multiplier", "Multiply the input by this value
↪", 2);
  }

  void compute(InputContext& op_input, OutputContext& op_output, ExecutionContext&)␣
↪override {
    auto value1 = op_input.receive<std::shared_ptr<ValueData>>("in1").value();
    auto value2 = op_input.receive<std::shared_ptr<ValueData>>("in2").value();

    HOLOSCAN_LOG_INFO("Middle message received (count: {})", count_++);
```

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```
20
21      HOLOSCAN_LOG_INFO("Middle message value1: {}", value1->data());
22      HOLOSCAN_LOG_INFO("Middle message value2: {}", value2->data());
23
24      // Multiply the values by the multiplier parameter
25      value1->data(value1->data() * multiplier_);
26      value2->data(value2->data() * multiplier_);
27
28      op_output.emit(value1, "out1");
29      op_output.emit(value2, "out2");
30    };
31
32   private:
33    int count_ = 1;
34    Parameter<int> multiplier_;
35  };
```

- We configure the input ports with the `std::shared_ptr<ValueData>` type on lines 8 and 9 using `spec.input<std::shared_ptr<ValueData>>()`.
- The values are received using `op_input.receive()` on lines 16 and 17 using the port names. The received values are of type `std::shared_ptr<ValueData>` as mentioned in the templated `receive()` method.

Python

```
1   class PingMxOp(Operator):
2       """Example of an operator modifying data.
3
4       This operator has:
5           inputs:  "in1", "in2"
6           outputs: "out1", "out2"
7
8       The data from each input is multiplied by a user-defined value.
9       """
10
11      def __init__(self, fragment, *args, **kwargs):
12          self.count = 1
13
14          # Need to call the base class constructor last
15          super().__init__(fragment, *args, **kwargs)
16
17      def setup(self, spec: OperatorSpec):
18          spec.input("in1")
19          spec.input("in2")
20          spec.output("out1")
21          spec.output("out2")
22          spec.param("multiplier", 2)
23
24      def compute(self, op_input, op_output, context):
25          value1 = op_input.receive("in1")
26          value2 = op_input.receive("in2")
```

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```
27          print(f"Middle message received (count: {self.count})")
28          self.count += 1
29
30          print(f"Middle message value1: {value1.data}")
31          print(f"Middle message value2: {value2.data}")
32
33          # Multiply the values by the multiplier parameter
34          value1.data *= self.multiplier
35          value2.data *= self.multiplier
36
37          op_output.emit(value1, "out1")
38          op_output.emit(value2, "out2")
```

Sending messages of arbitrary data types is pretty straightforward in Python. The code to define the operator input ports (lines 18-19), and to receive them (lines 25-26) did not change when we went from passing `int` to `ValueData` objects.

`PingMxOp` processes the data, then sends it out on two ports, similarly to what is done by `PingTxOp` above.

8.4.4 Receiving Any Number of Inputs

In this workflow, `PingRxOp` has a single input port - `receivers` - that is connected to two upstream ports from `PingMxOp`. When an input port needs to connect to multiple upstream ports, we define it with `spec.input()` and set the size to `IOSpec::kAnySize` (or `IOSpec.ANY_SIZE` in Python). This allows the input port to receive data from multiple sources. The inputs are then stored in a vector, following the order they were added with `add_flow()`.

C++

```cpp
class PingRxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingRxOp)

  PingRxOp() = default;

  void setup(OperatorSpec& spec) override {
    // // Since Holoscan SDK v2.3, users can define a multi-receiver input port using
↪'spec.input()'
    // // with 'IOSpec::kAnySize'.
    // // The old way is to use 'spec.param()' with 'Parameter<std::vector<IOSpec*>>␣
↪receivers_;'.
    // spec.param(receivers_, "receivers", "Input Receivers", "List of input receivers.",
↪ {});
    spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers", IOSpec::kAnySize);
  }

  void compute(InputContext& op_input, OutputContext&, ExecutionContext&) override {
    auto value_vector =
        op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();

    HOLOSCAN_LOG_INFO("Rx message received (count: {}, size: {})", count_++, value_
↪vector.size());
```

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```cpp
20
21      HOLOSCAN_LOG_INFO("Rx message value1: {}", value_vector[0]->data());
22      HOLOSCAN_LOG_INFO("Rx message value2: {}", value_vector[1]->data());
23    };
24
25   private:
26    // // Since Holoscan SDK v2.3, the following line is no longer needed.
27    // Parameter<std::vector<IOSpec*>> receivers_;
28    int count_ = 1;
29  };
```

- In the operator's `setup()` method, we define an input port `receivers` (line 12) with `holoscan::IOSpec::kAnySize` to allow any number of upstream ports to connect to it.
- The values are retrieved using `op_input.receive<std::vector<std::shared_ptr<ValueData>>>(...)`.
- The type of `value_vector` is `std::vector<std::shared_ptr<ValueData>>` (lines 16-17).

Please see *Receiving any number of inputs (C++)* for more information on how to retrieve any number of inputs in C++.

Python

```python
class PingRxOp(Operator):
    """Simple receiver operator.

    This operator has:
        input: "receivers"

    This is an example of a native operator that can dynamically have any
    number of inputs connected to its "receivers" port.
    """

    def __init__(self, fragment, *args, **kwargs):
        self.count = 1
        # Need to call the base class constructor last
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: OperatorSpec):
        # # Since Holoscan SDK v2.3, users can define a multi-receiver input port using
        # # 'spec.input()' with 'size=IOSpec.ANY_SIZE'.
        # # The old way is to use 'spec.param()' with 'kind="receivers"'.
        # spec.param("receivers", kind="receivers")
        spec.input("receivers", size=IOSpec.ANY_SIZE)

    def compute(self, op_input, op_output, context):
        values = op_input.receive("receivers")
        print(f"Rx message received (count: {self.count}, size: {len(values)})")
        self.count += 1
        print(f"Rx message value1: {values[0].data}")
        print(f"Rx message value2: {values[1].data}")
```

- In Python, a port that can be connected to multiple upstream ports is created by defining an input port and setting the argument `size=IOSpec.ANY_SIZE` (line 21).
- The call to `receive()` returns a tuple of `ValueData` objects (line 24).

Please see *Receiving any number of inputs (Python)* for more information on how to retrieve any number of inputs in Python.

The rest of the code creates the application, operators, and defines the workflow:

C++

```cpp
class MyPingApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
    auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
    auto mx = make_operator<ops::PingMxOp>("mx", Arg("multiplier", 3));
    auto rx = make_operator<ops::PingRxOp>("rx");

    // Define the workflow
    add_flow(tx, mx, {{"out1", "in1"}, {"out2", "in2"}});
    add_flow(mx, rx, {{"out1", "receivers"}, {"out2", "receivers"}});
  }
};

int main(int argc, char** argv) {
  auto app = holoscan::make_application<MyPingApp>();
  app->run();

  return 0;
}
```

Python

```python
class MyPingApp(Application):
    def compose(self):
        # Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
        tx = PingTxOp(self, CountCondition(self, 10), name="tx")
        mx = PingMxOp(self, name="mx", multiplier=3)
        rx = PingRxOp(self, name="rx")

        # Define the workflow
        self.add_flow(tx, mx, {("out1", "in1"), ("out2", "in2")})
        self.add_flow(mx, rx, {("out1", "receivers"), ("out2", "receivers")})


def main():
    app = MyPingApp()
    app.run()
```

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```python


if __name__ == "__main__":
    main()
```

- The operators `tx`, `mx`, and `rx` are created in the application's `compose()` similarly to previous examples.
- Since the operators in this example have multiple input/output ports, we need to specify the third, port name pair argument when calling `add_flow()`:
  - `tx/out1` is connected to `mx/in1`, and `tx/out2` is connected to `mx/in2`.
  - `mx/out1` and `mx/out2` are both connected to `rx/receivers`.

8.4.5 Running the Application

Running the application should give you output similar to the following in your terminal.

```
[info] [fragment.cpp:586] Loading extensions from configs...
[info] [gxf_executor.cpp:249] Creating context
[info] [gxf_executor.cpp:1960] Activating Graph...
[info] [gxf_executor.cpp:1992] Running Graph...
[info] [greedy_scheduler.cpp:191] Scheduling 3 entities
[info] [gxf_executor.cpp:1994] Waiting for completion...
[info] [ping_multi_port.cpp:80] Middle message received (count: 1)
[info] [ping_multi_port.cpp:82] Middle message value1: 1
[info] [ping_multi_port.cpp:83] Middle message value2: 2
[info] [ping_multi_port.cpp:116] Rx message received (count: 1, size: 2)
[info] [ping_multi_port.cpp:118] Rx message value1: 3
[info] [ping_multi_port.cpp:119] Rx message value2: 6
[info] [ping_multi_port.cpp:80] Middle message received (count: 2)
[info] [ping_multi_port.cpp:82] Middle message value1: 3
[info] [ping_multi_port.cpp:83] Middle message value2: 4
[info] [ping_multi_port.cpp:116] Rx message received (count: 2, size: 2)
[info] [ping_multi_port.cpp:118] Rx message value1: 9
[info] [ping_multi_port.cpp:119] Rx message value2: 12
...
[info] [ping_multi_port.cpp:80] Middle message received (count: 10)
[info] [ping_multi_port.cpp:82] Middle message value1: 19
[info] [ping_multi_port.cpp:83] Middle message value2: 20
[info] [ping_multi_port.cpp:116] Rx message received (count: 10, size: 2)
[info] [ping_multi_port.cpp:118] Rx message value1: 57
[info] [ping_multi_port.cpp:119] Rx message value2: 60
[info] [greedy_scheduler.cpp:372] Scheduler stopped: Some entities are waiting for␣
↪execution, but there are no periodic or async entities to get out of the deadlock.
[info] [greedy_scheduler.cpp:401] Scheduler finished.
[info] [gxf_executor.cpp:1997] Deactivating Graph...
[info] [gxf_executor.cpp:2005] Graph execution finished.
[info] [gxf_executor.cpp:278] Destroying context
```

Note: Depending on your log level you may see more or fewer messages. The output above was generated using the default value of `INFO`. Refer to the *Logging* section for more details on how to set the log level.

8.5 Video Replayer

So far we have been working with simple operators to demonstrate Holoscan SDK concepts. In this example, we look at two built-in Holoscan operators that have many practical applications.

In this example we'll cover:

- How to load a video file from disk using **VideoStreamReplayerOp** operator.
- How to display video using **HolovizOp** operator.
- How to configure your operator's parameters using a YAML configuration file.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.5.1 Operators and Workflow

Here is the diagram of the operators and workflow used in this example.

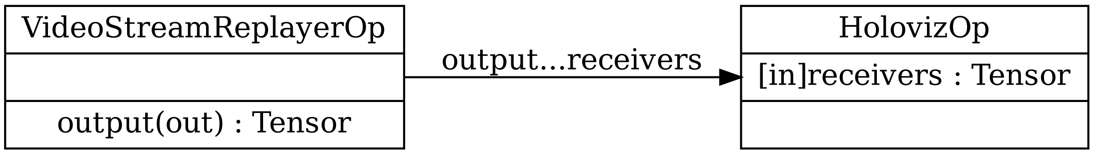


Fig. 8.4: Workflow to load and display video from a file

We connect the "output" port of the replayer operator to the "receivers" port of the Holoviz operator.

8.5.2 Video Stream Replayer Operator

The built-in video stream replayer operator can be used to replay a video stream that has been encoded as gxf entities. You can use the `convert_video_to_gxf_entities.py` script (installed in `/opt/nvidia/holoscan/bin` or available on GitHub) to encode a video file as gxf entities for use by this operator.

This operator processes the encoded file sequentially and supports realtime, faster than realtime, or slower than realtime playback of prerecorded data. The input data can optionally be repeated to loop forever or only for a specified count. For more details, see `VideoStreamReplayerOp`.

We will use the replayer to read GXF entities from disk and send the frames downstream to the Holoviz operator.

8.5.3 Holoviz Operator

The built-in Holoviz operator provides the functionality to composite realtime streams of frames with multiple different other layers like segmentation mask layers, geometry layers and GUI layers.

We will use Holoviz to display frames that have been sent by the replayer operator to its "receivers" port which can receive any number of inputs. In more intricate workflows, this port can receive multiple streams of input data where, for example, one stream is the original video data, while other streams detect objects in the video to create bounding boxes and/or text overlays.

8.5.4 Application Configuration File (YAML)

The SDK supports reading an optional YAML configuration file and can be used to customize the application's workflow and operators. For more complex workflows, it may be helpful to use the application configuration file to help separate operator parameter settings from your code. See *Configuring an Application* for additional details.

Tip: For C++ applications, the configuration file offers a convenient way to set the behavior of the application at runtime without needing to recompile the code.

This example uses the following configuration file to configure the parameters for the replayer and Holoviz operators. The full list of parameters can be found at `VideoStreamReplayerOp` and `HolovizOp`.

```
%YAML 1.2
replayer:
  directory: "../data/racerx"   # Path to gxf entity video data
  basename: "racerx"             # Look for <basename>.gxf_{entities|index}
  frame_rate: 0       # Frame rate to replay.  (default: 0 follow frame rate in␣
↪timestamps)
  repeat: true        # Loop video?   (default: false)
  realtime: true      # Play in realtime, based on frame_rate/timestamps   (default:␣
↪true)
  count: 0            # Number of frames to read  (default: 0 for no frame count␣
↪restriction)

holoviz:
  width: 854          # width of window size
  height: 480         # height of window size
  tensors:
    - name: ""        # name of tensor containing input data to display
      type: color     # input type e.g., color, triangles, text, depth_map
      opacity: 1.0    # layer opacity
      priority: 0     # determines render order, higher priority layers are rendered on␣
↪top
```

The code below shows our `video_replayer` example. Operator parameters are configured from a configuration file using `from_config()` (C++) and `self.**kwargs()` (Python).

C++

```cpp
1  #include <holoscan/holoscan.hpp>
2  #include <holoscan/operators/video_stream_replayer/video_stream_replayer.hpp>
3  #include <holoscan/operators/holoviz/holoviz.hpp>
4
5  class VideoReplayerApp : public holoscan::Application {
6   public:
7    void compose() override {
8      using namespace holoscan;
9
10     // Define the replayer and holoviz operators and configure using yaml configuration
11     auto replayer = make_operator<ops::VideoStreamReplayerOp>("replayer", from_config(
   ↪"replayer"));
12     auto visualizer = make_operator<ops::HolovizOp>("holoviz", from_config("holoviz"));
13
14     // Define the workflow: replayer -> holoviz
15     add_flow(replayer, visualizer, {{"output", "receivers"}});
16   }
17 };
18
19 int main(int argc, char** argv) {
20   // Get the yaml configuration file
21   auto config_path = std::filesystem::canonical(argv[0]).parent_path();
22   config_path /= std::filesystem::path("video_replayer.yaml");
23   if ( argc >= 2 ) {
24     config_path = argv[1];
25   }
26
27   auto app = holoscan::make_application<VideoReplayerApp>();
28   app->config(config_path);
29   app->run();
30
31   return 0;
32 }
```

- The built-in **VideoStreamReplayerOp** and **HolovizOp** operators are included from lines 1 and 2, respectively.
- We create an instance of **VideoStreamReplayerOp** named "replayer" with parameters initialized from the YAML configuration file using the call to `from_config()` (line 11).
- We create an instance of **HolovizOp** named "holoviz" with parameters initialized from the YAML configuration file using the call to `from_config()` (line 12).
- The "output" port of "replayer" operator is connected to the "receivers" port of the "holoviz" operator and defines the application workflow (line 34).
- The application's YAML configuration file contains the parameters for our operators, and is loaded on line 28. If no argument is passed to the executable, the application looks for a file with the name "video_replayer.yaml" in the same directory as the executable (lines 21-22), otherwise it treats the argument as the path to the application's YAML configuration file (lines 23-25).

Python

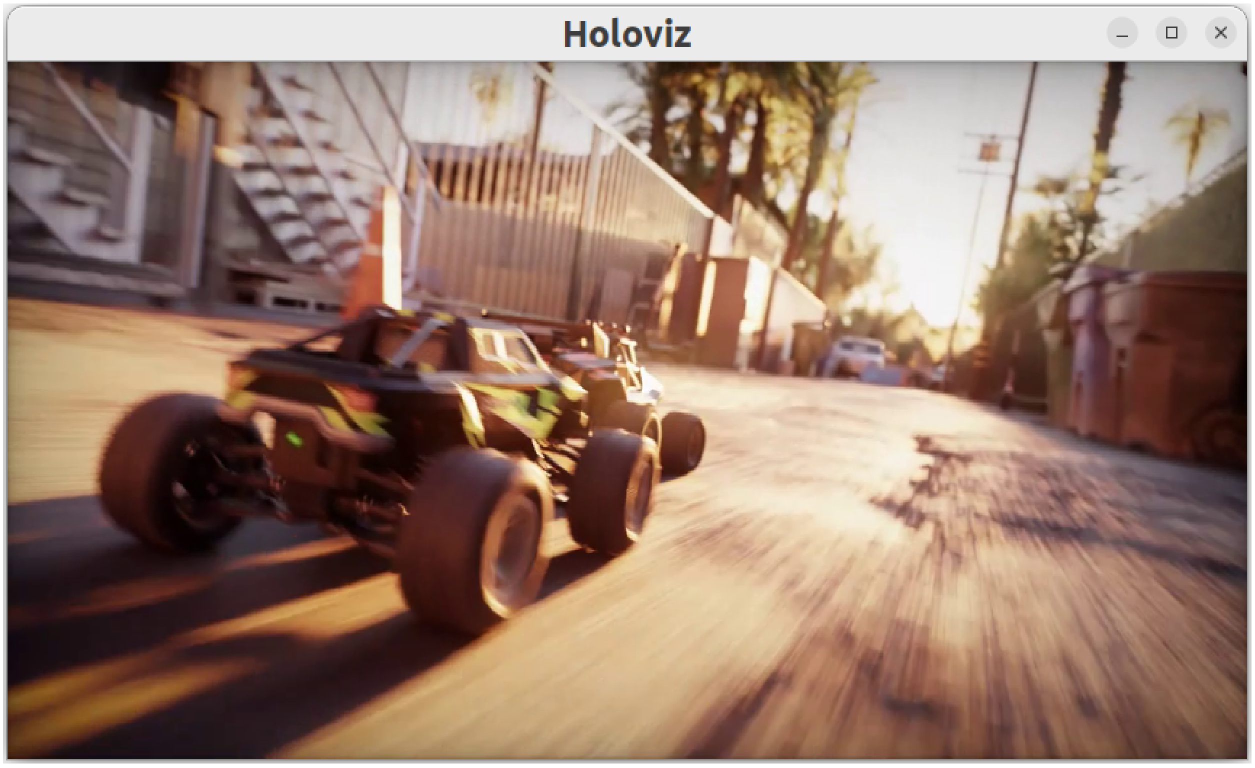
```python
1  import os
2  import sys
3
4  from holoscan.core import Application
5  from holoscan.operators import HolovizOp, VideoStreamReplayerOp
6
7  sample_data_path = os.environ.get("HOLOSCAN_INPUT_PATH", "../data")
8
9
10 class VideoReplayerApp(Application):
11     """Example of an application that uses the operators defined above.
12
13     This application has the following operators:
14
15     - VideoStreamReplayerOp
16     - HolovizOp
17
18     The VideoStreamReplayerOp reads a video file and sends the frames to the HolovizOp.
19     The HolovizOp displays the frames.
20     """
21
22     def compose(self):
23         video_dir = os.path.join(sample_data_path, "racerx")
24         if not os.path.exists(video_dir):
25             raise ValueError(f"Could not find video data: {video_dir=}")
26
27         # Define the replayer and holoviz operators
28         replayer = VideoStreamReplayerOp(
29             self, name="replayer", directory=video_dir, **self.kwargs("replayer")
30         )
31         visualizer = HolovizOp(self, name="holoviz", **self.kwargs("holoviz"))
32
33         # Define the workflow
34         self.add_flow(replayer, visualizer, {("output", "receivers")})
35
36
37 def main(config_file):
38     app = VideoReplayerApp()
39     # if the --config command line argument was provided, it will override this config_
   ↪file
40     app.config(config_file)
41     app.run()
42
43
44 if __name__ == "__main__":
45     config_file = os.path.join(os.path.dirname(__file__), "video_replayer.yaml")
46     main(config_file=config_file)
```

- The built-in **VideoStreamReplayerOp** and **HolovizOp** operators are imported on line 5.
- We create an instance of **VideoStreamReplayerOp** named "replayer" with parameters initialized from the YAML configuration file using `**self.kwargs()` (lines 28-30).

- For the Python script, the path to the GXF entity video data is not set in the application configuration file, but determined by the code on lines 7 and 23 and is passed directly as the "directory" argument (line 29). This allows more flexibility for the user to run the script from any directory by setting the `HOLOSCAN_INPUT_PATH` directory (line 7).
- We create an instance of **HolovizOp** named "holoviz" with parameters initialized from the YAML configuration file using `**self.kwargs()` (line 31).
- The "output" port of "replayer" operator is connected to the "receivers" port of the "holoviz" operator and defines the application workflow (line 34).
- The application's YAML configuration file contains the parameters for our operators, and is loaded on line 45. If no argument is passed to the Python script, the application looks for a file with the name "video_replayer.yaml" in the same directory as the script (line 39). Otherwise it treats the argument as the path to the app's YAML configuration file (lines 41-42).

8.5.5 Running the Application

Running the application should bring up video playback of the video referenced in the YAML file.



8.6 Video Replayer (Distributed)

In this example, we extend the previous *video replayer application* into a multi-node *distributed application*. A distributed application is made up of multiple Fragments (`C++`/`Python`), each of which may run on its own node.

In the distributed case we will:

- Create one fragment that loads a video file from disk using **VideoStreamReplayerOp** operator.
- Create a second fragment that will display the video using the **HolovizOp** operator.

These two fragments will be combined into a distributed application such that the display of the video frames could occur on a separate node from the node where the data is read.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.6.1 Operators and Workflow

Here is the diagram of the operators and workflow used in this example.

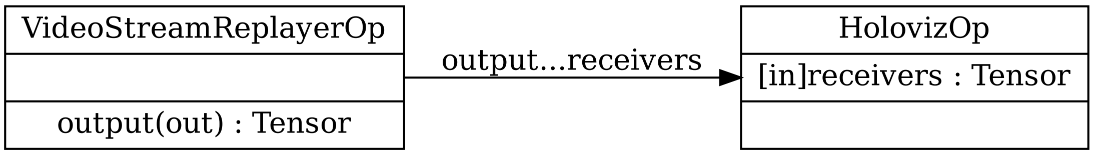


Fig. 8.5: Workflow to load and display video from a file

This is the same workflow as the *single fragment video replayer*. Each operator is assigned to a separate fragment and there is now a network connection between the fragments.

8.6.2 Defining and Connecting Fragments

Distributed applications define fragments explicitly to isolate the different units of work that could be distributed to different nodes. In this example:

- We define two classes that inherit from `Fragment`:
  - **Fragment1** contains an instance of **VideoStreamReplayerOp** named "replayer."
  - **Fragment2** contains an instance of **HolovizOp** name "holoviz."
- We create an application, **DistributedVideoReplayerApp**. In its compose method:
  - we call **make_fragment** to initialize both fragments.
  - we then connect the "output" port of "replayer" operator in fragment1 to the "receivers" port of the "holoviz" operator in fragment2 to define the application workflow.

- The operators instantiated in the fragments can still be configured with parameters initialized from the YAML configuration ingested by the application using `from_config()` (C++) or `kwargs()` (Python).

C++

```cpp
#include <holoscan/holoscan.hpp>
#include <holoscan/operators/holoviz/holoviz.hpp>
#include <holoscan/operators/video_stream_replayer/video_stream_replayer.hpp>

class Fragment1 : public holoscan::Fragment {
 public:
  void compose() override {
    using namespace holoscan;

    auto replayer = make_operator<ops::VideoStreamReplayerOp>("replayer", from_config(
↪"replayer"));
    add_operator(replayer);
  }
};

class Fragment2 : public holoscan::Fragment {
 public:
  void compose() override {
    using namespace holoscan;

    auto visualizer = make_operator<ops::HolovizOp>("holoviz", from_config("holoviz"));
    add_operator(visualizer);
  }
};

class DistributedVideoReplayerApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    auto fragment1 = make_fragment<Fragment1>("fragment1");
    auto fragment2 = make_fragment<Fragment2>("fragment2");

    // Define the workflow: replayer -> holoviz
    add_flow(fragment1, fragment2, {{"replayer.output", "holoviz.receivers"}});
  }
};

int main(int argc, char** argv) {
  // Get the yaml configuration file
  auto config_path = std::filesystem::canonical(argv[0]).parent_path();
  config_path /= std::filesystem::path("video_replayer_distributed.yaml");

  auto app = holoscan::make_application<DistributedVideoReplayerApp>();
  app->config(config_path);
  app->run();

```

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```
  return 0;
}
```

Python

```python
import os

from holoscan.core import Application, Fragment
from holoscan.operators import HolovizOp, VideoStreamReplayerOp

sample_data_path = os.environ.get("HOLOSCAN_INPUT_PATH", "../data")


class Fragment1(Fragment):
    def __init__(self, app, name):
        super().__init__(app, name)

    def compose(self):
        # Set the video source
        video_path = self._get_input_path()
        logging.info(
            f"Using video from {video_path}"
        )

        # Define the replayer and holoviz operators
        replayer = VideoStreamReplayerOp(
            self, name="replayer", directory=video_path, **self.kwargs("replayer")
        )

        self.add_operator(replayer)

    def _get_input_path(self):
        path = os.environ.get(
            "HOLOSCAN_INPUT_PATH", os.path.join(os.path.dirname(__file__), "data")
        )
        return os.path.join(path, "racerx")


class Fragment2(Fragment):
    def compose(self):
        visualizer = HolovizOp(self, name="holoviz", **self.kwargs("holoviz"))

        self.add_operator(visualizer)


class DistributedVideoReplayerApp(Application):
    """Example of a distributed application that uses the fragments and operators␣
↪defined above.

    This application has the following fragments:
```

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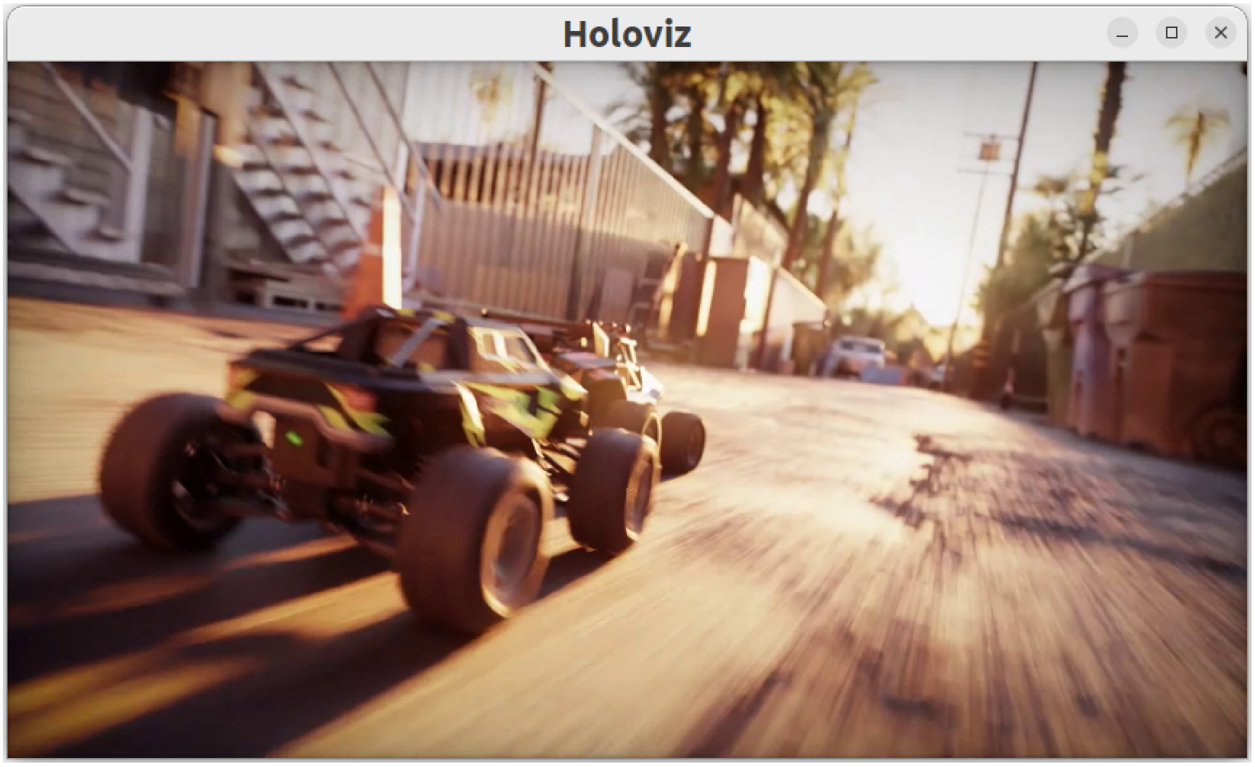
```python
    - Fragment1
      - holding VideoStreamReplayerOp
    - Fragment2
      - holding HolovizOp

    The VideoStreamReplayerOp reads a video file and sends the frames to the HolovizOp.
    The HolovizOp displays the frames.
    """

    def compose(self):
        # Define the fragments
        fragment1 = Fragment1(self, name="fragment1")
        fragment2 = Fragment2(self, name="fragment2")

        # Define the workflow
        self.add_flow(fragment1, fragment2, {("replayer.output", "holoviz.receivers")})


def main():
    config_file_path = os.path.join(os.path.dirname(__file__), "video_replayer_
↪distributed.yaml")

    logging.info(f"Reading application configuration from {config_file_path}")

    app = DistributedVideoReplayerApp()
    app.config(config_file_path)
    app.run()


if __name__ == "__main__":
    main()
```

This particular distributed application only has one operator per fragment, so the operators were added via **`add_operator`** (**`C++`**/**`Python`**). In general, each fragment may have multiple operators and connections between operators within a fragment would be made using `add_flow()` (`C++`/`Python`) method within the fragment's `compute()` (`C++`/`Python`) method.

8.6.3 Running the Application

Running the application should bring up video playback of the video referenced in the YAML file.



Note: Instructions for running the distributed application involve calling the application from the "driver" node as well as from any worker nodes. For details, see the application run instructions in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples/video_replayer_distributed` in the NGC container and the Debian package.

Tip: Refer to *UCX Network Interface Selection* when running a distributed application across multiple nodes.

8.7 Bring Your Own Model (BYOM)

The Holoscan platform is optimized for performing AI inferencing workflows. This section shows how the user can easily modify the `bring_your_own_model` example to create their own AI applications.

In this example we'll cover:

- The usage of `FormatConverterOp`, `InferenceOp`, `SegmentationPostprocessorOp` operators to add AI inference into the workflow.
- How to modify the existing code in this example to create an ultrasound segmentation application to visualize the results from a spinal scoliosis segmentation model.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

8.7.1 Operators and Workflow

Here is the diagram of the operators and workflow used in the byom.py example.

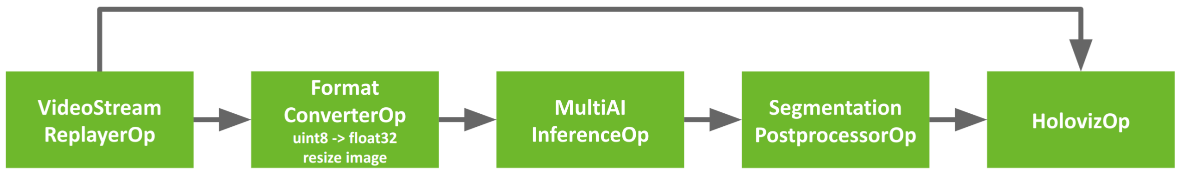


Fig. 8.6: The BYOM inference workflow

The example code already contains the plumbing required to create the pipeline above where the video is loaded by `VideoStreamReplayer` and passed to two branches. The first branch goes directly to `Holoviz` to display the original video. The second branch in this workflow goes through AI inferencing and can be used to generate overlays such as bounding boxes, segmentation masks, or text to add additional information.

This second branch has three operators we haven't yet encountered.

- **Format Converter**: The input video stream goes through a preprocessing stage to convert the tensors to the appropriate shape/format before being fed into the AI model. It is used here to convert the datatype of the image from `uint8` to `float32` and resized to match the model's expectations.
- **Inference**: This operator performs AI inferencing on the input video stream with the provided model. It supports inferencing of multiple input video streams and models.
- **Segmentation Postprocessor**: This postprocessing stage takes the output of inference, either with the final softmax layer (multiclass) or sigmoid (2-class), and emits a tensor with `uint8` values that contain the highest probability class index. The output of the segmentation postprocessor is then fed into the Holoviz visualizer to create the overlay.

8.7.2 Prerequisites

To follow along this example, you can download the ultrasound dataset with the following commands:

```
./scripts/download_ngc_data --url nvidia/clara-holoscan/holoscan_ultrasound_sample_
↪data:20220608
```

You can also follow along using your own dataset by adjusting the operator parameters based on your input video and model, and converting your video and model to a format that is understood by Holoscan.

Input Video

The video stream replayer supports reading video files that are encoded as GXF entities. These files are provided with the ultrasound dataset as the `ultrasound_256x256.gxf_entities` and `ultrasound_256x256.gxf_index` files.

Note: To use your own video data, you can use the `convert_video_to_gxf_entities.py` script (installed in `/opt/nvidia/holoscan/bin` or on GitHub) to encode your video. Note that - using this script - the metadata in the generated GXF tensor files will indicate that the data should be copied to the GPU on read.

Input model

Currently, the inference operators in Holoscan are able to load ONNX models, or TensorRT engine files built for the GPU architecture on which you will be running the model. TensorRT engines are automatically generated from ONNX by the operators when the applications run.

If you are converting your model from PyTorch to ONNX, chances are your input is NCHW and will need to be converted to NHWC. We provide an example transformation script named `graph_surgeon.py`, installed in `/opt/nvidia/holoscan/bin` or available on GitHub. You may need to modify the dimensions as needed before modifying your model.

Tip: To get a better understanding of your model, and if this step is necessary, websites such as netron.app can be used.

8.7.3 Understanding the Application Code

Before modifying the application, let's look at the existing code to get a better understanding of how it works.

Python

```python
import os
from argparse import ArgumentParser

from holoscan.core import Application

from holoscan.operators import (
    FormatConverterOp,
    HolovizOp,
    InferenceOp,
    SegmentationPostprocessorOp,
    VideoStreamReplayerOp,
)
from holoscan.resources import UnboundedAllocator


class BYOMApp(Application):
    def __init__(self, data):
        """Initialize the application

        Parameters
        ----------
        data : Location to the data
        """

        super().__init__()

        # set name
        self.name = "BYOM App"

        if data == "none":
```

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```
31             data = os.environ.get("HOLOSCAN_INPUT_PATH", "../data")
32
33         self.sample_data_path = data
34
35         self.model_path = os.path.join(os.path.dirname(__file__), "../model")
36         self.model_path_map = {
37             "byom_model": os.path.join(self.model_path, "identity_model.onnx"),
38         }
39
40         self.video_dir = os.path.join(self.sample_data_path, "racerx")
41         if not os.path.exists(self.video_dir):
42             raise ValueError(f"Could not find video data: {self.video_dir=}")
```

- The built-in FormatConvertOp, InferenceOp, and SegmentationPostprocessorOp operators are imported on lines 7, 9, and 10. These 3 operators make up the preprocessing, inference, and postprocessing stages of our AI pipeline respectively.
- The UnboundedAllocator resource is imported on line 13. This is used by our application's operators for memory allocation.
- The paths to the identity model are defined on lines 35-38. This model passes its input tensor to its output, and acts as a placeholder for this example.
- The directory of the video files are defined on line 40.

Next, we look at the operators and their parameters defined in the application YAML file.

Python

```
    def compose(self):
        host_allocator = UnboundedAllocator(self, name="host_allocator")

        source = VideoStreamReplayerOp(
            self, name="replayer", directory=self.video_dir, **self.kwargs("replayer")
        )

        preprocessor = FormatConverterOp(
            self, name="preprocessor", pool=host_allocator, **self.kwargs("preprocessor")
        )

        inference = InferenceOp(
            self,
            name="inference",
            allocator=host_allocator,
            model_path_map=self.model_path_map,
            **self.kwargs("inference"),
        )

        postprocessor = SegmentationPostprocessorOp(
            self, name="postprocessor", allocator=host_allocator, **self.kwargs(
↪"postprocessor")
        )
```

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```
23
24          viz = HolovizOp(self, name="viz", **self.kwargs("viz"))
```

- An instance of the `UnboundedAllocator` resource class is created (line `2`) and used by subsequent operators for memory allocation. This allocator allocates memory dynamically on the host as needed. For applications where latency becomes an issue, an allocator supporting a memory pool such as `BlockMemoryPool` or `RMMAllocator` could be used instead.
- The preprocessor operator (line `8`) takes care of converting the input video from the source video to a format that can be used by the AI model.
- The inference operator (line `12`) feeds the output from the preprocessor to the AI model to perform inference.
- The postprocessor operator (line `20`) postprocesses the output from the inference operator before passing it down-stream to the visualizer. Here, the segmentation postprocessor checks the probabilities output from the model to determine which class is most likely and emits this class index. This is then used by the `Holoviz` operator to create a segmentation mask overlay.

YAML

```yaml
%YAML 1.2
replayer:  # VideoStreamReplayer
  basename: "racerx"
  frame_rate: 0 # as specified in timestamps
  repeat: true # default: false
  realtime: true # default: true
  count: 0 # default: 0 (no frame count restriction)

preprocessor:  # FormatConverter
  out_tensor_name: source_video
  out_dtype: "float32"
  resize_width: 512
  resize_height: 512

inference:  # Inference
  backend: "trt"
  pre_processor_map:
    "byom_model": ["source_video"]
  inference_map:
    "byom_model": ["output"]

postprocessor:  # SegmentationPostprocessor
  in_tensor_name: output
  # network_output_type: None
  data_format: nchw

viz:  # Holoviz
  width: 854
  height: 480
  color_lut: [
    [0.65, 0.81, 0.89, 0.1],
    ]
```

- The preprocessor converts the tensors to `float32` values (line `11`) and ensures that the image is resized to 512x512 (line `12-13`).
- The `pre_processor_map` parameter (lines `17-18`) maps the model name(s) to input tensor name(s). Here, "source_video" matches the output tensor name of the preprocessor (line `10`). The `inference_map` parameter maps the model name(s) to the output tensor name(s). Here, "output" matches the input tensor name of the postprocessor (line `23`). For more details on `InferenceOp` parameters, see *Customizing the Inference Operator* or refer to *Inference*.
- The `network_output_type` parameter is commented out on line `24` to remind ourselves that this second branch is currently not generating anything interesting. If not specified, this parameter defaults to "softmax" for `SegmentationPostprocessorOp`.
- The color lookup table defined on lines `30-32` is used here to create a segmentation mask overlay. The values of each entry in the table are RGBA values between 0.0 and 1.0. For the alpha value, 0.0 is fully transparent and 1.0 is fully opaque.

Finally, we define the application and workflow.

Python

```
1          # Define the workflow
2          self.add_flow(source, viz, {("output", "receivers")})
3          self.add_flow(source, preprocessor, {("output", "source_video")})
4          self.add_flow(preprocessor, inference, {("tensor", "receivers")})
5          self.add_flow(inference, postprocessor, {("transmitter", "in_tensor")})
6          self.add_flow(postprocessor, viz, {("out_tensor", "receivers")})
7
8
9  def main(config_file, data):
10     app = BYOMApp(data=data)
11     # if the --config command line argument was provided, it will override this config_
   ↪file
12     app.config(config_file)
13     app.run()
14
15
16 if __name__ == "__main__":
17     # Parse args
18     parser = ArgumentParser(description="BYOM demo application.")
19     parser.add_argument(
20         "-d",
21         "--data",
22         default="none",
23         help=("Set the data path"),
24     )
25
26     args = parser.parse_args()
27     config_file = os.path.join(os.path.dirname(__file__), "byom.yaml")
28     main(config_file=config_file, data=args.data)
```

- The `add_flow()` on line `2` defines the first branch to display the original video.
- The `add_flow()` commands from line `3-6` defines the second branch to display the segmentation mask overlay.

8.7.4 Modifying the Application for Ultrasound Segmentation

To create the ultrasound segmentation application, we need to swap out the input video and model to use the ultrasound files, and adjust the parameters to ensure the input video is resized correctly to the model's expectations.

We will need to modify the Python and YAML files to change our application to the ultrasound segmentation application.

Python

```
 1  class BYOMApp(Application):
 2      def __init__(self, data):
 3          """Initialize the application
 4
 5          Parameters
 6          ----------
 7          data : Location to the data
 8          """
 9
10          super().__init__()
11
12          # set name
13          self.name = "BYOM App"
14
15          if data == "none":
16              data = os.environ.get("HOLOSCAN_INPUT_PATH", "../data")
17
18          self.sample_data_path = data
19
20          self.model_path = os.path.join(self.sample_data_path, "ultrasound_segmentation",
    ↪"model")
21          self.model_path_map = {
22              "byom_model": os.path.join(self.model_path, "us_unet_256x256_nhwc.onnx"),
23         }
24
25          self.video_dir = os.path.join(self.sample_data_path, "ultrasound_segmentation",
    ↪"video")
26          if not os.path.exists(self.video_dir):
27              raise ValueError(f"Could not find video data: {self.video_dir=}")
```

- Update `self.model_path_map` to the ultrasound segmentation model (lines `20-23`).
- Update `self.video_dir` to point to the directory of the ultrasound video files (line `25`).

YAML

```
1  replayer:  # VideoStreamReplayer
2    basename: "ultrasound_256x256"
3    frame_rate: 0 # as specified in timestamps
4    repeat: true # default: false
5    realtime: true # default: true
6    count: 0 # default: 0 (no frame count restriction)
7
8  preprocessor:  # FormatConverter
9    out_tensor_name: source_video
10   out_dtype: "float32"
11   resize_width: 256
12   resize_height: 256
13
14 inference:  # Inference
15   backend: "trt"
16   pre_processor_map:
17     "byom_model": ["source_video"]
18   inference_map:
19     "byom_model": ["output"]
20
21 postprocessor:  # SegmentationPostprocessor
22   in_tensor_name: output
23   network_output_type: softmax
24   data_format: nchw
25
26 viz:  # Holoviz
27   width: 854
28   height: 480
29   color_lut: [
30     [0.65, 0.81, 0.89, 0.1],
31     [0.2, 0.63, 0.17, 0.7]
32     ]
```

- Update `basename` to the basename of the ultrasound video files (line `2`).
- The AI model expects the width and height of the images to be 256x256, update the preprocessor's parameters to resize the input to 256x256 (line `11-12`).
- The AI model's final output layer is a softmax, so we indicate this to the postprocessor (line `23`).
- Since this model predicts between two classes, we need another entry in Holoviz's color lookup table (line `31`). Note that the alpha value of the first color entry is `0.1` (line `30`) so the mask for the background class may not be visible. The second entry we just added is a green color and has an alpha value of `0.7` so it will be easily visible.

The above changes are enough to update the BYOM example to the ultrasound segmentation application.

In general, when deploying your own AI models, you will need to consider the operators in the second branch. This example uses a pretty typical AI workflow:

- **Input**: This could be a video on disk, an input stream from a capture device, or other data stream.
- **Preprocessing**: You may need to preprocess the input stream to convert tensors into the shape and format that is expected by your AI model (e.g., converting datatype and resizing).
- **Inference**: Your model will need to be in ONNX or TensorRT format.

- **Postprocessing**: An operator that postprocesses the output of the model to a format that can be readily used by downstream operators.
- **Output**: The postprocessed stream can be displayed or used by other downstream operators.

The Holoscan SDK comes with a number of built-in operators that you can use to configure your own workflow. If needed, you can write your own custom operators or visit Holohub for additional implementations and ideas for operators.

8.7.5 Running the Application

After modifying the application as instructed above, running the application should bring up the ultrasound video with a segmentation mask overlay similar to the image below.

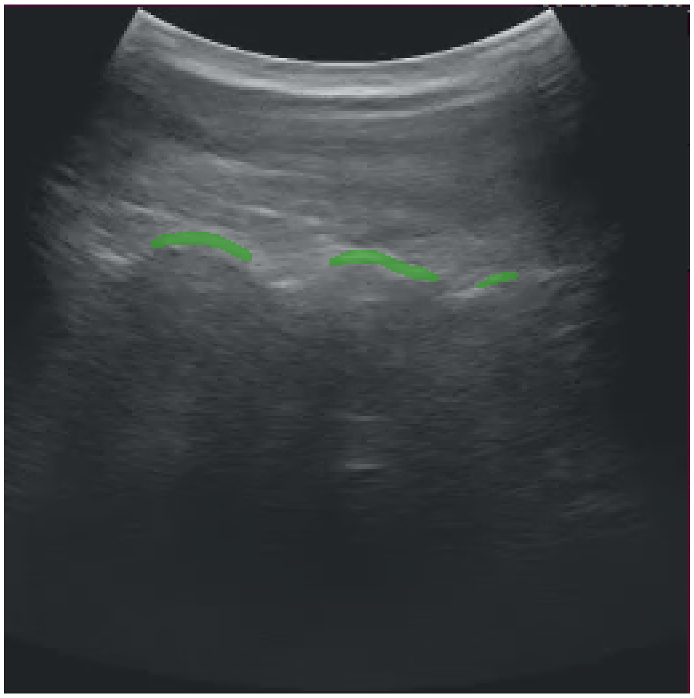


Fig. 8.7: Ultrasound Segmentation

Note: If you run the byom.py application without modification and are using the debian installation, you may run into the following error message:

```
[error] Error in Inference Manager ... TRT Inference: failed to build TRT engine file.
```

In this case, modifying the write permissions for the model directory should help (use with caution):

```
sudo chmod a+w /opt/nvidia/holoscan/examples/bring_your_own_model/model
```

8.7.6 Customizing the Inference Operator

The built-in `InferenceOp` operator provides the functionality of the *Inference*. This operator has a `receivers` port that can connect to any number of upstream ports to allow for multiai inferencing, and one `transmitter` port to send results downstream. Below is a description of some of the operator's parameters and a general guidance on how to use them.

- `backend`: If the input models are in `tensorrt engine file` format, select `trt` as the backend. If the input models are in `onnx` format select either `trt` or `onnx` as the backend.
- `allocator`: Can be passed to this operator to specify how the output tensors are allocated.
- `model_path_map`: Contains dictionary keys with unique strings that refer to each model. The values are set to the path to the model files on disk. All models must be either in `onnx` or in `tensorrt engine file` format. The Holoscan Inference Module will do the `onnx` to `tensorrt` model conversion if the TensorRT engine files do not exist.
- `pre_processor_map`: This dictionary should contain the same keys as `model_path_map`, mapping to the output tensor name for each model.
- `inference_map`: This dictionary should contain the same keys as `model_path_map`, mapping to the output tensor name for each model.
- `enable_fp16`: Boolean variable indicating if half-precision should be used to speed up inferencing. The default value is False, and uses single-precision (32-bit fp) values.
- `input_on_cuda`: Indicates whether input tensors are on device or host.
- `output_on_cuda`: Indicates whether output tensors are on device or host.
- `transmit_on_cuda`: If True, it means the data transmission from the inference will be on **Device**, otherwise it means the data transmission from the inference will be on **Host**.

8.7.7 Common Pitfalls Deploying New Models

Color Channel Order

It is important to know what channel order your model expects. This may be indicated by the training data, pre-training transformations performed at training, or the expected inference format used in your application.

For example, if your inference data is RGB, but your model expects BGR, you will need to add the following to your segmentation_preprocessor in the yaml file: `out_channel_order: [2,1,0]`.

Normalizing Your Data

Similarly, default scaling for streaming data is `[0,1]`, but dependent on how your model was trained, you may be expecting `[0,255]`.

For the above case, you would add the following to your segmentation_preprocessor in the YAML file:

`scale_min: 0.0` `scale_max: 255.0`

Network Output Type

Models often have different output types such as `Sigmoid`, `Softmax`, or perhaps something else, and you may need to examine the last few layers of your model to determine which applies to your case.

As in the case of our ultrasound segmentation example above, we added the following in our YAML file: `network_output_type: softmax`

8.8 Custom Cuda Kernel Samples

There are 2 examples for custom CUDA kernel ingestion in the Holoscan SDK. These examples demonstrate usage of **InferenceProcessorOp** to ingest a custom CUDA kernel for processing.

- custom_cuda_kernel_1d_sample: Example shows ingestion of a single 1D custom CUDA kernel.
- custom_cuda_kernel_multi_sample: example shows ingestion of multiple custom CUDA kernels. Specifically a 1D and a 2D kernel are ingested through a single instance of the operator via parameter set.

In these examples we'll cover:

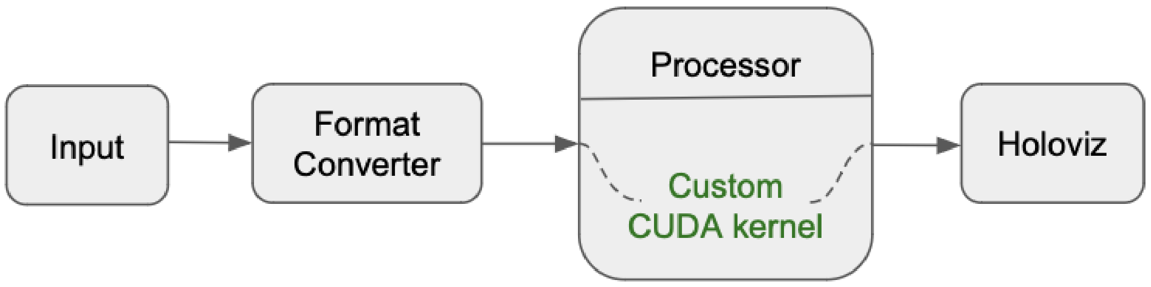
- How to use parameter set with **InferenceProcessorOp** operator to ingest a custom CUDA kernel.
- Rules for writing custom CUDA kernel in the parameter set.

Note: The example source code and run instructions can be found in the examples directory on GitHub, or under `/opt/nvidia/holoscan/examples` in the NGC container and the Debian package, alongside their executables.

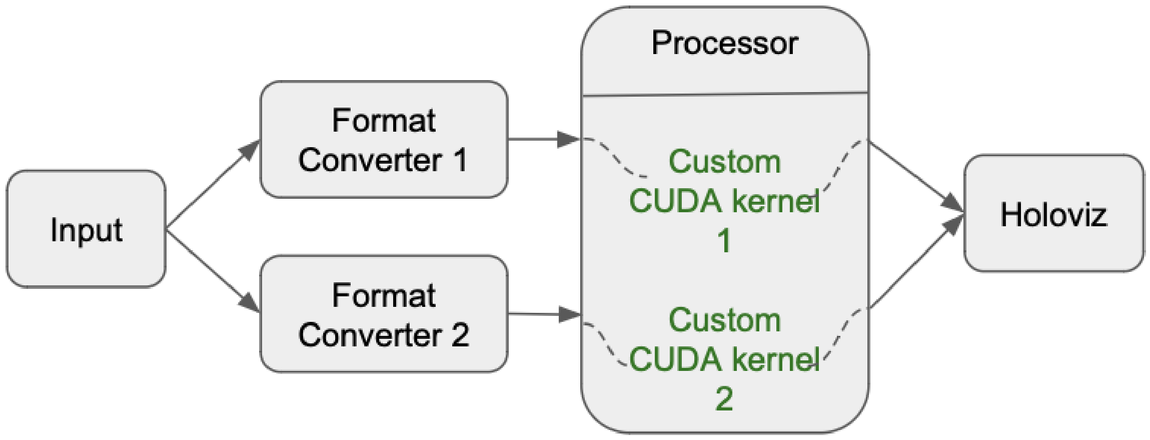
8.8.1 Operators and Workflow

Here is the diagram of the operators and workflow used in both the examples.

- custom_cuda_kernel_1d_sample: In the diagram below, the workflow input comes from video_replayer operator followed by format conversion via the format_converter operator. The inference processor operator then ingests and applies custom CUDA kernels and the result is then sent to the Holoviz operator for display.



- custom_cuda_kernel_multi_sample: This sample has multiple custom CUDA kernels ingested into the workflow. In the diagram below, input in the workflow comes through the video_replayer operator. There are two instances of the format_converter operator that convert the format of the input data for the two custom CUDA kernels. The inference processor operator then ingests both the tensors from format converter operators, and applies custom CUDA kernels as per the specifications in the workflow. The result is then sent to the Holoviz operator for display.



8.8.2 Video Stream Replayer Operator

The built-in video stream replayer operator can be used to replay a video stream that has been encoded as GXF entities. You can use the `convert_video_to_gxf_entities.py` script (installed in `/opt/nvidia/holoscan/bin` or available on GitHub) to encode a video file as GXF entities for use by this operator.

This operator processes the encoded file sequentially and supports realtime, faster than realtime, or slower than realtime playback of prerecorded data. The input data can optionally be repeated to loop forever or only for a specified count. For more details, see `VideoStreamReplayerOp`.

We will use the replayer to read GXF entities from disk and send the frames downstream to the Holoviz operator.

8.8.3 Format Converter Operator

The built-in format converter operator converts the size and datatype of the incoming tensor.

8.8.4 Processor Operator

Inference Processor operator (`InferenceProcessorOp`) is designed using APIs from Holoscan Inference Component. The operator performs data processing operations specifically for inference examples in Holoscan SDK. The Inference Processor operator is updated to ingest custom CUDA kernels written by the user. The user must follow the conventions described below when designing and using custom CUDA kernels:

- Custom Cuda Kernel name must be: custom_cuda_kernel-*identifier*. E.g. A custom CUDA kernel with identifier as 1 must be named as custom_cuda_kernel-1. The identifier must be unique for all the custom kernels and is used in defining the kernels further in the parameter set.
- Named custom CUDA kernel is invoked in the parameter set as shown below. Custom CUDA operation is mapped to the input tensor **input_tensor** via **process_operations** map in the parameter set.

```
processor_op:
    process_operations:
        "input_tensor": ["custom_cuda_kernel-1"]
```

- Custom CUDA kernel is defined using **custom_kernels** map in the parameter set.

```
processor_op:
    cuda_kernels:
        cuda_kernel-1: |
                      extern "C" __global__ void customKernel1(const unsigned char*␣
↪input,
                                                                unsigned char* output,␣
↪int size) {}
        out_dtype-1: "kUInt8"
        thread_per_block-1: "256"
```

- Custom CUDA kernel is defined with key cuda_kernel-*identifier*. In the example above, CUDA kernel with identifier **1** is defined using the key **cuda_kernel-1** in the **cuda_kernels** parameter.
  - Custom CUDA kernel name must follow the following convention: *customKernelIdentifier*. For e.g in the example in the parameter set above, function name is *customKernel1* with identifier *1*.
  - Function name must be preceded: by `extern "C"` and the `__global__` keyword as shown in the example above.
  - Multi dimensional custom CUDA kernels are supported, though function arguments support is limited to the following:
    - 1D: (const void* input, void* output, int size)
    - 2D: (const void* input, void* output, int width, int height)
    - 3D: (const void* input, void* output, int width, int height, int depth)
  - Output buffer allocation is of same size as input. Customized buffer dimension support will come in future releases.
  - Custom CUDA kernel can be ingested via a filepath or a string. If the custom CUDA kernel is ingested via a filepath, the operator will read the kernel from the file. If the custom CUDA kernel is ingested via a string in the parameter set, the operator will use the kernel from the string. Filepath must end with **.cu** extension. All specifications for the kernel must be present in the file.
- Output data type for custom CUDA kernel with identifier **1** is defined as **out_dtype-1**.
  - Options: kFloat32, kFloat16, kUInt8, kInt8, kInt32, kInt64
- Threads per block for custom CUDA kernel with identifier **1** is defined with key **thread_per_block-1**. By default, custom CUDA kernel is 1D and if this parameter is not specified, the operator will assume it to be a 1D kernel with 256 threads.
- **threads_per_block-identifier** parameter in the **cuda_kernels** map is used in identifying the dimension of the kernel. For a 2D kernel, this parameter must be present with 2 values of threads per block (in x and y dimension) separated by a comma (,). For e.g. *thread_per_block-identifier: "16,16"*. Similarly for a 3D kernel, *thread_per_block-identifier: "8,8,8"*.

- Multi Custom CUDA kernel support: User can create one of more custom CUDA kernel in the same instance of the **InferenceProcessorOp** and can define it in the same parameter set.

```
processor_op:
    process_operations:
        "input_tensor": ["custom_cuda_kernel-1"]
    cuda_kernels:
        cuda_kernel-1: |
                      extern "C" __global__ void customKernel1(const unsigned char*␣
↪input,
```

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```
                                                            unsigned char* output,␣
↪int size) {}
       out_dtype-1: "kUInt8"
       thread_per_block-1: "256"
       cuda_kernel-2: |
                  extern "C" __global__ void customKernel2(const unsigned char*␣
↪input,
                                                            unsigned char* output,␣
↪int size) {}
       out_dtype-2: "kUInt8"
       thread_per_block-2: "16,16"
```

  - In the example above, two custom CUDA kernels are defined. *cuda_kernel-1* is 1D and *custom_kernel-2* is a 2D kernel, they both are used in the same parameter set.

- Templated kernels are not supported in this release.

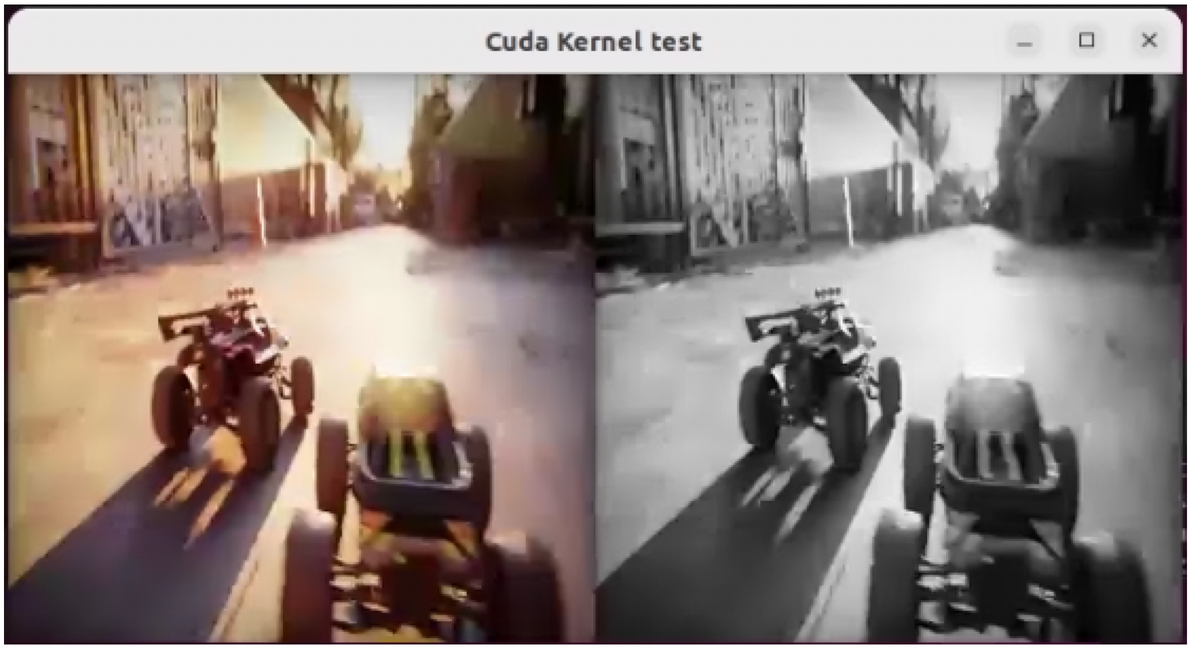
8.8.5 Holoviz Operator

The built-in Holoviz operator provides the functionality to composite realtime streams of frames with multiple different other layers like segmentation mask layers, geometry layers and GUI layers. We will use Holoviz to display frames that have been sent by the replayer operator and processor operator to its "receivers" port which can receive any number of inputs.

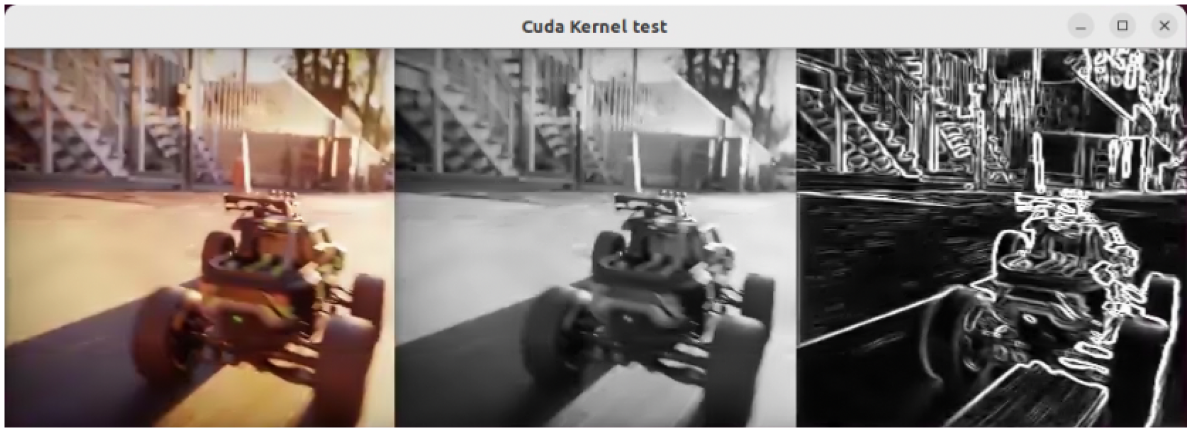
8.8.6 Running the Application

Running the application should bring up holoviz display for each of the example as shown below.

- custom_cuda_kernel_1d_sample: This example shows the input frame and grayscale of the input frame side by side. Grayscale conversion is executed by the custom CUDA kernel.



- custom_cuda_kernel_multi_sample: This example shows the input frame and grayscale of the input frame, followed by edge detection in the frame. Grayscale conversion is executed by a 1D CUDA kernel, edge detection is performed by a customized 2D CUDA kernel.



CHAPTER

NINE

CREATING AN APPLICATION

In this section, we'll address:

- How to *define an Application class*.
- How to *configure an Application*.
- How to *define different types of workflows*.
- How to *build and run your application*.

Note: This section covers basics of applications running as a single fragment. For multi-fragment applications, refer to the *distributed application documentation*.

9.1 Defining an Application Class

The following code snippet shows an example Application code skeleton:

C++

- We define the `App` class that inherits from the `Application` base class.
- We create an instance of the `App` class in `main()` using the `make_application()` function.
- The `run()` method starts the application which will execute its `compose()` method where the custom workflow will be defined.

```cpp
#include <holoscan/holoscan.hpp>

class App : public holoscan::Application {
 public:
  void compose() override {
    // Define Operators and workflow
    //   ...
  }
};

int main() {
  auto app = holoscan::make_application<App>();
  app->run();
```

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```
  return 0;
}
```

Python

- We define the App class that inherits from the Application base class.
- We create an instance of the App class in a main() function that is called from __main__.
- The run() method starts the application which will execute its compose() method where the custom workflow will be defined.

```python
from holoscan.core import Application

class App(Application):

    def compose(self):
        # Define Operators and workflow
        #   ...


def main():
    app = App()
    app.run()

if __name__ == "__main__":
    main()
```

Note: It is recommended to call run() from within a separate main() function rather than calling it directly from __main__. This will ensure that the Application's destructor is called before the Python process exits.

Tip: This is also illustrated in the *hello_world* example.

It is also possible to instead launch the application asynchronously (i.e., non-blocking for the thread launching the application), as shown below:

C++

This can be done simply by replacing the call to run() with run_async() which returns a std::future. Calling future.get() will block until the application has finished running and throw an exception if a runtime error occurred during execution.

```cpp
int main() {
  auto app = holoscan::make_application<App>();
  auto future = app->run_async();
  future.get();
  return 0;
}
```

Python

This can be done simply by replacing the call to `run()` with `run_async()` which returns a Python `concurrent.futures.Future`. Calling `future.result()` will block until the application has finished running and raise an exception if a runtime error occurred during execution.

```python
def main():
    app = App()
    future = app.run_async()
    future.result()


if __name__ == "__main__":
    main()
```

Tip: This is also illustrated in the ping_simple_run_async example.

9.2 Configuring an Application

An application can be configured at different levels:

1. *providing the GXF extensions that need to be loaded* (when using *GXF operators*).
2. configuring parameters for your application, including for: a. *the operators* in the workflow. b. *the scheduler* of your application.
3. *configuring some runtime properties* when deploying for production.

The sections below will describe how to configure each of them, starting with a native support for YAML-based configuration for convenience.

9.2.1 YAML configuration support

Holoscan supports loading arbitrary parameters from a YAML configuration file at runtime, making it convenient to configure each item listed above, or other custom parameters you wish to add on top of the existing API. For C++ applications, it also provides the ability to change the behavior of your application without needing to recompile it.

Note: Usage of the YAML utility is optional. Configurations can be hardcoded in your program, or done using any parser that you choose.

Here is an example YAML configuration:

```yaml
string_param: "test"
float_param: 0.50
bool_param: true
dict_param:
  key_1: value_1
  key_2: value_2
```

Ingesting these parameters can be done using the two methods below:

C++

- The `config()` method takes the path to the YAML configuration file. If the input path is relative, it will be relative to the current working directory.
- The `from_config()` method returns an `ArgList` object for a given key in the YAML file. It holds a list of `Arg` objects, each of which holds a name (key) and a value.
  - If the `ArgList` object has only one `Arg` (when the key is pointing to a scalar item), it can be converted to the desired type using the `as()` method by passing the type as an argument.
  - The key can be a dot-separated string to access nested fields.
- The `config_keys()` method returns an unordered set of the key names accessible via `from_config()`.

```cpp
// Pass configuration file
auto app = holoscan::make_application<App>();
app->config("path/to/app_config.yaml");

// Scalars
auto string_param = app->from_config("string_param").as<std::string>();
auto float_param = app->from_config("float_param").as<float>();
auto bool_param = app->from_config("bool_param").as<bool>();

// Dict
auto dict_param = app->from_config("dict_param");
auto dict_nested_param = app->from_config("dict_param.key_1").as<std::string>();

// Print
std::cout << "string_param: " << string_param << std::endl;
std::cout << "float_param: " << float_param << std::endl;
std::cout << "bool_param: " << bool_param << std::endl;
std::cout << "dict_param:\n" << dict_param.description() << std::endl;
std::cout << "dict_param['key1']: " << dict_nested_param << std::endl;

// // Output
// string_param: test
// float_param: 0.5
// bool_param: 1
// dict_param:
// name: arglist
// args:
//   - name: key_1
//     type: YAML::Node
//     value: value_1
//   - name: key_2
//     type: YAML::Node
//     value: value_2
// dict_param['key1']: value_1
```

Python

- The `config()` method takes the path to the YAML configuration file. If the input path is relative, it will be relative to the current working directory.
- The `kwargs()` method return a regular Python dict for a given key in the YAML file.
  - **Advanced**: this method wraps the `from_config()` method similar to the C++ equivalent, which returns an `ArgList` object if the key is pointing to a map item, or an `Arg` object if the key is pointing to a scalar item. An `Arg` object can be cast to the desired type (e.g., `str(app.from_config("string_param"))`).
- The `config_keys()` method returns a set of the key names accessible via `from_config()`.

```python
# Pass configuration file
app = App()
app.config("path/to/app_config.yaml")

# Scalars
string_param = app.kwargs("string_param")["string_param"]
float_param = app.kwargs("float_param")["float_param"]
bool_param = app.kwargs("bool_param")["bool_param"]

# Dict
dict_param = app.kwargs("dict_param")
dict_nested_param = dict_param["key_1"]

# Print
print(f"string_param: {string_param}")
print(f"float_param: {float_param}")
print(f"bool_param: {bool_param}")
print(f"dict_param: {dict_param}")
print(f"dict_param['key_1']: {dict_nested_param}")

# # Output:
# string_param: test
# float_param: 0.5
# bool_param: True
# dict_param: {'key_1': 'value_1', 'key_2': 'value_2'}
# dict_param['key_1']: 'value_1'
```

Warning: `from_config()` cannot be used as inputs to the `built-in operators` at this time. Therefore, it's recommended to use `kwargs()` in Python.

Tip: This is also illustrated in the *video_replayer* example.

Attention: With both `from_config` and `kwargs`, the returned `ArgList`/dictionary will include both the key and its associated item if that item value is a scalar. If the item is a map/dictionary itself, the input key is dropped, and the output will only hold the key/values from that item.

9.2.2 Loading GXF extensions

If you use operators that depend on GXF extensions for their implementations (known as *GXF operators*), the shared libraries (`.so`) of these extensions need to be dynamically loaded as plugins at runtime.

The SDK already automatically handles loading the required extensions for the *built-in operators* in both C++ and Python, as well as common extensions (listed here). To load additional extensions for your own operators, you can use one of the following approach:

YAML

```yaml
extensions:
  - libgxf_myextension1.so
  - /path/to/libgxf_myextension2.so
```

C++

```cpp
auto app = holoscan::make_application<App>();
auto exts = {"libgxf_myextension1.so", "/path/to/libgxf_myextension2.so"};
for (auto& ext : exts) {
  app->executor().extension_manager()->load_extension(ext);
}
```

PYTHON

```python
from holoscan.gxf import load_extensions
from holoscan.core import Application
app = Application()
context = app.executor.context_uint64
exts = ["libgxf_myextension1.so", "/path/to/libgxf_myextension2.so"]
load_extensions(context, exts)
```

Note: To be discoverable, paths to these shared libraries need to either be absolute, relative to your working directory, installed in the `lib/gxf_extensions` folder of the holoscan package, or listed under the `HOLOSCAN_LIB_PATH` or `LD_LIBRARY_PATH` environment variables.

Please see other examples in the system tests in the Holoscan SDK repository.

9.2.3 Configuring operators

Operators are defined in the `compose()` method of your application. They are not instantiated (with the `initialize` method) until an application's `run()` method is called.

Operators have three type of fields which can be configured: parameters, conditions, and resources.

Configuring operator parameters

Operators could have parameters defined in their `setup` method to better control their behavior (see details when *creating your own operators*). The snippet below would be the implementation of this method for a minimal operator named `MyOp`, that takes a string and a boolean as parameters; we'll ignore any extra details for the sake of this example:

C++

```cpp
void setup(OperatorSpec& spec) override {
  spec.param(string_param_, "string_param");
  spec.param(bool_param_, "bool_param");
}
```

PYTHON

```python
def setup(self, spec: OperatorSpec):
  spec.param("string_param")
  spec.param("bool_param")
  # Optional in python. Could define `self.<param_name>` instead in `def __init__`
```

Tip: Given an instance of an operator class, you can print a human-readable description of its specification to inspect the parameter fields that can be configured on that operator class:

C++

```cpp
std::cout << operator_object->spec()->description() << std::endl;
```

PYTHON

```python
print(operator_object.spec)
```

Given this YAML configuration:

```yaml
myop_param:
  string_param: "test"
  bool_param: true

bool_param: false # we'll use this later
```

We can configure an instance of the `MyOp` operator in the application's `compose` method like this:

C++

```cpp
void compose() override {
  // Using YAML
  auto my_op1 = make_operator<MyOp>("my_op1", from_config("myop_param"));

  // Same as above
  auto my_op2 = make_operator<MyOp>("my_op2",
    Arg("string_param", std::string("test")), // can use Arg(key, value)...
    Arg("bool_param") = true                  // ... or Arg(key) = value
  );
}
```

PYTHON

```python
def compose(self):
  # Using YAML
  my_op1 = MyOp(self, name="my_op1", **self.kwargs("myop_param"))

  # Same as above
  my_op2 = MyOp(self,
    name="my_op2",
    string_param="test",
    bool_param=True,
  )
```

Tip: This is also illustrated in the *ping_custom_op* example.

If multiple `ArgList` are provided with duplicate keys, the latest one overrides them:

C++

```cpp
void compose() override {
  // Using YAML
  auto my_op1 = make_operator<MyOp>("my_op1",
    from_config("myop_param"),
    from_config("bool_param")
  );

  // Same as above
  auto my_op2 = make_operator<MyOp>("my_op2",
    Arg("string_param", "test"),
    Arg("bool_param") = true,
    Arg("bool_param") = false
  );

  // -> my_op `bool_param_` will be set to `false`
}
```

PYTHON

```python
def compose(self):
  # Using YAML
  my_op1 = MyOp(self, name="my_op1",
    from_config("myop_param"),
    from_config("bool_param"),
  )

  # Note: We're using from_config above since we can't merge automatically with kwargs
  # as this would create duplicated keys. However, we recommend using kwargs in Python
  # to avoid limitations with wrapped operators, so the code below is preferred.

  # Same as above
  params = self.kwargs("myop_param").update(self.kwargs("bool_param"))
  my_op2 = MyOp(self, name="my_op2", params)

  # -> my_op `bool_param` will be set to `False`
```

Configuring operator conditions

By default, operators with no input ports will continuously run, while operators with input ports will run as long as they receive inputs (as they're configured with the `MessageAvailableCondition`).

To change that behavior, one or more other *conditions*' classes can be passed to the constructor of an operator to define when it should execute.

For example, we set three conditions on this operator `my_op`:

C++

```cpp
void compose() override {
  // Limit to 10 iterations
  auto c1 = make_condition<CountCondition>("my_count_condition", 10);

  // Wait at least 200 milliseconds between each execution
  auto c2 = make_condition<PeriodicCondition>("my_periodic_condition", "200ms");

  // Stop when the condition calls `disable_tick()`
  auto c3 = make_condition<BooleanCondition>("my_bool_condition");

  // Pass directly to the operator constructor
  auto my_op = make_operator<MyOp>("my_op", c1, c2, c3);
}
```

PYTHON

```python
def compose(self):
  # Limit to 10 iterations
  c1 = CountCondition(self, 10, name="my_count_condition")

  # Wait at least 200 milliseconds between each execution
  c2 = PeriodicCondition(self, timedelta(milliseconds=200), name="my_periodic_condition")

  # Stop when the condition calls `disable_tick()`
  c3 = BooleanCondition(self, name="my_bool_condition")

  # Pass directly to the operator constructor
  my_op = MyOp(self, c1, c2, c3, name="my_op")
```

Tip: This is also illustrated in the conditions' examples.

Note: You'll need to specify a unique name for the conditions if there are multiple conditions applied to an operator.

Configuring operator resources

Some *resources* can be passed to the operator's constructor, typically an *allocator* passed as a regular parameter.

For example:

C++

```cpp
void compose() override {
  // Allocating memory pool of specific size on the GPU
  // ex: width * height * channels * channel size in bytes
  auto block_size = 640 * 480 * 4 * 2;
  auto p1 = make_resource<BlockMemoryPool>("my_pool1", 1, size, 1);

  // Provide unbounded memory pool
  auto p2 = make_condition<UnboundedAllocator>("my_pool2");

  // Pass to operator as parameters (name defined in operator setup)
  auto my_op = make_operator<MyOp>("my_op",
                                   Arg("pool1", p1),
                                   Arg("pool2", p2));
}
```

PYTHON

```
def compose(self):
  # Allocating memory pool of specific size on the GPU
  # ex: width * height * channels * channel size in bytes
  block_size = 640 * 480 * 4 * 2;
  p1 = BlockMemoryPool(self, name="my_pool1", storage_type=1, block_size=block_size, num_
↪blocks=1)

  # Provide unbounded memory pool
  p2 = UnboundedAllocator(self, name="my_pool2")

  # Pass to operator as parameters (name defined in operator setup)
  auto my_op = MyOp(self, name="my_op", pool1=p1, pool2=p2)
```

Native resource creation

The resources bundled with the SDK are wrapping an underlying GXF component. However, it is also possible to define a "native" resource without any need to create and wrap an underlying GXF component. Such a resource can also be passed conditionally to an operator in the same way as the resources created in the previous section.

For example:

C++

To create a native resource, implement a class that inherits from `Resource`

```
namespace holoscan {

class MyNativeResource : public holoscan::Resource {
 public:
  HOLOSCAN_RESOURCE_FORWARD_ARGS_SUPER(MyNativeResource, Resource)

  MyNativeResource() = default;

  // add any desired parameters in the setup method
  // (a single string parameter is shown here for illustration)
  void setup(ComponentSpec& spec) override {
    spec.param(message_, "message", "Message string", "Message String", std::string(
↪"test message"));
  }

  // add any user-defined methods (these could be called from an Operator's compute␣
↪method)
  std::string message() { return message_.get(); }

 private:
  Parameter<std::string> message_;
};
}  // namespace: holoscan
```

The `setup` method can be used to define any parameters needed by the resource.

This resource can be used with a C++ operator, just like any other resource. For example, an operator could have a parameter holding a shared pointer to `MyNativeResource` as below.

```
private:

class MyOperator : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(MyOperator)

  MyOperator() = default;

  void setup(OperatorSpec& spec) override {
    spec.param(message_resource_, "message_resource", "message resource",
               "resource printing a message");
  }

  void compute(InputContext&, OutputContext& op_output, ExecutionContext&) override {
    HOLOSCAN_LOG_TRACE("MyOp::compute()");

    // get a resource based on its name (this assumes the app author named the resource
↪"message_resource")
    auto res = resource<MyNativeResource>("message_resource");
    if (!res) {
      throw std::runtime_error("resource named 'message_resource' not found!");
    }

    // call a method on the retrieved resource class
    auto message = res->message();

  };

private:
    Parameter<std::shared_ptr<holoscan::MyNativeResource> message_resource_;
}
```

The `compute` method above demonstrates how the templated `resource` method can be used to retrieve a resource.

and the resource could be created and passed via a named argument in the usual way

```
// example code for within Application::compose (or Fragment::compose)

    auto message_resource = make_resource<holoscan::MyNativeResource>(
        "message_resource", holoscan::Arg("message", "hello world");

    auto my_op = std::make_operator<holoscan::ops::MyOperator>(
        "my_op", holoscan::Arg("message_resource", message_resource));
```

As with GXF-based resources, it is also possible to pass a native resource as a positional argument to the operator constructor.

For a concreate example of native resource use in a real application, see the volume_rendering_xr application on Holohub. This application uses a native XrSession resource type which corresponds to a single OpenXR session. This single "session" resource can then be shared by both the `XrBeginFrameOp` and `XrEndFrameOp` operators.

Python

To create a native resource, implement a class that inherits from `Resource`.

```python
class MyNativeResource(Resource):
    def __init__(self, fragment, message="test message", *args, **kwargs):
        self.message = message
        super().__init__(fragment, *args, **kwargs)

    # Could optionally define Parameter as in C++ via spec.param as below.
    # Here, we chose instead to pass message as an argument to __init__ above.
    # def setup(self, spec: ComponentSpec):
    #     spec.param("message", "test message")

    # define a custom method
    def message(self):
        return self.message
```

The below shows how some custom operator could use such a resource in its compute method

```python
class MyOperator(Operator):
    def compute(self, op_input, op_output, context):
        resource = self.resource("message_resource")
        if resource is None:
            raise ValueError("expected message resource not found")
        assert isinstance(resource, MyNativeResource)

        print(f"message = {resource.message()")
```

where this native resource could have been created and passed positionally to `MyOperator` as follows

```python
# example code within Application.compose (or Fragment.compose)

    message_resource = MyNativeResource(
        fragment=self, message="hello world", name="message_resource")

    # pass the native resource as a positional argument to MyOperator
    my_op = MyOperator(fragment=self, message_resource)
```

There is a minimal example of native resource use in the examples/native folder.

9.2.4 Configuring the scheduler

The *scheduler* controls how the application schedules the execution of the operators that make up its *workflow*.

The default scheduler is a single-threaded *GreedyScheduler*. An application can be configured to use a different scheduler `Scheduler` (`C++`/`Python`) or change the parameters from the default scheduler, using the `scheduler()` function (`C++`/`Python`).

For example, if an application needs to run multiple operators in parallel, the *MultiThreadScheduler* or *EventBasedScheduler* can instead be used. The difference between the two is that the MultiThreadScheduler is based on actively polling operators to determine if they are ready to execute, while the EventBasedScheduler will instead wait for an event indicating that an operator is ready to execute.

The code snippet belows shows how to set and configure a non-default scheduler:

C++

- We create an instance of a holoscan::Scheduler derived class by using the `make_scheduler()` function. Like operators, parameters can come from explicit `Args` or `ArgList`, or from a YAML configuration.
- The `scheduler()` method assigns the scheduler to be used by the application.

```cpp
auto app = holoscan::make_application<App>();
auto scheduler = app->make_scheduler<holoscan::EventBasedScheduler>(
  "myscheduler",
  Arg("worker_thread_number", static_cast<int64_t>(4)),
  Arg("stop_on_deadlock", true)
);
app->scheduler(scheduler);
app->run();
```

Python

- We create an instance of a `Scheduler` class in the `schedulers` module. Like operators, parameters can come from an explicit `Arg` or `ArgList`, or from a YAML configuration.
- The `scheduler()` method assigns the scheduler to be used by the application.

```python
app = App()
scheduler = holoscan.schedulers.EventBasedScheduler(
    app,
    name="myscheduler",
    worker_thread_number=4,
    stop_on_deadlock=True,
)
app.scheduler(scheduler)
app.run()
```

Tip: This is also illustrated in the multithread example.

9.2.5 Configuring worker thread pools

Both the `MultiThreadScheduler` and `EventBasedScheduler` discussed in the previous section automatically create an internal worker thread pool by default. In some scenarios, it may be desirable for users to instead assign operators to specific user-defined thread pools. This also allows optionally pinning operators to a specific thread.

Assuming that, I have three operators, `op1`, `op2` and `op3`. Assume that I want to assign these two a thread pool and that I would like operators 2 and 3 to be pinned to specific threads in the thread pool. The code for configuring thread pools from the Fragment `compose` method is shown in the example below.

C++

We create thread pools via calls to the `make_thread_pool()` method. The first argument is a user-defined name for the thread pool while the second is the number of threads initially in the thread pool. This `make_thread_pool` method returns a shared pointer to a `ThreadPool` object. The `add()` method of that object can then be used to add a single operator or a vector of operators to the thread pool. The second argument to the `add` function is a boolean indicating whether the given operators should be pinned to always run on a specific thread within the thread pool.

```
    // The following code would be within `Fragment::compose` after operators have been␣
↪defined
    // Assume op1, op2 and op3 are `shared_ptr<OperatorType>` as returned by `make_
↪operator`

    // create a thread pool with a three threads
    auto pool1 = make_thread_pool("pool1", 3);
    // assign a single operator to the thread pool (unpinned)
    pool1->add(op1, false);
    // assign multiple operators to this thread pool (pinned)
    pool1->add({op2, op3}, true);
```

Python

We create thread pools via calls to the `make_thread_pool()` method. The first argument is a user-defined name for the thread pool while the second is the initial size of the thread pool. It is not necessary to modify this as the size will be incremented as needed automatically. This `make_thread_pool` method returns a shared pointer to a `ThreadPool` object. The `add()` method of that object can then be used to add a single operator or a vector of operators to the thread pool. The second argument to the `add` function is a boolean indicating whether the given operators should be pinned to always run on a specific thread within the thread pool.

```
    # The following code would be within `Fragment::compose` after operators have been␣
↪defined
    # Assume op1, op2 and op3 are `shared_ptr<OperatorType>` as returned by `make_
↪operator`

    # create a thread pool with a single thread
    pool1 = self.make_thread_pool("pool1", 1);
    # assign a single operator to the thread pool (unpinned)
    pool1.add(op1, True);
    # assign multiple operators to this thread pool (pinned)
    pool1.add([op2, op3], True);
```

Note: It is not necessary to define a thread pool for Holoscan applications. There is a default thread pool that gets used for any operators the user did not explicitly assign to a thread pool. The use of thread pools provides a way to explicitly indicate that threads should be pinned.

One case where separate thread pools **must** be used is in order to support pinning of operators involving separate GPU devices. Only a single GPU device should be used from any given thread pool. Operators associated with a GPU device resource are those using one of the CUDA-based allocators like `BlockMemoryPool`, `CudaStreamPool`, `RMMAllocator` or `StreamOrderedAllocator`.

Tip: A concrete example of a simple application with two pairs of operators in separate thread pools is given in the thread pool resource example.

Note that any given operator can only belong to a single thread pool. Assigning the same operator to multiple thread pools may result in errors being logged at application startup time.

There is also a related boolean parameter, `strict_thread_pinning` that can be passed as a `holoscan::Arg` to the `MultiThreadScheduler` constructor. When this argument is set to `false` and an operator is pinned to a specific thread, it is allowed for other operators to also run on that same thread whenever the pinned operator is not ready to execute. When `strict_thread_pinning` is `true`, the thread can ONLY be used by the operator that was pinned to the thread. For the `EventBasedScheduler`, it is always in strict pinning mode and there is no such parameter.

If a thread pool is configured by the single-thread `GreedyScheduler` is used a warning will be logged indicating that the user-defined thread pools would be ignored. Only `MultiThreadScheduler` and `EventBasedScheduler` can make use of the thread pools.

9.2.6 Configuring runtime properties

As described *below*, applications can run simply by executing the C++ or Python application manually on a given node, or by *packaging it* in a *HAP container*. With the latter, runtime properties need to be configured: refer to the *App Runner Configuration* for details.

9.3 Application Workflows

Note: Operators are initialized according to the topological order of its fragment-graph. When an application runs, the operators are executed in the same topological order. Topological ordering of the graph ensures that all the data dependencies of an operator are satisfied before its instantiation and execution. Currently, we do not support specifying a different and explicit instantiation and execution order of the operators.

9.3.1 One-operator Workflow

The simplest form of a workflow would be a single operator.

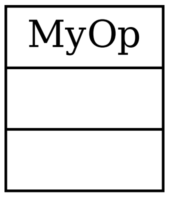


Fig. 9.1: A one-operator workflow

The graph above shows an **Operator** (`C++/Python`) (named `MyOp`) that has neither inputs nor output ports.

- Such an operator may accept input data from the outside (e.g., from a file) and produce output data (e.g., to a file) so that it acts as both the source and the sink operator.
- Arguments to the operator (e.g., input/output file paths) can be passed as parameters as described in the *section above*.

We can add an operator to the workflow by calling `add_operator` (`C++`/`Python`) method in the `compose()` method.

The following code shows how to define a one-operator workflow in `compose()` method of the `App` class (assuming that the operator class `MyOp` is declared/defined in the same file).

CPP

```cpp
class App : public holoscan::Application {
 public:
  void compose() override {
    // Define Operators
    auto my_op = make_operator<MyOp>("my_op");

    // Define the workflow
    add_operator(my_op);
  }
};
```

PYTHON

```python
class App(Application):

    def compose(self):
        # Define Operators
        my_op = MyOp(self, name="my_op")

        # Define the workflow
        self.add_operator(my_op)
```

9.3.2 Linear Workflow

Here is an example workflow where the operators are connected linearly:

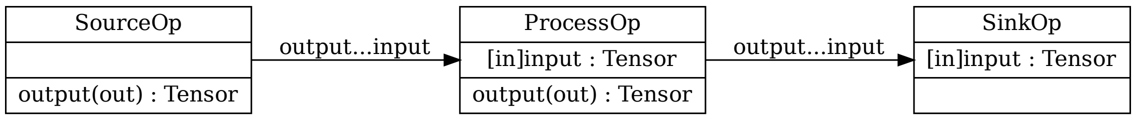


Fig. 9.2: A linear workflow

In this example, **SourceOp** produces a message and passes it to **ProcessOp**. **ProcessOp** produces another message and passes it to **SinkOp**.

We can connect two operators by calling the `add_flow()` method (`C++`/`Python`) in the `compose()` method.

The `add_flow()` method (`C++`/`Python`) takes the source operator, the destination operator, and the optional port name pairs. The port name pair is used to connect the output port of the source operator to the input port of the destination operator. The first element of the pair is the output port name of the upstream operator and the second element is the input port name of the downstream operator. An empty port name ("") can be used for specifying a port name if the operator has only one input/output port. If there is only one output port in the upstream operator and only one input port in the downstream operator, the port pairs can be omitted.

The following code shows how to define a linear workflow in the `compose()` method of the `App` class (assuming that the operator classes `SourceOp`, `ProcessOp`, and `SinkOp` are declared/defined in the same file).

CPP

```cpp
class App : public holoscan::Application {
 public:
  void compose() override {
    // Define Operators
    auto source = make_operator<SourceOp>("source");
    auto process = make_operator<ProcessOp>("process");
    auto sink = make_operator<SinkOp>("sink");

    // Define the workflow
    add_flow(source, process); // same as `add_flow(source, process, {{"output", "input"}
↪});`
    add_flow(process, sink);   // same as `add_flow(process, sink, {{"", ""}});`
  }
};
```

PYTHON

```python
class App(Application):

    def compose(self):
        # Define Operators
        source = SourceOp(self, name="source")
        process = ProcessOp(self, name="process")
        sink = SinkOp(self, name="sink")

        # Define the workflow
        self.add_flow(source, process) # same as `self.add_flow(source, process, {(
↪"output", "input")})`
        self.add_flow(process, sink)   # same as `self.add_flow(process, sink, {("", "")}
↪)`
```

9.3.3 Complex Workflow (Multiple Inputs and Outputs)

You can design a complex workflow like below where some operators have multi-inputs and/or multi-outputs:

CPP

```cpp
class App : public holoscan::Application {
 public:
  void compose() override {
    // Define Operators
    auto reader1 = make_operator<Reader1>("reader1");
    auto reader2 = make_operator<Reader2>("reader2");
    auto processor1 = make_operator<Processor1>("processor1");
    auto processor2 = make_operator<Processor2>("processor2");
    auto processor3 = make_operator<Processor3>("processor3");
    auto writer = make_operator<Writer>("writer");
    auto notifier = make_operator<Notifier>("notifier");

    // Define the workflow
    add_flow(reader1, processor1, {{"image", "image1"}, {"image", "image2"}, {"metadata",
↪ "metadata"}});
    add_flow(reader1, processor1, {{"image", "image2"}});
    add_flow(reader2, processor2, {{"roi", "roi"}});
    add_flow(processor1, processor2, {{"image", "image"}});
    add_flow(processor1, writer, {{"image", "image"}});
    add_flow(processor2, notifier);
    add_flow(processor2, processor3);
    add_flow(processor3, writer, {{"seg_image", "seg_image"}});
  }
};
```

PYTHON

```python
class App(Application):

    def compose(self):
        # Define Operators
        reader1 = Reader1Op(self, name="reader1")
        reader2 = Reader2Op(self, name="reader2")
        processor1 = Processor1Op(self, name="processor1")
        processor2 = Processor2Op(self, name="processor2")
        processor3 = Processor3Op(self, name="processor3")
        notifier = NotifierOp(self, name="notifier")
        writer = WriterOp(self, name="writer")

        # Define the workflow
        self.add_flow(reader1, processor1, {("image", "image1"), ("image", "image2"), (
↪"metadata", "metadata")})
        self.add_flow(reader2, processor2, {("roi", "roi")})
        self.add_flow(processor1, processor2, {("image", "image")})
        self.add_flow(processor1, writer, {("image", "image")})
```

(continues on next page)

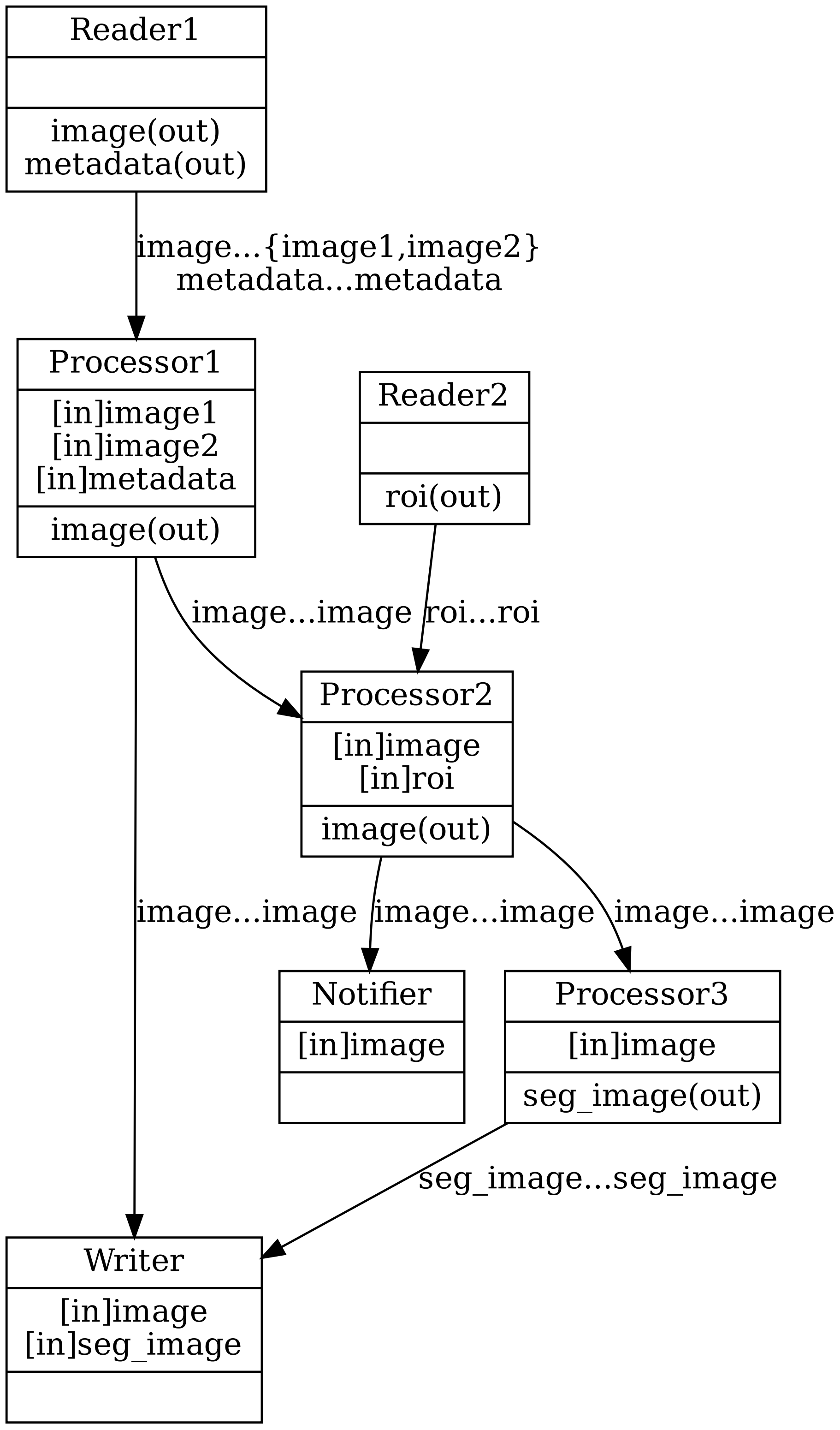


Fig. 9.3: A complex workflow (multiple inputs and outputs)

(continued from previous page)

```
        self.add_flow(processor2, notifier)
        self.add_flow(processor2, processor3)
        self.add_flow(processor3, writer, {("seg_image", "seg_image")})
```

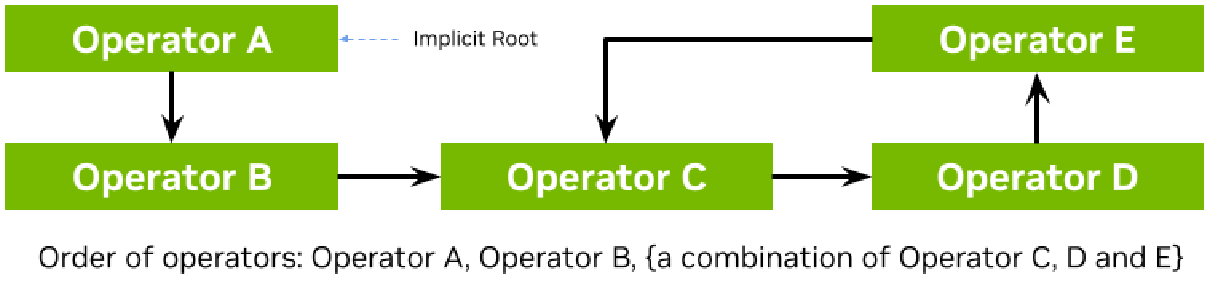
If there is a cycle in the graph with no implicit root operator, the root operator is either the first operator in the first call to `add_flow` method (C++/Python), or the operator in the first call to `add_operator` method (C++/Python).

C++

```
auto op1 = make_operator<...>("op1");
auto op2 = make_operator<...>("op2");
auto op3 = make_operator<...>("op3");

add_flow(op1, op2);
add_flow(op2, op3);
add_flow(op3, op1);
// There is no implicit root operator
// op1 is the root operator because op1 is the first operator in the first call to add_
↪flow
```

If there is a cycle in the graph with an implicit root operator which has no input port, then the initialization and execution orders of the operators are still topologically sorted as far as possible until the cycle needs to be explicitly broken. An example is given below:


Operator A
Implicit Root
Operator E
Operator B
Operator C
Operator D
Order of operators: Operator A, Operator B, {a combination of Operator C, D and E}

9.3.4 Dynamic Flow Control for Complex Workflows

As of Holoscan v3.0, the dynamic flow control feature is available, enabling operators to modify their connections with other operators at runtime. This allows for the creation of complex workflows with conditional branching, loops, and dynamic routing patterns.

Key features include:

- Implicit input/output execution ports for execution dependency control
- The Start operator concept (`start_op()` (C++/Python)) for managing workflow entry points
- Dynamic flow modification using `set_dynamic_flows()` (C++/Python) and `add_dynamic_flow()` (C++/Python) methods
- Flow information management via the `FlowInfo` (C++/Python) class

For details, please refer to the *Dynamic Flow Control* section of the user guide.

9.3.5 Application Execution Control APIs

Holoscan provides APIs for controlling the execution of operators at the application or fragment level.

stop_execution

The `stop_execution()` (C++/Python) method allows an application to stop the execution of a specific operator or the entire application:

C++

```cpp
virtual void stop_execution(const std::string& op_name = "");
```

When called with an operator name, this method stops the execution of the specified operator. When called with an empty string (the default), it stops all operators in the fragment, effectively shutting down the application.

Example usage to stop a specific operator:

```cpp
// From within a Fragment/Application method
stop_execution("source_operator");
```

Example usage to stop the entire application:

```cpp
// From within a Fragment/Application method
stop_execution();
```

Example usage to access `stop_execution()` method from within an operator:

```cpp
// From within an operator's compute method
fragment()->stop_execution(); // `fragment()` returns a pointer to the fragment object
```

Python

```python
def stop_execution(self, op_name="")
```

When called with an operator name, this method stops the execution of the specified operator. When called with an empty string (the default), it stops all operators in the fragment, effectively shutting down the application.

Example usage to stop a specific operator:

```python
# From within a Fragment/Application method
self.stop_execution("source_operator")
```

Example usage to stop the entire application:

```python
# From within a Fragment/Application method
self.stop_execution()
```

Example usage to access `stop_execution()` method from within an operator:

```python
# From within an operator's compute method
self.fragment.stop_execution() # `self.fragment` is the fragment object
```

For a complete example of how to use these methods to implement advanced monitoring behavior, see the operator_status_tracking example, which demonstrates:

1. A source operator that runs for a limited number of iterations
2. A monitor operator that independently tracks the status of other operators
3. Automatic application shutdown when all processing operators have completed

9.4 Building and running your Application

C++

You can build your C++ application using CMake, by calling `find_package(holoscan)` in your `CMakeLists.txt` to load the SDK libraries. Your executable will need to link against:

- `holoscan::core`
- any operator defined outside your `main.cpp` which you wish to use in your app workflow, such as:
  - SDK *built-in operators* under the `holoscan::ops` namespace.
  - operators created separately in your project with `add_library`.
  - operators imported externally using with `find_library` or `find_package`.

Listing 9.1: <src_dir>/CMakeLists.txt

```cmake
# Your CMake project
cmake_minimum_required(VERSION 3.20)
project(my_project CXX)

# Finds the holoscan SDK
find_package(holoscan REQUIRED CONFIG PATHS "/opt/nvidia/holoscan")

# Create an executable for your application
add_executable(my_app main.cpp)

# Link your application against holoscan::core and any existing operators you'd like to␣
↪use
target_link_libraries(my_app
  PRIVATE
    holoscan::core
    holoscan::ops::<some_built_in_operator_target>
    <some_other_operator_target>
    <...>
)
```

Tip: This is also illustrated in all the examples:

- in `CMakeLists.txt` for the SDK installation directory - `/opt/nvidia/holoscan/examples`.
- in `CMakeLists.min.txt` for the SDK source directory.

Once your CMakeLists.txt is ready in <src_dir>, you can build in <build_dir> with the command line below. You can optionally pass Holoscan_ROOT if the SDK installation you'd like to use differs from the PATHS given to find_package(holoscan) above.

```
# Configure
cmake -S <src_dir> -B <build_dir> -D Holoscan_ROOT="/opt/nvidia/holoscan"
# Build
cmake --build <build_dir> -j
```

You can then run your application by running <build_dir>/my_app.

Python

Python applications do not require building. Simply ensure that:

- The holoscan python module is installed in your dist-packages or is listed under the PYTHONPATH env variable so you can import holoscan.core and any built-in operator you might need in holoscan.operators.
- Any external operators are available in modules in your dist-packages or contained in PYTHONPATH.

Note: While Python applications do not need to be built, they might depend on operators that wrap C++ operators. All Python operators built-in in the SDK already ship with the Python bindings pre-built. Follow *this section* if you are wrapping C++ operators yourself to use in your Python application.

You can then run your application by running python3 my_app.py.

Note: Given a CMake project, a pre-built executable, or a Python application, you can also use the *Holoscan CLI to package and run your Holoscan application* in a OCI-compliant container image.

9.5 Dynamic Application Metadata

As of Holoscan v2.3 (for C++) or v2.4 (for Python) it is possible to send metadata alongside the data emitted from an operator's output ports. This metadata can then be used and/or modified by any downstream operators. The subsections below describe how this feature can be used.

9.5.1 Enabling application metadata

As of Holoscan v3.0, the metadata feature is enabled by default (in older releases it had to be explicitly enabled). If the application author does not wish to use the metadata feature it will not hurt to leave the feature enabled. To avoid even the minor overhead of checking for metadata in received messages, the feature can be explicitly disabled as shown below.

C++

```
app = holoscan::make_application<MyApplication>();

// Disable metadata feature before calling app->run() or app->run_async()
app->enable_metadata(false);

app->run();
```

Python

```
app = MyApplication()

# Disable metadata feature before calling app.run() or app.run_async()
app.enable_metadata(False)
app.run()
```

None of the built-in operators provided by the SDK itself currently require that the feature be enabled, but it is possible that some third-party operators might require it in order to work as expected. An example is the `V4L2FormatTranslateOp` defined as part of the v4l2_camera example (video format information is stored in the metadata).

Note that the `enable_metadata` method exists on the Application, Fragment and Operator classes. Calling this method on the application sets the default for all fragments of a distributed application. Calling the method on an individual fragment sets the default to be used for that fragment (overrides the application-level default). Similarly, calling the method on an individual operator overrides the setting for that specific operator within a fragment.

9.5.2 Understanding Metadata Flow

Each operator in the workflow has an associated `MetadataDictionary` object. At the start of each operator's `compute()` call this metadata dictionary will be empty (i.e. metadata does not persist from previous compute calls). When any call to `receive()` data is made, any metadata also found in the input message will be merged into the operator's local metadata dictionary. The operator's compute method can then read, append to or remove metadata as explained in the next section. Whenever the operator emits data via a call to `emit()` the current status of the operator's metadata dictionary will be transmitted on that port alonside the data passed via the first argument to the emit call. Any downstream operators will then receive this metadata via their input ports.

9.5.3 Working With Metadata from Operator::compute

Within the operator's `compute()` method, the `metadata()` method can be called to get a shared pointer to the `MetadataDictionary` of the operator. The metadata dictionary provides a similar API to a `std::unordered_map` (C++) or `dict` (Python) where the keys are strings (`std::string` for C++) and the values can store any object type (via a C++ `MetadataObject` holding a `std::any`).

C++

Templated `get()` and `set()` method are provided as demonstrated below to allow directly setting values of a given type without having to explicitly work with the internal `MetadataObject` type.

```cpp
// Receiving from a port updates operator metadata with any metadata found on the port
auto input_tensors = op_input.receive<TensorMap>("in");

// Get a reference to the shared metadata dictionary
auto meta = metadata();

// Retrieve existing values.
// Use get<Type> to automatically cast the `std::any` contained within the␣
↪`holsocan::Message`
auto name = meta->get<std::string>("patient_name");
auto age = meta->get<int>("age");

// Get also provides a two-argument version where a default value to be assigned is␣
↪given by
// the second argument. The type of the default value should match the expected type of␣
↪the value.
auto flag = meta->get("flag", false);

// Add a new value (if a key already exists, the value will be updated according to the
// operator's metadata_policy).
std::vector<float> spacing{1.0, 1.0, 3.0};
meta->set("pixel_spacing"s, spacing);

// Remove an item
meta->erase("patient_name");

// Check if a key exists
bool has_patient_name = meta->has_key("patient_name");

// Get a vector<std::string> of all keys in the metadata
const auto& keys = meta->keys();

// ... Some processing to produce output `data` could go here ...

// Current state of `meta` will automatically be emitted along with `data` in the call␣
↪below
op_output.emit(data, "output1");

// Can clear all items
meta->clear();

// Any emit call after this point would not transmit a metadata object
op_output.emit(data, "output2");
```

See the `MetadataDictionary` API docs for all available methods.

Python

A Pythonic interface is provided for the `MetadataObject` type.

```python
# Receiving from a port updates operator metadata with any metadata found on the port
input_tensors = op_input.receive("in")

# self.metadata can be used to access the shared MetadataDictionary
# for example we can check if a key exists
has_key = "my_key" in self.metadata

# get the number of keys
num_keys = len(self.metadata)

# get a list of the keys
print(f"metadata keys = {self.metadata.keys()}")

# iterate over the values in the dictionary using the `items()` method
for key, value in self.metadata.items():
    # process item
    pass

# print a Python dict of the keys/values
print(self.metadata)

# Retrieve existing values. If the underlying value is a C++ class, a conversion to an␣
↪equivalent Python object will be made (e.g. `std::vector<std::string>` to `List[str]`).
name = self.metadata["patient_name"]
age = self.metadata["age"]

# It is also supported to use the get method along with an optional default value to use
# if the key is not present.
flag = self.metadata.get("flag", False)

# print the current metadata policy
print(f"metadata policy = {self.metadata_policy}")

# Add a new value (if a key already exists, the value will be updated according to the
# operator's metadata_policy). If the value is set via the indexing operator as below,
# the Python object itself is stored as the value.
spacing = (1.0, 1.0, 3.0)
self.metadata["pixel_spacing"] = spacing

# In some cases, if sending metadata to downstream C++-based operators, it may be desired
# to instead store the metadata value as an equivalent C++ type. In that case, it is
# necessary to instead set the value using the `set` method with `cast_to_cpp=True`.
# Automatic casting is supported for bool, str, and various numeric and iterator or
# sequence types.

# The following would result in the spacing `Tuple[float]` being stored as a
# C++ `std::vector<double>`. Here we show use of the `pop` method to remove a previous␣
↪value
```

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```
# if present.
self.metadata.pop("pixel_spacing", None)
self.metadata.set("pixel_spacing", spacing, cast_to_cpp=True)

# To store floating point elements at a different than the default (double) precision or
# integers at a different precision than int64_t, use the dtype argument and pass a
# numpy.dtype argument corresponding to the desired C++ type. For example, the following
# would instead store `spacing` as a std::vector<float> instead. In this case we show
# use of Python's `del` instead of the pop method to remove an existing item.
del self.metadata["pixel_spacing"]
self.metadata.set("pixel_spacing", spacing, dtype=np.float32, cast_to_cpp=True)

# Remove a value
del self["patient name"]

# ... Some processing to produce output `data` could go here ...

# Current state of `meta` will automatically be emitted along with `data` in the call␣
↪below
op_output.emit(data, "output1")

# Can clear all items
self.metadata.clear()

# Any emit call after this point would not transmit a metadata object
op_output.emit(data, "output2")
```

See the `MetadataDictionary` API docs for all available methods.

The above code illustrated various ways of working with and updating an operator's metadata.

Note: Pay particular attention to the details of how metadata is set. When working with pure Python applications it is best to just use `self.metadata[key] = value` or `self.metadata.set(key, value)` to pass Python objects as the value. This will just use a shared object and not result in copies to/from corresponding C++ types. However, when interacting with other operators that wrap a C++ implementation, their `compute` method would expected C++ metadata. In that case, the `set` method with `cast_to_cpp=True` is needed to cast to the expected C++ type. This was shown in some of the "pixel_spacing" set calls in the example above. For convenience, the `value` passed to the `set` method can also be a NumPy array, but note that in this case, a copy into a new C++ std::vector is performed. The dtype of the array will be respected when creating the vector. In general, the types that can currently be cast to C++ are scalar numeric values, strings and Python Iterators or Sequences of these (the sequence will be converted to a 1D or 2D C++ std::vector so the items in the Python sequence cannot be of mixed type).

Metadata Update Policies

C++

The operator class also has a `metadata_policy()` method that can be used to set a `MetadataPolicy` to use when handling duplicate metadata keys across multiple input ports of the operator. The available options are:

- "update" (`MetadataPolicy::kUpdate`): replace any existing key from a prior `receive` call with one present in a subsequent `receive` call.
- "reject" (`MetadataPolicy::kReject`): Reject the new key/value pair when a key already exists due to a prior `receive` call.
- "raise" (`MetadataPolicy::kRaise`): Throw a `std::runtime_error` if a duplicate key is encountered. This is the default policy.

The metadata policy would typically be set during `compose()` as in the following example:

```cpp
// Example for setting metadata policy from Application::compose()
my_op = make_operator<MyOperator>("my_op");
my_op->metadata_policy(holoscan::MetadataPolicy::kRaise);
```

Python

The operator class also has a `metadata_policy()` property that can be used to set a `MetadataPolicy` to use when handling duplicate metadata keys across multiple input ports of the operator. The available options are:

- "update" (`MetadataPolicy.UPDATE`): replace any existing key from a prior `receive` call with one present in a subsequent `receive` call. This is the default policy.
- "reject" (`MetadataPolicy.REJECT`): Reject the new key/value pair when a key already exists due to a prior `receive` call.
- "raise" (`MetadataPolicy.RAISE`): Throw an exception if a duplicate key is encountered.

The metadata policy would typically be set during `compose()` as in the following example:

```python

# Example for setting metadata policy from Application.compose()
my_op = MyOperator(self, name="my_op")
my_op.metadata_policy = holoscan.core.MetadataPolicy.RAISE

```

The policy applied as in the example above only applies to the operator on which it was set. The default metadata policy can also be set for the application as a whole via `Application::metadata_policy` (C++/Python) or for individual fragments of a distributed application via `Fragment::metadata_policy` (C++/Python).

9.5.4 Use of Metadata in Distributed Applications

Sending metadata between two fragments of a distributed application is supported, but there are a couple of aspects to be aware of.

1. Sending metadata over the network requires serialization and deserialization of the metadata keys and values. The value types supported for this are the same as for data emitted over output ports (see the table in the section on *object serialization*). The only exception is that `Tensor` and `TensorMap` values cannot be sent as metadata values between fragments (this restriction also applies to tensor-like Python objects). Any *custom codecs* registered for the SDK will automatically also be available for serialization of metadata values.
2. There is a practical size limit of several kilobytes in the amount of metadata that can be transmitted between fragments. This is because metadata is currently sent along with other entity header information in the UCX header, which has fixed size limit (the metadata is stored along with other header information within the size limit defined by the `HOLOSCAN_UCX_SERIALIZATION_BUFFER_SIZE` *environment variable*).

The above restrictions only apply to metadata sent **between** fragments. Within a fragment there is no size limit on metadata (aside from system memory limits) and no serialization or deserialization step is needed.

9.5.5 Current limitations

1. The current metadata API is only fully supported for native holoscan Operators and is not currently supported by operators that wrap a GXF codelet (i.e. inheriting from `GXFOperator` or created via `GXFCodeletOp`). Aside from `GXFCodeletOp`, the built-in operators provided under the `holoscan::ops` namespace are all native operators, so the feature will work with these. Currently none of these built-in opereators add their own metadata, but any metadata received on input ports will automatically be passed on to their output ports (as long as `app->enable_metadata(false)` was not set to disable the metadata feature).

9.6 CUDA Stream Handling APIs

Please see the dedicated *Holoscan CUDA stream handling* page for details on how Holoscan applications using non-default CUDA streams can be written.

CHAPTER

TEN

CREATING A DISTRIBUTED APPLICATION

Distributed applications refer to those where the workflow is divided into multiple fragments that may be run on separate nodes. For example, data might be collected via a sensor at the edge, sent to a separate workstation for processing, and then the processed data could be sent back to the edge node for visualization. Each node would run a single fragment consisting of a computation graph built up of operators. Thus one fragment is the equivalent of a non-distributed application. In the distributed context, the application initializes the different fragments and then defines the connections between them to build up the full distributed application workflow.

In this section we'll describe:

- How to *define a distributed application*.
- How to *build and run a distributed application*.

10.1 Defining a Distributed Application Class

Tip: Defining distributed applications is also illustrated in the *video_replayer_distributed* and ping_distributed examples. The `ping_distributed` examples also illustrate how to update C++ or Python applications to parse user-defined arguments in a way that works without disrupting support for distributed application command line arguments (e.g., `--driver`, `--worker`).

Defining a single fragment (`C++`/`Python`) involves adding operators using `make_operator()` (`C++`) or the operator constructor (`Python`), and defining the connections between them using the `add_flow()` method (`C++`/`Python`) in the `compose()` method. Thus, defining a fragment is just like defining a non-distributed application except that the class should inherit from fragment instead of application.

The application will then be defined by initializing fragments within the application's `compose()` method. The `add_flow()` method (`C++`/`Python`) can be used to define the connections across fragments.

C++

- We define the `Fragment1` and `Fragment2` classes that inherit from the `Fragment` base class.
- We define the `App` class that inherits from the `Application` base class.
- The `App` class initializes any fragments used and defines the connections between them. Here we have used dummy port and operator names in the example `add_flow` call connecting the fragments since no specific operators are shown in this example.
- We create an instance of the `App` class in `main()` using the `make_application()` function.

- The `run()` method starts the application which will execute its `compose()` method where the custom workflow will be defined.

```cpp
#include <holoscan/holoscan.hpp>

class Fragment1 : public holoscan::Fragment {
 public:
  void compose() override {
    // Define Operators and workflow for Fragment1
    //   ...
  }
};

class Fragment2 : public holoscan::Fragment {
 public:
  void compose() override {
    // Define Operators and workflow for Fragment2
    //   ...
  }
};

class App : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    auto fragment1 = make_fragment<Fragment1>("fragment1");
    auto fragment2 = make_fragment<Fragment2>("fragment2");

    // Define the workflow: replayer -> holoviz
    add_flow(fragment1, fragment2, {{"fragment1_operator_name.output_port_name",
                                     "fragment2_operator_name.input_port_name"}});
  }
};


int main() {
  auto app = holoscan::make_application<App>();
  app->run();
  return 0;
}
```

Python

- We define the `Fragment1` and `Fragment2` classes that inherit from the `Fragment` base class.
- We define the `App` class that inherits from the `Application` base class.
- The `App` class initializes any fragments used and defines the connections between them. Here we have used dummy port and operator names in the example add_flow call connecting the fragments since no specific operators are shown in this example.
- We create an instance of the `App` class in `__main__`.

- The `run()` method starts the application which will execute its `compose()` method where the custom workflow will be defined.

```python
from holoscan.core import Application, Fragment

class Fragment1(Fragment):

    def compose(self):
        # Define Operators and workflow
        #   ...

class Fragment2(Fragment):

    def compose(self):
        # Define Operators and workflow
        #   ...

class App(Application):

    def compose(self):
        fragment1 = Fragment1(self, name="fragment1")
        fragment2 = Fragment2(self, name="fragment2")

        self.add_flow(fragment1, fragment2, {("fragment1_operator_name.output_port_name",
                                               "fragment2_operator_name.input_port_name")}
↪)


def main():
    app = App()
    app.run()


if __name__ == "__main__":
    main()
```

10.1.1 Serialization of Custom Data Types for Distributed Applications

Transmission of data between fragments of a multi-fragment application is done via the Unified Communications X (UCX) library. In order to transmit data, it must be serialized into a binary form suitable for transmission over a network. For Tensors (`C++`/`Python`), strings and various scalar and vector numeric types, serialization is already built in. For more details on concrete examples of how to extend the data serialization support to additional user-defined classes, see the separate page on *serialization*.

10.2 Building and running a Distributed Application

C++

Building a distributed application works in the same way as for a non-distributed one. See *Dynamic Flow Control for Complex Workflows*

Python

Python applications do not require building. See *Dynamic Flow Control for Complex Workflows*.

Running an application in a distributed setting requires launching the application binary on all nodes involved in the distributed application. A single node must be selected to act as the application driver. This is achieved by using the `--driver` command-line option. Worker nodes are initiated by launching the application with the `--worker` command-line option. It's possible for the driver node to also serve as a worker if both options are specified.

The address of the driver node must be specified for each process (both the driver and worker(s)) to identify the appropriate network interface for communication. This can be done via the `--address` command-line option, which takes a value in the form of `[<IPv4/IPv6 address or hostname>][:<port>]` (e.g., `--address 192.168.50.68:10000`):

- The driver's IP (or hostname) **MUST** be set for each process (driver and worker(s)) when running distributed applications on multiple nodes (default: `0.0.0.0`). It can be set without the port (e.g., `--address 192.168.50.68`).
- In a single-node application, the driver's IP (or hostname) can be omitted, allowing any network interface (`0.0.0.0`) to be selected by the UCX library.
- The port is always optional (default: `8765`). It can be set without the IP (e.g., `--address :10000`).

The worker node's address can be defined using the `--worker-address` command-line option (`[<IPv4/IPv6 address or hostname>][:<port>]`). If it's not specified, the application worker will default to the host address (`0.0.0.0`) with a randomly chosen port number between `10000` and `32767` that is not currently in use. This argument automatically sets the `HOLOSCAN_UCX_SOURCE_ADDRESS` environment variable if the worker address is a local IP address. Refer to *this section* for details.

The `--fragments` command-line option is used in combination with `--worker` to specify a comma-separated list of fragment names to be run by a worker. If not specified, the application driver will assign a single fragment to the worker. To indicate that a worker should run all fragments, you can specify `--fragments all`.

The `--config` command-line option can be used to designate a path to a configuration file to be used by the application.

Below is an example launching a three fragment application named `my_app` on two separate nodes:

- The application driver is launched at `192.168.50.68:10000` on the first node (A), with a worker running two fragments, "fragment1" and "fragment3."
- On a separate node (B), the application launches a worker for "fragment2," which will connect to the driver at the address above.

C++

```
# Node A
my_app --driver --worker --address 192.168.50.68:10000 --fragments fragment1,fragment3
# Node B
my_app --worker --address 192.168.50.68:10000 --fragments fragment2
```

Python

```
# Node A
python3 my_app.py --driver --worker --address 192.168.50.68:10000 --fragments fragment1,
↪fragment3
# Node B
python3 my_app.py --worker --address 192.168.50.68:10000 --fragments fragment2
```

Note:

UCX Network Interface Selection

UCX is used in the Holoscan SDK for communication across fragments in distributed applications. It is designed to select the best network device based on performance characteristics (bandwidth, latency, NUMA locality, etc.). In some scenarios (under investigation), UCX cannot find the correct network interface to use, and the application fails to run. In this case, you can manually specify the network interface to use by setting the `UCX_NET_DEVICES` environment variable.

For example, if the user wants to use the network interface `eth0`, you can set the environment variable as follows, before running the application:

```
export UCX_NET_DEVICES=eth0
```

Or, if you are running a packaged distributed application with the *Holoscan CLI*, use the `--nic eth0` option to manually specify the network interface to use.

The available network interface names can be found by running the following command:

```
ucx_info -d | grep Device: | awk '{print $3}' | sort | uniq
# or
ip -o -4 addr show | awk '{print $2, $4}' # to show interface name and IP
```

Warning:

Known limitations

The following are known limitations of the distributed application support in the SDK, some of which will be addressed in future updates:

1. A connection error message is displayed even when the distributed application is running correctly.

The message `Connection dropped with status -25 (Connection reset by remote peer)` appears in the console even when the application is functioning properly. This is a known issue and will be addressed in future updates, ensuring that this message will only be displayed in the event of an actual connection error. It currently is printed once some fragments complete their work and start shutdown. Any connections from those fragments to ones that remain open are disconnected at that point, resulting in the logged message.

2. GPU tensors can only currently be sent/received by UCX from a single device on a given node.

By default, device ID 0 is used by the UCX extensions to send/receive data between fragments. To override this default, the user can set environment variable `HOLOSCAN_UCX_DEVICE_ID`.

3. Health check service is turned off by default

The health checker service in a distributed application is turned off by default. However, it can be enabled by setting the environment variable `HOLOSCAN_ENABLE_HEALTH_CHECK` to `true` (can use `1` and `on,` case-insensitive). If the environment variable is not set or is invalid, the default value (disabled) is used.

4. The use of the management port is unsupported on the NVIDIA IGX Orin Developer Kit.

IGX devices come with two ethernet ports, noted as port #4 and #5 in the NVIDIA IGX Orin User Guide. To run distributed applications on these devices, the user must ensure that ethernet port #4 is used to connect the driver and the workers.

Note:

GXF UCX Extension

Holoscan's distributed application feature makes use of the GXF UCX Extension. Its documentation may provide useful additional context into how data is transmitted between fragments.

Tip: Given a CMake project, a pre-built executable, or a Python application, you can also use the *Holoscan CLI* to *package and run your Holoscan application* in a OCI-compliant container image.

10.2.1 Environment Variables for Distributed Applications

Holoscan SDK environment variables

You can set environment variables to modify the default actions of services and the scheduler when executing a distributed application.

- **HOLOSCAN_ENABLE_HEALTH_CHECK**: determines whether the health check service should be active for distributed applications. Accepts values such as "true," "1," or "on" (case-insensitive) as true, enabling the health check. If unspecified, it defaults to "false." When enabled, the gRPC Health Checking Service is activated, allowing tools like grpc-health-probe to monitor liveness and readiness. This environment variable is only used when the distributed application is launched with `--driver` or `--worker` options. The health check service in a distributed application runs on the same port as the App Driver (default: `8765`) and/or the App Worker.
- **HOLOSCAN_DISTRIBUTED_APP_SCHEDULER** : controls which scheduler is used for distributed applications. It can be set to either `greedy`, `multi_thread` or `event_based`. `multithread` is also allowed as a synonym for `multi_thread` for backwards compatibility. If unspecified, the default scheduler is `multi_thread`.
- **HOLOSCAN_STOP_ON_DEADLOCK** : can be used in combination with `HOLOSCAN_DISTRIBUTED_APP_SCHEDULER` to control whether or not the application will automatically stop on deadlock. Values of "True", "1" or "ON" will be interpreted as true (enable stop on deadlock). It is "true" if unspecified. This environment variable is only used when `HOLOSCAN_DISTRIBUTED_APP_SCHEDULER` is explicitly set.
- **HOLOSCAN_STOP_ON_DEADLOCK_TIMEOUT** : controls the delay (in ms) without activity required before an application is considered to be in deadlock. It must be an integer value (units are ms).
- **HOLOSCAN_MAX_DURATION_MS** : sets the application to automatically terminate after the requested maximum duration (in ms) has elapsed. It must be an integer value (units are ms). This environment variable is only used when `HOLOSCAN_DISTRIBUTED_APP_SCHEDULER` is explicitly set.
- **HOLOSCAN_CHECK_RECESSION_PERIOD_MS** : controls how long (in ms) the scheduler waits before re-checking the status of operators in an application. It must be a floating point value (units are ms). This environment variable is only used when `HOLOSCAN_DISTRIBUTED_APP_SCHEDULER` is explicitly set.
- **HOLOSCAN_UCX_SERIALIZATION_BUFFER_SIZE** : can be used to override the default 7 kB serialization buffer size. This should typically not be needed as tensor types store only a small header in this buffer to avoid explicitly making a copy of their data. However, other data types do get directly copied to the serialization buffer and in some cases it may be necessary to increase it.
- **HOLOSCAN_UCX_ASYNCHRONOUS** : If set to false, asynchronous transmit of UCX messages is disabled (this is the default since Holoscan 3.0, which matches the prior behavior from Holoscan 1.0). In Holoscan 2.x, the default was true, but this was deemed harder for application developers to use, so that decision has been reverted. Synchronous mode makes it easier to use an allocator like `BlockMemoryPool` as additional tensors would not be queued before the prior one was sent.
- **HOLOSCAN_UCX_DEVICE_ID** : The GPU ID of the device that will be used by UCX transmitter/receivers in distributed applications. If unspecified, it defaults to 0. A list of discrete GPUs available in a system can be obtained via `nvidia-smi -L`. GPU data sent between fragments of a distributed application must be on this device.
- **HOLOSCAN_UCX_PORTS** : This defines the preferred port numbers for the SDK when specific ports for UCX communication need to be predetermined, such as in a Kubernetes environment. If the distributed application requires three ports (UCX receivers) and the environment variable is unset, the SDK chooses three unused ports sequentially from the range 10000~32767. Specifying a value, for example, `HOLOSCAN_UCX_PORTS=10000`, results in the selection of ports 10000, 10001, and 10002. Multiple starting values can be comma-separated. The system increments from the last provided port if more ports are needed. Any unused specified ports are ignored.

- **HOLOSCAN_UCX_SOURCE_ADDRESS** : This environment variable specifies the local IP address (source) for the UCX connection. This variable is especially beneficial when a node has multiple network interfaces, enabling the user to determine which one should be utilized for establishing a UCX client (UcxTransmitter). If it is not explicitly specified, the default address is set to `0.0.0.0`, representing any available interface.

UCX-specific environment variables

Transmission of data between fragments of a multi-fragment application is done via the Unified Communications X (UCX) library, a point-to-point communication framework designed to utilize the best available hardware resources (shared memory, TCP, GPUDirect RDMA, etc). UCX has many parameters that can be controlled via environment variables. A few that are particularly relevant to Holoscan SDK distributed applications are listed below:

- The `UCX_TLS` environment variable can be used to control which transport layers are enabled. By default, `UCX_TLS=all` and UCX will attempt to choose the optimal transport layer automatically.
- The `UCX_NET_DEVICES` environment variable is by default set to `all`, meaning that UCX may choose to use any available network interface controller (NIC). In some cases it may be necessary to restrict UCX to a specific device or set of devices, which can be done by setting `UCX_NET_DEVICES` to a comma separated list of the device names (i.e., as obtained by Linux command `ifconfig -a` or `ip link show`).
- Setting `UCX_TCP_CM_REUSEADDR=y` is recommended to enable ports to be reused without having to wait the full socket TIME_WAIT period after a socket is closed.
- The `UCX_LOG_LEVEL` environment variable can be used to control the logging level of UCX. The default is setting is WARN, but changing to a lower level such as INFO will provide more verbose output on which transports and devices are being used.
- By default, Holoscan SDK will automatically set `UCX_PROTO_ENABLE=y` upon application launch to enable the newer "v2" UCX protocols. If for some reason, the older v1 protocols are needed, one can set `UCX_PROTO_ENABLE=n` in the environment to override this setting. When the v2 protocols are enabled, one can optionally set `UCX_PROTO_INFO=y` to enable detailed logging of what protocols are being used at runtime.
- By default, Holoscan SDK will automatically set `UCX_MEMTYPE_CACHE=n` upon application launch to disable the UCX memory type cache (See UCX documentation for more information. It can cause about 0.2 microseconds of pointer type checking overhead with the cudacudaPointerGetAttributes() CUDA API). If for some reason the memory type cache is needed, one can set `UCX_MEMTYPE_CACHE=y` in the environment to override this setting.
- By default, the Holoscan SDK will automatically set `UCX_CM_USE_ALL_DEVICES=n` at application startup to disable consideration of all devices for data transfer. If for some reason the opposite behavior is desired, one can set `UCX_CM_USE_ALL_DEVICES=y` in the environment to override this setting. Setting `UCX_CM_USE_ALL_DEVICES=n` can be used to workaround an issue where UCX sometimes defaults to a device that might not be the most suitable for data transfer based on the host's available devices. On a host with address 10.111.66.60, UCX, for instance, might opt for the `br-80572179a31d` (192.168.49.1) device due to its superior bandwidth as compared to `eno2` (10.111.66.60). With `UCX_CM_USE_ALL_DEVICES=n`, UCX will ensure consistency by using the same device for data transfer that was initially used to establish the connection. This ensures more predictable behavior and can avoid potential issues stemming from device mismatches during the data transfer process.
- Setting `UCX_TCP_PORT_RANGE=<start>-<end>` can be used to define a specific range of ports that UCX should utilize for data transfer. This is particularly useful in environments where ports need to be predetermined, such as in a Kubernetes setup. In such contexts, Pods often have ports that need to be exposed, and these ports must be specified ahead of time. Moreover, in scenarios where firewall configurations are stringent and only allow specified ports, having a predetermined range ensures that the UCX communication does not get blocked. This complements the `HOLOSCAN_UCX_SOURCE_ADDRESS`, which specifies the local IP address for the UCX connection, by giving further control over which ports on that specified address should be used. By setting a port range, users can ensure that UCX operates within the boundaries of the network and security policies of their infrastructure.

Tip: A list of all available UCX environment variables and a brief description of each can be obtained by running `ucx_info -f` from the Holoscan SDK container. Holoscan SDK uses UCX's active message (AM) protocols, so environment variables related to other protocols such as tag-mat.

10.3 Serialization

Distributed applications must serialize any objects that are to be sent between the fragments of a multi-fragment application. Serialization involves binary serialization to a buffer that will be sent from one fragment to another via the Unified Communications X (UCX) library. For tensor types (e.g., holoscan::Tensor), no actual copy is made, but instead transmission is done directly from the original tensor's data and only a small amount of header information is copied to the serialization buffer.

A table of the types that have codecs pre-registered so that they can be serialized between fragments using Holoscan SDK is given below.

Type Class	Specific Types
integers	int8_t, int16_t, int32_t, int64_t, uint8_t, uint16_t, uint32_t, uint64_t
floating point	float, double, complex <float>, complex<double>
boolean	bool
strings	std::string
std::vector<T>	T is std::string or any of the boolean, integer or floating point types above
std::vector<std::vector<T>>	T is std::string or any of the boolean, integer or floating point types above
std::vector<HolovizOp::InputSpec>	a vector of InputSpec objects that are specific to HolovizOp
std::shared_ptr<T>	T is any of the scalar, vector or std::string types above
tensor types	holoscan::Tensor, nvidia::gxf::Tensor, nvidia::gxf::VideoBuffer, nvidia::gxf::AudioBuffer
GXF-specific types	nvidia::gxf::TimeStamp, nvidia::gxf::EndOfStream

Warning: If an operator transmitting both CPU and GPU tensors is to be used in distributed applications, the same output port cannot mix both GPU and CPU tensors. CPU and GPU tensor outputs should be placed on separate output ports. This is a limitation of the underlying UCX library being used for zero-copy tensor serialization between operators.

As a concrete example, assume an operator, `MyOperator` with a single output port named "out" defined in it's setup method. If the output port is only ever going to connect to other operators within a fragment, but never across fragments then it is okay to have a `TensorMap` with a mixture of host and device arrays on that single port.

C++

```cpp
void MyOperator::setup(OperatorSpec& spec) {
  spec.output<holoscan::TensorMap>("out");
}

void MyOperator::compute(OperatorSpec& spec) {

  // omitted: some computation resulting in multiple holoscan::Tensors
  // (two on CPU ("cpu_coords_tensor" and "cpu_metric_tensor") and one on device (
↪"gpu_tensor").
```

```
  TensorMap out_message;

  // insert all tensors in one TensorMap (mixing CPU and GPU tensors is okay when␣
↪ports only connect within a Fragment)
  out_message.insert({"coordinates", cpu_coords_tensor});
  out_message.insert({"metrics", cpu_metric_tensor});
  out_message.insert({"mask", gpu_tensor});

  op_output.emit(out_message, "out");
}
```

Python

```python
class MyOperator:

    def setup(self, spec: OperatorSpec):
        spec.output("out")


    def compute(self, op_input, op_output, context):
        # Omitted: assume some computation resulting in three holoscan::Tensor or␣
↪tensor-like
        # objects. Two on CPU ("cpu_coords_tensor" and "cpu_metric_tensor") and one␣
↪on device
        # ("gpu_tensor").

        # mixing CPU and GPU tensors in a single dict is okay only for within-
↪Fragment connections
        op_output.emit(
            dict(
                coordinates=cpu_coords_tensor,
                metrics=cpu_metrics_tensor,
                mask=gpu_tensor,
            ),
            "out"
        )
```

However, this mixing of CPU and GPU arrays on a single port will not work for distributed apps and instead separate ports should be used if it is necessary for an operator to communicate across fragments.

C++

```cpp
void MyOperator::setup(OperatorSpec& spec) {
  spec.output<holoscan::TensorMap>("out_host");
  spec.output<holoscan::TensorMap>("out_device");
}

void MyOperator::compute(OperatorSpec& spec) {

  // some computation resulting in a pair of holoscan::Tensor, one on CPU ("cpu_tensor
↪") and one on device ("gpu_tensor").
```

```
  TensorMap out_message_host;
  TensorMap out_message_device;

  // put all CPU tensors on one port
  out_message_host.insert({"coordinates", cpu_coordinates_tensor});
  out_message_host.insert({"metrics", cpu_metrics_tensor});
  op_output.emit(out_message_host, "out_host");

  // put all GPU tensors on another
  out_message_device.insert({"mask", gpu_tensor});
  op_output.emit(out_message_device, "out_device");
}
```

Python

```
class MyOperator:

    def setup(self, spec: OperatorSpec):
        spec.output("out_host")
        spec.output("out_device")


    def compute(self, op_input, op_output, context):
        # Omitted: assume some computation resulting in three holoscan::Tensor or␣
↪tensor-like
        # objects. Two on CPU ("cpu_coords_tensor" and "cpu_metric_tensor") and one␣
↪on device
        # ("gpu_tensor").

        # split CPU and GPU tensors across ports for compatibility with inter-
↪fragment communication
        op_output.emit(
            dict(coordinates=cpu_coords_tensor, metrics=cpu_metrics_tensor),
            "out_host"
        )
        op_output.emit(dict(mask=gpu_tensor), "out_device")
```

10.3.1 Python

For the Python API, any array-like object supporting the DLPack interface, `__array_interface__` or `__cuda_array_interface__` will be transmitted using `Tensor` serialization. This is done to avoid data copies for performance reasons. Objects of type `list[holoscan.HolovizOp.InputSpec]` will be sent using the underlying C++ serializer for `std::vector<HolovizOp::InputSpec>`. All other Python objects will be serialized to/from a `std::string` using the cloudpickle library.

Warning: A restriction imposed by the use of cloudpickle is that all fragments in a distributed application must be running the same Python version.

Warning: Distributed applications behave differently than single fragment applications when `op_output.emit()` is called to emit a tensor-like Python object. Specifically, for array-like objects such as a PyTorch tensor, the same Python object will **not** be received by any call to `op_input.receive()` in a downstream Python operator (even if the upstream and downstream operators are part of the same fragment). An object of type `holoscan.Tensor` will be received as a `holoscan.Tensor`. Any other array-like objects with data stored on device (GPU) will be received as a CuPy tensor. Similarly, any array-like object with data stored on the host (CPU) will be received as a NumPy array. The user must convert back to the original array-like type if needed (typically possible in a zero-copy fashion via DLPack or array interfaces).

10.3.2 C++

For any additional C++ classes that need to be serialized for transmission between fragments in a distributed application, the user must create their own codec and register it with the Holoscan SDK framework. As a concrete example, suppose that we had the following simple Coordinate class that we wish to send between fragments.

```
struct Coordinate {
  float x;
  float y;
  float z;
};
```

To create a codec capable of serializing and deserializing this type, one should define a `holoscan::codec` class for it as shown below.

```
#include "holoscan/core/codec_registry.hpp"
#include "holoscan/core/errors.hpp"
#include "holoscan/core/expected.hpp"


namespace holoscan {

template <>
struct codec<Coordinate> {
  static expected<size_t, RuntimeError> serialize(const Coordinate& value, Endpoint*␣
↪endpoint) {
    return serialize_trivial_type<Coordinate>(value, endpoint);
  }
  static expected<Coordinate, RuntimeError> deserialize(Endpoint* endpoint) {
    return deserialize_trivial_type<Coordinate>(endpoint);
  }
};

}  // namespace holoscan
```

In this example, the first argument to `serialize` is a const reference to the type to be serialized and the return value is an `expected` containing the number of bytes that were serialized. The `deserialize` method returns an `expected` containing the deserialized object. The `Endpoint` class is a base class representing the serialization endpoint (For distributed applications, the actual endpoint class used is `UcxSerializationBuffer`).

The helper functions `serialize_trivial_type` (`deserialize_trivial_type`) can be used to serialize (deserialize) any plain-old-data (POD) type. Specifically, POD types can be serialized by just copying `sizeof(Type)` bytes to/from the endpoint. The `read_trivial_type()` and `~holoscan::Endpoint::write_trivial_type` methods could be used directly instead.

```cpp
template <>
struct codec<Coordinate> {
  static expected<size_t, RuntimeError> serialize(const Coordinate& value, Endpoint*␣
↪endpoint) {
      return endpoint->write_trivial_type(&value);
  }
  static expected<Coordinate, RuntimeError> deserialize(Endpoint* endpoint) {
      Coordinate encoded;
    auto maybe_value = endpoint->read_trivial_type(&encoded);
    if (!maybe_value) { return forward_error(maybe_value); }
    return encoded;
  }
};
```

In practice, one would not actually need to define `codec<Coordinate>` at all since `Coordinate` is a trivially serializable type and the existing `codec` treats any types for which there is not a template specialization as a trivially serializable type. It is, however, still necessary to register the codec type with the `CodecRegistry` as described below.

For non-trivial types, one will likely also need to use the `read()` and `write()` methods to implement the codec. Example use of these for the built-in codecs can be found in `holoscan/core/codecs.hpp`.

Once such a codec has been defined, the remaining step is to register it with the static `CodecRegistry` class. This will make the UCX-based classes used by distributed applications aware of the existence of a codec for serialization of this object type. If the type is specific to a particular operator, then one can register it via the `register_codec()` class.

```cpp
#include "holoscan/core/codec_registry.hpp"

namespace holoscan::ops {

void MyCoordinateOperator::initialize() {
  register_codec<Coordinate>("Coordinate");

  // ...

  // parent class initialize() call must be after the argument additions above
  Operator::initialize();
}

}  // namespace holoscan::ops
```

Here, the argument provided to `register_codec` is the name the registry will use for the codec. This name will be serialized in the message header so that the deserializer knows which deserialization function to use on the received data. In this example, we chose a name that matches the class name, but that is not a requirement. If the name matches one that is already present in the `CodecRegistry` class, then any existing codec under that name will be replaced by the newly registered one.

It is also possible to directly register the type outside of the context of `initialize()` by directly retrieving the static instance of the codec registry as follows.

```cpp
namespace holoscan {

CodecRegistry::get_instance().add_codec<Coordinate>("Coordinate");

}  // namespace holoscan
```

Tip: CLI arguments (such as `--driver`, `--worker` ,`--fragments`) are parsed by the `Application` (C++/`Python`) class and the remaining arguments are available as `app.argv` (C++/`Python`).

C++

A concrete example of using `app->argv()` in the ping_distributed.cpp example is covered in the section on *user-defined command line arguments*.

If you want to get access to the arguments before creating the C++ instance, you can access them through `holoscan::Application().argv()`.

The following example shows how to access the arguments in your application.

```
#include <holoscan/holoscan.hpp>

class MyPingApp : public holoscan::Application {
// ...
};

int main(int argc, char** argv) {
  auto my_argv =
      holoscan::Application({"myapp", "--driver", "my_arg1", "--address=10.0.0.1"}).
↪argv();
  HOLOSCAN_LOG_INFO(" my_argv: {}", fmt::join(my_argv, " "));

  HOLOSCAN_LOG_INFO(
      "    argv: {} (argc: {}) ",
      fmt::join(std::vector<std::string>(argv, argv + argc), " "),
      argc);

  auto app_argv = holoscan::Application().argv();  // do not use reference ('auto&') here␣
↪(lifetime issue)
  HOLOSCAN_LOG_INFO("app_argv: {} (size: {})", fmt::join(app_argv, " "), app_argv.
↪size());

  auto app = holoscan::make_application<MyPingApp>();
  HOLOSCAN_LOG_INFO("app->argv() == app_argv: {}", app->argv() == app_argv);

  app->run();
  return 0;
}

// $ ./myapp --driver --input image.dat --address 10.0.0.20

//  my_argv: myapp my_arg1
//     argv: ./myapp --driver --input image.dat --address 10.0.0.20 (argc: 6)
// app_argv: ./myapp --input image.dat (size: 3)
// app->argv() == app_argv: true
```

Please see other examples in the Application unit tests in the Holoscan SDK repository.

Python

A concrete example of usage of `app.argv` in the ping_distributed.py example is covered in the section on *user-defined command line arguments*.

If you want to get access to the arguments before creating the `Python` instance, you can access them through `Application().argv`.

The following example shows how to access the arguments in your application.

```python
import argparse
import sys
from holoscan.core import Application


class MyApp(Application):
    def compose(self):
        pass


def main():
    app = MyApp()  # or alternatively, MyApp([sys.executable, *sys.argv])
    app.run()


if __name__ == "__main__":

    print("sys.argv:", sys.argv)
    print("Application().argv:", app.argv)

    parser = argparse.ArgumentParser()
    parser.add_argument("--input")
    args = parser.parse_args(app.argv[1:])
    print("args:", args)

    main()

# $ python cli_test.py --address 10.0.0.20 --input image.dat
# sys.argv: ['cli_test.py', '--address', '10.0.0.20', '--input', 'image.dat']
# Application().argv: ['cli_test.py', '--input', 'image.dat']
# args: Namespace(input='a')
```

```
>>> from holoscan.core import Application
>>> import sys
>>> Application().argv == sys.argv
True
>>> Application([]).argv == sys.argv
True
>>> Application([sys.executable, *sys.argv]).argv == sys.argv
True
>>> Application(["python3", "myapp.py", "--driver", "my_arg1", "--address=10.0.0.1"]).
↪argv
['myapp.py', 'my_arg1']
```

Please see other examples in the Application unit tests (TestApplication class) in the Holoscan SDK repository.

10.3.3 Adding user-defined command line arguments

When adding user-defined command line arguments to an application, one should avoid the use of any of the default command line argument names as `--help`, `--version`, `--config`, `--driver`, `--worker`, `--address`, `--worker-address`, `--fragments` as covered in the section on *running a distributed application*. It is recommended to parse user-defined arguments from the `argv` ((C++/Python)) method/property of the application as covered in the note above, instead of using C++ `char* argv[]` or Python `sys.argv` directly. This way, only the new, user-defined arguments will need to be parsed.

A concrete example of this for both C++ and Python can be seen in the existing ping_distributed example where an application-defined boolean argument (`--gpu`) is specified in addition to the default set of application arguments.

C++

```
int main() {
  auto app = holoscan::make_application<App>();

  // Parse args
  bool tensor_on_gpu = false;
  auto& args = app->argv();
  if (std::find(args.begin(), args.end(), "--gpu") != std::end(args)) { tensor_on_gpu =␣
↪true; }

  // configure tensor on host vs. GPU
  app->gpu_tensor(tensor_on_gpu);

  // run the application
  app->run();

  return 0;
}
```

Python

```
def main(on_gpu=False):
    app = MyPingApp()

    tensor_str = "GPU" if on_gpu else "host"
    print(f"Configuring application to use {tensor_str} tensors")
    app.gpu_tensor = on_gpu

    app.run()


if __name__ == "__main__":

    # get the Application's arguments
```

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```
    app_argv = Application().argv

    parser = ArgumentParser(description="Distributed ping application.")
    parser.add_argument(
        "--gpu",
        action="store_true",
        help="Use a GPU tensor instead of a host tensor",
    )
    # pass app_argv[1:] to parse_args (app_argv[0] is the path of the application)
    args = parser.parse_args(app_argv[1:])
    main(on_gpu=args.gpu)
```

For Python, `app.argv[1:]` can be used with an `ArgumentParser` from Python's argparse module.

Alternatively, it may be preferable to instead use `parser.parse_known_args()` to allow any arguments not defined by the user's parser to pass through to the application class itself. If one also sets `add_help=False` when constructing the `ArgumentParser`, it is possible to print the parser's help while still preserving the default application help (covering the default set of distributed application arguments). An example of this style is shown in the code block below.

```
    parser = ArgumentParser(description="Distributed ping application.", add_help=False)
    parser.add_argument(
        "--gpu",
        action="store_true",
        help="Use a GPU tensor instead of a host tensor",
    )

    # use parse_known_args to ignore other CLI arguments that may be used by Application
    args, remaining = parser.parse_known_args()

    # can print the parser's help here prior to the Application's help output
    if "-h" in remaining or "--help" in remaining:
        print("Additional arguments supported by this application:")
        print(textwrap.indent(parser.format_help(), "  "))
    main(on_gpu=args.gpu)
```

CHAPTER

ELEVEN

PACKAGING HOLOSCAN APPLICATIONS

The *Holoscan App Packager*, included as part of the *Holoscan CLI* as the `package` command, allows you to package your Holoscan applications into a *HAP-compliant* container image for distribution and deployment.

11.1 Prerequisites

11.1.1 Dependencies

Ensure the following are installed in the environment where you want to run the *CLI*:

- **NVIDIA Container Toolkit with Docker**
  - Developer Kits (aarch64): already included in IGX Software and JetPack
  - x86_64: tested with NVIDIA Container Toolkit 1.13.3 with Docker v24.0.1
- **Docker BuildX plugin**
  1. Check if it is installed:

     ```
     $ docker buildx version
     github.com/docker/buildx v0.10.5 86bdced
     ```

  2. If not, run the following commands based on the official doc:

     ```
     # Install Docker dependencies
     sudo apt-get update
     sudo apt-get install ca-certificates curl gnupg

     # Add Docker Official GPG Key
     sudo install -m 0755 -d /etc/apt/keyrings
     curl -fsSL https://download.docker.com/linux/ubuntu/gpg | sudo gpg --dearmor -o␣
     ↪/etc/apt/keyrings/docker.gpg
     sudo chmod a+r /etc/apt/keyrings/docker.gpg

     # Configure Docker APT Repository
     echo \
     "deb [arch="$(dpkg --print-architecture)" signed-by=/etc/apt/keyrings/docker.
     ↪gpg] https://download.docker.com/linux/ubuntu \
     "$(. /etc/os-release && echo "$VERSION_CODENAME")" stable" | \
     sudo tee /etc/apt/sources.list.d/docker.list > /dev/null
     ```

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```
# Install Docker BuildX Plugin
sudo apt-get update
sudo apt-get install docker-buildx-plugin
```

- QEMU *(Optional)*
  - used for packaging container images of different architectures than the host (example: x86_64 -> arm64).

11.1.2 CLI Installation

The Holoscan CLI is available as a PyPI package and can be installed with the following command:

```
$ pip install holoscan-cli
```

Verify the installation:

```
$ holoscan version
```

Tip: Always install Holoscan SDK first, followed by Holoscan CLI on a system that requires both. This ensures that all necessary dependencies and packages are installed correctly, allowing for smooth operation of the Holoscan CLI.

11.2 Package an application

Tip: The packager feature is also illustrated in the cli_packager and video_replayer_distributed examples.

Additional arguments are required when launching the container to enable the packaging of Holoscan applications inside the NGC Holoscan container. Please see the NGC Holoscan container page for additional details.

1. Ensure to use the *HAP environment variables* wherever possible when accessing data. For example:

   Let's take a look at the distributed video replayer example (`examples/video_replayer_distributed`).

   - **Using the Application Configuration File**

     #### C++

     In the `main` function, we call the `app->config(config_path)` function with the default configuration file. The `app->config(...)` checks to see if the application was executed with `--config` argument first. If `--config` was set, the method uses the configuration file from the `--config` argument. Otherwise, it checks if the environment variable `HOLOSCAN_CONFIG_PATH` is set and uses that value as the source. If neither were set, the default configuration file (`config_path`) is used.

```cpp
int main(int argc, char** argv) {
  // Get the yaml configuration file
  auto config_path = std::filesystem::canonical(argv[0]).parent_path();
  config_path /= std::filesystem::path("video_replayer_distributed.yaml");

  auto app = holoscan::make_application<DistributedVideoReplayerApp>();
```

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```
  app->config(config_path);
  app->run();

  return 0;
}
```

Python

In the main function, we call the app.config(config_file_path) function with the default configuration file. The app.config(...) method checks to see if the application was executed with --config argument first. If --config was set, the method uses the configuration file from the --config argument. Otherwise, it checks if the environment variable HOLOSCAN_CONFIG_PATH is set and uses that value as the source. If neither were set, the default configuration file (config_file_path) is used.

```
def main():
    input_path = get_input_path()
    config_file_path = os.path.join(os.path.dirname(__file__), "video_replayer_
↪distributed.yaml")

    logging.info(f"Reading application configuration from {config_file_path}")

    app = DistributedVideoReplayerApp(input_path)
    app.config(config_file_path)
    app.run()
```

- **Using Environment Variable HOLOSCAN_INPUT_PATH for Data Input**

C++

In Fragment1, we try to set the input video directory with the value defined in HOLOSCAN_INPUT_PATH. When we instantiate a new Video Stream Replayer operator, we pass in all configuration values from the from_config("replayer") call. In addition, we include args that we created with the value from HOLOSCAN_INPUT_PATH if available as the last argument to override the directory setting.

```
class Fragment1 : public holoscan::Fragment {
 public:
  void compose() override {
    using namespace holoscan;
    ArgList args;
    auto data_directory = std::getenv("HOLOSCAN_INPUT_PATH");
    if (data_directory != nullptr && data_directory[0] != '\0') {
      auto video_directory = std::filesystem::path(data_directory);
      video_directory /= "racerx";
      args.add(Arg("directory", video_directory.string()));
      HOLOSCAN_LOG_INFO("Using video from {}", video_directory.string());
    }
    auto replayer =
        make_operator<ops::VideoStreamReplayerOp>("replayer", from_config(
↪"replayer"), args);
    add_operator(replayer);
```

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```
    }
};
```

Python

In `Fragment1`, we try to set the input video directory with the value defined in `HOLOSCAN_INPUT_PATH`. When we instantiate a new Video Stream Replayer operator, we pass in the `video_path` along with all `replayer` configurations found in the configuration file.

```python
class Fragment1(Fragment):
    def __init__(self, app, name):
        super().__init__(app, name)

    def __init__(self, app, name):
        super().__init__(app, name)

    def compose(self):
        # Set the video source
        video_path = self._get_input_path()
        logging.info(
            f"Using video from {video_path}"
        )

        # Define the replayer and holoviz operators
        replayer = VideoStreamReplayerOp(
            self, name="replayer", directory=video_path, **self.kwargs("replayer
↪")
        )

        self.add_operator(replayer)

    def _get_input_path(self):
        path = os.environ.get(
            "HOLOSCAN_INPUT_PATH", os.path.join(os.path.dirname(__file__), "data
↪")
        )
        return os.path.join(path, "racerx")
```

2. Include a YAML configuration file as described in the *Application Runner Configuration* page.
3. Use the *`holoscan package`* command to create a HAP container image. For example:

```
holoscan package --platform x64-workstation --tag my-awesome-app --config /path/to/
↪my/awesome/application/config.yaml /path/to/my/awesome/application/
```

11.2.1 Additional Requirements for Non-Distributed Applications

In addition to using HAP-defined environment variables, applications must also handle parsing the -config argument when packaging a non-distributed application.

- **Handle --config argument**

C++

Define a parse_arguments function to handle parsing the data path and the config file path:

```
bool parse_arguments(int argc, char** argv, std::string& data_path, std::string&␣
↪config_path) {
  static struct option long_options[] = {
      {"data", required_argument, 0, 'd'}, {"config", required_argument, 0, 'c'},
↪{0, 0, 0, 0}};

  while (int c = getopt_long(argc, argv, "d:c:", long_options, NULL)) {
    if (c == -1 || c == '?') break;

    switch (c) {
      case 'c':
        config_path = optarg;
        break;
      case 'd':
        data_path = optarg;
        break;
      default:
        holoscan::log_error("Unhandled option '{}'", static_cast<char>(c));
        return false;
    }
  }

  return true;
}
```

Use the parse_arguments() function defined above in the main function:

```
int main(int argc, char** argv) {
// Parse the arguments
std::string config_path = "";
std::string data_directory = "";
if (!parse_arguments(argc, argv, data_directory, config_path)) { return 1; }
if (data_directory.empty()) {
  // Get the input data environment variable
  auto input_path = std::getenv("HOLOSCAN_INPUT_PATH");
  if (input_path != nullptr && input_path[0] != '\0') {
    data_directory = std::string(input_path);
  } else {
    HOLOSCAN_LOG_ERROR(
        "Input data not provided. Use --data or set HOLOSCAN_INPUT_PATH␣
↪environment variable.");
    exit(-1);
```

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```
    }
  }

  if (config_path.empty()) {
    // Get the input data environment variable
    auto config_file_path = std::getenv("HOLOSCAN_CONFIG_PATH");
    if (config_file_path == nullptr || config_file_path[0] == '\0') {
      auto config_file = std::filesystem::canonical(argv[0]).parent_path();
      config_path = config_file / std::filesystem::path("app-config.yaml");
    } else {
      config_path = config_file_path;
    }
  }

  auto app = holoscan::make_application<App>();

  HOLOSCAN_LOG_INFO("Using configuration file from {}", config_path);
  app->config(config_path);

  HOLOSCAN_LOG_INFO("Using input data from {}", data_directory);
  app->set_datapath(data_directory);

  app->run();

  return 0;
}
```

Python

Define a parse_arguments function to parse the arguments:

```python
def parse_arguments() -> argparse.Namespace:
    parser = argparse.ArgumentParser(description="My Application")
    parser.add_argument(
        "--data",
        type=str,
        required=False,
        default=os.environ.get("HOLOSCAN_INPUT_PATH", None),
        help="Input dataset",
    )
    parser.add_argument(
        "--config",
        type=str,
        required=False,
        default=os.environ.get(
            "HOLOSCAN_CONFIG_PATH",
            os.path.join(os.path.dirname(__file__), "app-config.yaml"),
        ),
        help="Application configurations",
    )
```

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```
    args, _ = parser.parse_known_args()

    return args
```

Parse the arguments using `parse_arguments()` defined above and start the application:

```
if __name__ == "__main__":
    args = parse_arguments()

    if args.data is None:
        logger.error(
            "Input data not provided. Use --data or set HOLOSCAN_INPUT_PATH␣
↪environment variable."
        )
        sys.exit(-1)

    app = MyApp(args.data)
    app.config(args.config)
    app.run()
```

11.2.2 Common Issues When Using Holoscan Packager

DNS Name Resolution Error

The Holoscan Packager may be unable to resolve hostnames in specific networking environments and may show errors similar to the following:

```
curl: (6) Could not resolve host: github.com.
Failed to establish a new connection:: [Errno -3] Temporary failure in name solution...
```

To resolve these errors, edit the `/etc/docker/daemon.json` file to include `dns` and `dns-serach` fields as follows:

```
{
    "default-runtime": "nvidia",
    "runtimes": {
        "nvidia": {
            "args": [],
            "path": "nvidia-container-runtime"
        }
    },
    "dns": ["IP-1", "IP-n"],
    "dns-search": ["DNS-SERVER-1", "DNS-SERVER-n"]
}
```

You may need to consult your IT team and replace `IP-x` and `DNS-SERVER-x` with the provided values.

11.3 Run a packaged application

The packaged Holoscan application container image can run with the *Holoscan App Runner*:

```
holoscan run -i /path/to/my/input -o /path/to/application/generated/output my-
↪application:1.0.1
```

Since the packaged Holoscan application container images are OCI-compliant, they're also compatible with Docker, Kubernetes, and containerd.

Each packaged Holoscan application container image includes tools inside for extracting the embedded application, manifest files, models, etc. To access the tool and to view all available options, run the following:

```
docker run -it my-container-image[:tag] help
```

The command should prints following:

```
USAGE: /var/holoscan/tools [command] [arguments]...
 Command List
    extract  ---------------------------  Extract data based on mounted volume paths.
        /var/run/holoscan/export/app        extract the application
        /var/run/holoscan/export/config     extract app.json and pkg.json manifest files␣
↪and application YAML.
        /var/run/holoscan/export/models     extract models
        /var/run/holoscan/export/docs       extract documentation files
        /var/run/holoscan/export            extract all of the above
        IMPORTANT: ensure the directory to be mounted for data extraction is created␣
↪first on the host system.
                   and has the correct permissions. If the directory had been created by␣
↪the container previously
                   with the user and group being root, please delete it and manually␣
↪create it again.
    show  -----------------------------  Print manifest file(s): [app|pkg] to the␣
↪terminal.
        app                                 print app.json
        pkg                                 print pkg.json
    env  -------------------------  Print all environment variables to the terminal.
```

Note: The tools can also be accessed inside the Docker container via `/var/holoscan/tools`.

For example, run the following commands to extract the manifest files and the application configuration file:

```
# create a directory on the host system first
mkdir -p config-files

# mount the directory created to /var/run/holoscan/export/config
docker run -it --rm -v $(pwd)/config-files:/var/run/holoscan/export/config my-container-
↪image[:tag] extract

# include -u 1000 if the above command reports a permission error
docker run -it --rm -u 1000 -v $(pwd)/config-files:/var/run/holoscan/export/config my-
↪container-image[:tag] extract
```

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```
# If the permission error continues to occur, please check if the mounted directory has␣
↪the correct permission.
# If it doesn't, please recreate it or change the permissions as needed.

# list files extracted
ls config-files/

# output:
# app.json  app.yaml  pkg.json
```

CHAPTER

TWELVE

CREATING OPERATORS

Tip: Creating a custom operator is also illustrated in the *ping_custom_op* example.

12.1 C++ Operators

When assembling a C++ application, two types of operators can be used:

1. ***Native C++ operators***: custom operators defined in C++ without using the GXF API, by creating a subclass of `holoscan::Operator`. These C++ operators can pass arbitrary C++ objects around between operators.
2. ***GXF Operators***: operators defined in the underlying C++ library by inheriting from the `holoscan::ops::GXFOperator` class. These operators wrap GXF codelets from GXF extensions. Examples are `VideoStreamReplayerOp` for replaying video files, `FormatConverterOp` for format conversions, and `HolovizOp` for visualization.

Note: It is possible to create an application using a mixture of GXF operators and native operators. In this case, some special consideration to cast the input and output tensors appropriately must be taken, as shown in *a section below*.

12.1.1 Native C++ Operators

Operator Lifecycle (C++)

The lifecycle of a `holoscan::Operator` is made up of three stages:

- `start()` is called once when the operator starts, and is used for initializing heavy tasks such as allocating memory resources and using parameters.
- `compute()` is called when the operator is triggered, which can occur any number of times throughout the operator lifecycle between `start()` and `stop()`.
- `stop()` is called once when the operator is stopped, and is used for deinitializing heavy tasks such as deallocating resources that were previously assigned in `start()`.

All operators on the workflow are scheduled for execution. When an operator is first executed, the `start()` method is called, followed by the `compute()` method. When the operator is stopped, the `stop()` method is called. The `compute()` method is called multiple times between `start()` and `stop()`.

If any of the scheduling conditions specified by *Conditions* are not met (for example, the `CountCondition` would cause the scheduling condition to not be met if the operator has been executed a certain number of times), the operator is stopped and the `stop()` method is called.

We will cover how to use Conditions in the *Specifying operator inputs and outputs (C++)* section of the user guide.

Typically, the `start()` and the `stop()` functions are only called once during the application's lifecycle. However, if the scheduling conditions are met again, the operator can be scheduled for execution, and the `start()` method will be called again.

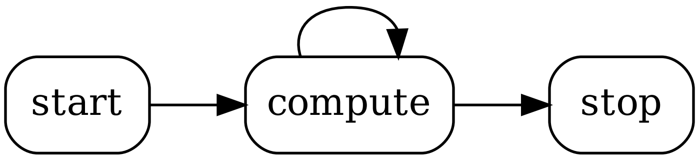

Fig. 12.1: The sequence of method calls in the lifecycle of a Holoscan Operator

Warning: If Python bindings are going to be created for this C++ operator, it is recommended to put any cleanup of resources allocated in the `initialize()` and/or `start()` methods into the `stop()` method of the operator and **not** in its destructor. This is necessary as a workaround to a current issue where it is not guaranteed that the destructor always gets called prior to Python application termination. The `stop()` method will always be explicitly called, so we can be assured that any cleanup happens as expected.

We can override the default behavior of the operator by implementing the above methods. The following example shows how to implement a custom operator that overrides start, stop, and compute methods.

Listing 12.1: The basic structure of a Holoscan Operator (C++)

```cpp
#include "holoscan/holoscan.hpp"

using holoscan::Operator;
using holoscan::OperatorSpec;
using holoscan::InputContext;
using holoscan::OutputContext;
using holoscan::ExecutionContext;
using holoscan::Arg;
using holoscan::ArgList;

class MyOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(MyOp)

  MyOp() = default;

  void setup(OperatorSpec& spec) override {
  }
```

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```cpp

  void start() override {
    HOLOSCAN_LOG_TRACE("MyOp::start()");
  }

  void compute(InputContext&, OutputContext& op_output, ExecutionContext&) override {
    HOLOSCAN_LOG_TRACE("MyOp::compute()");
  };

  void stop() override {
    HOLOSCAN_LOG_TRACE("MyOp::stop()");
  }
};
```

Creating a custom operator (C++)

To create a custom operator in C++, it is necessary to create a subclass of `holoscan::Operator`. The following example demonstrates how to use native operators (the operators that do not have an underlying, pre-compiled GXF Codelet).

Code Snippet: examples/ping_multi_port/cpp/ping_multi_port.cpp

Listing 12.2: examples/ping_multi_port/cpp/ping_multi_port.cpp

```cpp
#include "holoscan/holoscan.hpp"

class ValueData {
 public:
  ValueData() = default;
  explicit ValueData(int value) : data_(value) {
    HOLOSCAN_LOG_TRACE("ValueData::ValueData(): {}", data_);
  }
  ~ValueData() { HOLOSCAN_LOG_TRACE("ValueData::~ValueData(): {}", data_); }

  void data(int value) { data_ = value; }

  int data() const { return data_; }

 private:
  int data_;
};

namespace holoscan::ops {

class PingTxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingTxOp)

  PingTxOp() = default;

  void setup(OperatorSpec& spec) override {
    spec.output<std::shared_ptr<ValueData>>("out1");
```

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```
    spec.output<std::shared_ptr<ValueData>>("out2");
  }

  void compute(InputContext&, OutputContext& op_output, ExecutionContext&) override {
    auto value1 = std::make_shared<ValueData>(index_++);
    op_output.emit(value1, "out1");

    auto value2 = std::make_shared<ValueData>(index_++);
    op_output.emit(value2, "out2");
  };
  int index_ = 1;
};

class PingMxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingMxOp)

  PingMxOp() = default;

  void setup(OperatorSpec& spec) override {
    spec.input<std::shared_ptr<ValueData>>("in1");
    spec.input<std::shared_ptr<ValueData>>("in2");
    spec.output<std::shared_ptr<ValueData>>("out1");
    spec.output<std::shared_ptr<ValueData>>("out2");
    spec.param(multiplier_, "multiplier", "Multiply the input by this value
↪", 2);
  }

  void compute(InputContext& op_input, OutputContext& op_output, ExecutionContext&)␣
↪override {
    auto value1 = op_input.receive<std::shared_ptr<ValueData>>("in1").value();
    auto value2 = op_input.receive<std::shared_ptr<ValueData>>("in2").value();

    HOLOSCAN_LOG_INFO("Middle message received (count: {})", count_++);

    HOLOSCAN_LOG_INFO("Middle message value1: {}", value1->data());
    HOLOSCAN_LOG_INFO("Middle message value2: {}", value2->data());

    // Multiply the values by the multiplier parameter
    value1->data(value1->data() * multiplier_);
    value2->data(value2->data() * multiplier_);

    op_output.emit(value1, "out1");
    op_output.emit(value2, "out2");
  };

 private:
  int count_ = 1;
  Parameter<int> multiplier_;
};

class PingRxOp : public Operator {
```

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```
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingRxOp)

  PingRxOp() = default;

  void setup(OperatorSpec& spec) override {
    // // Since Holoscan SDK v2.3, users can define a multi-receiver input port using
↪'spec.input()'
    // // with 'IOSpec::kAnySize'.
    // // The old way is to use 'spec.param()' with 'Parameter<std::vector<IOSpec*>>␣
↪receivers_;'.
    // spec.param(receivers_, "receivers", "Input Receivers", "List of input receivers.",
↪ {});
    spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers", IOSpec::kAnySize);
  }

  void compute(InputContext& op_input, OutputContext&, ExecutionContext&) override {
    auto value_vector =
        op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();

    HOLOSCAN_LOG_INFO("Rx message received (count: {}, size: {})", count_++, value_
↪vector.size());

    HOLOSCAN_LOG_INFO("Rx message value1: {}", value_vector[0]->data());
    HOLOSCAN_LOG_INFO("Rx message value2: {}", value_vector[1]->data());
  };

 private:
  // // Since Holoscan SDK v2.3, the following line is no longer needed.
  // Parameter<std::vector<IOSpec*>> receivers_;
  int count_ = 1;
};

}  // namespace holoscan::ops

class MyPingApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
    auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
    auto mx = make_operator<ops::PingMxOp>("mx", Arg("multiplier", 3));
    auto rx = make_operator<ops::PingRxOp>("rx");

    // Define the workflow
    add_flow(tx, mx, {{"out1", "in1"}, {"out2", "in2"}});
    add_flow(mx, rx, {{"out1", "receivers"}, {"out2", "receivers"}});
  }
};

int main(int argc, char** argv) {
```

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```
  auto app = holoscan::make_application<MyPingApp>();
  app->run();

  return 0;
}
```

In this application, three operators are created: `PingTxOp`, `PingMxOp`, and `PingRxOp`

1. The `PingTxOp` operator is a source operator that emits two values every time it is invoked. The values are emitted on two different output ports, `out1` (for odd integers) and `out2` (for even integers).
2. The `PingMxOp` operator is a middle operator that receives two values from the `PingTxOp` operator and emits two values on two different output ports. The values are multiplied by the `multiplier` parameter.
3. The `PingRxOp` operator is a sink operator that receives two values from the `PingMxOp` operator. The values are received on a single input, `receivers`, which is a vector of input ports. The `PingRxOp` operator receives the values in the order they are emitted by the `PingMxOp` operator.

As covered in more detail below, the inputs to each operator are specified in the `setup()` method of the operator. Then inputs are received within the `compute()` method via `op_input.receive()` and outputs are emitted via `op_output.emit()`.

Note that for native C++ operators as defined here, any object including a shared pointer can be emitted or received. For large objects such as tensors, it may be preferable from a performance standpoint to transmit a shared pointer to the object rather than making a copy. When shared pointers are used and the same tensor is sent to more than one downstream operator, you should avoid in-place operations on the tensor or race conditions between operators may occur.

If you need to configure arguments or perform other setup tasks before or after the operator is initialized, you can override the `initialize()` method. This method is called once before the `start()` method.

Example:

```
  void initialize() override {
    // Register custom type and codec for serialization
    register_converter<std::array<float, 3>>();
    register_codec<std::vector<InputSpec>>("std::vector
↪<holoscan::ops::HolovizOp::InputSpec>", true);

    // Set up prerequisite parameters before calling Operator::initialize()
    auto frag = fragment();

    // Check if an argument for 'allocator' exists
    auto has_allocator = std::find_if(
        args().begin(), args().end(), [](const auto& arg) { return (arg.name() ==
↪"allocator"); });
    // Create the allocator if no argument is provided
    if (has_allocator == args().end()) {
      allocator_ = frag->make_resource<UnboundedAllocator>("allocator");
      add_arg(allocator_.get());
    }

    // Call the parent class's initialize() method to complete the initialization.
    // Operator::initialize must occur after all arguments have been added.
    Operator::initialize();
```

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```
    // After Operator::initialize(), the operator is ready for use and the parameters␣
↪are set
    int multiplier = multiplier_;
    HOLOSCAN_LOG_INFO("Multiplier: {}", multiplier);
  }
```

For details on the `register_converter()` and `register_codec()` methods, refer to `holoscan::ComponentBase::register_converter()` for the custom parameter type and the section on *object serialization* for distributed applications.

Specifying operator parameters (C++)

In the example `holoscan::ops::PingMxOp` operator above, you have a parameter `multiplier` that is declared as part of the class as a private member using the `param()` templated type:

```
Parameter<int> multiplier_;
```

It is then added to the `OperatorSpec` attribute of the operator in its `setup()` method, where an associated string key must be provided. Other properties can also be mentioned such as description and default value:

```
// Provide key, and optionally other information
spec.param(multiplier_, "multiplier", "Multiplier", "Multiply the input by this value",␣
↪2);
```

Note: If your parameter is of a custom type, you must register that type and provide a YAML encoder/decoder, as documented under `holoscan::ComponentBase::register_converter()`

See the Configuring operator parameters *section to learn how an application can set these parameters.*

Specifying operator inputs and outputs (C++)

To configure the input(s) and output(s) of C++ native operators, call the `spec.input()` and `spec.output()` methods within the `setup()` method of the operator.

The `spec.input()` and `spec.output()` methods should be called once for each input and output to be added. The `OperatorSpec` object and the `setup()` method will be initialized and called automatically by the `Application` class when its `run()` method is called.

These methods (`spec.input()` and `spec.output()`) return an `IOSpec` object that can be used to configure the input/output port.

By default, the `holoscan::MessageAvailableCondition` and `holoscan::DownstreamMessageAffordableCondition` conditions are applied (with a `min_size` of `1`) to the input/output ports. This means that the operator's `compute()` method will not be invoked until a message is available on the input port and the downstream operator's input port (queue) has enough capacity to receive the message.

```
  void setup(OperatorSpec& spec) override {
    spec.input<std::shared_ptr<ValueData>>("in");
    // Above statement is equivalent to:
    //   spec.input<std::shared_ptr<ValueData>>("in")
    //       .condition(ConditionType::kMessageAvailable, Arg("min_size") = static_cast
↪<uint64_t>(1));
```

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```
    spec.output<std::shared_ptr<ValueData>>("out");
    // Above statement is equivalent to:
    //   spec.output<std::shared_ptr<ValueData>>("out")
    //       .condition(ConditionType::kDownstreamMessageAffordable, Arg("min_size") =␣
↪static_cast<uint64_t>(1));
    ...
  }
```

In the above example, the `spec.input()` method is used to configure the input port to have the `holoscan::MessageAvailableCondition` with a minimum size of 1. This means that the operator's `compute()` method will not be invoked until a message is available on the input port of the operator. Similarly, the `spec.output()` method is used to configure the output port to have the `holoscan::DownstreamMessageAffordableCondition` with a minimum size of 1. This means that the operator's `compute()` method will not be invoked until the downstream operator's input port has enough capacity to receive the message.

If you want to change this behavior, use the `IOSpec::condition()` method to configure the conditions. For example, to configure the input and output ports to have no conditions, you can use the following code:

```
  void setup(OperatorSpec& spec) override {
    spec.input<std::shared_ptr<ValueData>>("in")
        .condition(ConditionType::kNone);

    spec.output<std::shared_ptr<ValueData>>("out")
        .condition(ConditionType::kNone);
    // ...
  }
```

The example code in the `setup()` method configures the input port to have no conditions, which means that the `compute()` method will be called as soon as the operator is ready to compute. Since there is no guarantee that the input port will have a message available, the `compute()` method should check if there is a message available on the input port before attempting to read it.

The `receive()` method of the `InputContext` object can be used to access different types of input data within the `compute()` method of your operator class, where its template argument (`DataT`) is the data type of the input. This method takes the name of the input port as an argument (which can be omitted if your operator has a single input port), and returns the input data. If input data is not available, the method returns an object of the `holoscan::expected<std::shared_ptr<ValueData>, holoscan::RuntimeError>` type. The `holoscan::expected<T, E>` class template is used to represent expected objects, which can either hold a value of type `T` or an error of type `E`. The expected object is used to return and propagate errors in a more structured way than using error codes or exceptions. In this case, the expected object can hold either a `std::shared_ptr<ValueData>` object or a `holoscan::RuntimeError` class that contains an error message describing the reason for the failure.

The `holoscan::RuntimeError` class is a derived class of `std::runtime_error` and supports accessing more error information, for example, with the `what()` method.

In the example code fragment below, the `PingRxOp` operator receives input on a port called "in" with data type `std::shared_ptr<ValueData>`. The `receive()` method is used to access the input data. The `maybe_value` is checked to be valid or not with the `if` condition. If there is an error in the input data, the error message is logged and the operator throws the error. If the input data is valid, we can access the reference of the input data using the `value()` method of the `expected` object. To avoid copying the input data (or creating another shared pointer), the reference of the input data is stored in the `value` variable (using `auto& value = maybe_value.value()`). The `data()` method of the `ValueData` class is then called to get the value of the input data.

```cpp
// ...

class PingRxOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingRxOp)
  PingRxOp() = default;

  void setup(holoscan::OperatorSpec& spec) override {
    spec.input<std::shared_ptr<ValueData>>("in");
  }

  void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
               holoscan::ExecutionContext&) override {
    auto maybe_value = op_input.receive<std::shared_ptr<ValueData>>("in");

    if (!maybe_value) {
      HOLOSCAN_LOG_ERROR("Failed to receive message - {}", maybe_value.error().what());
      // [error] Failed to receive message - InputContext receive() Error: No message is␣
↪received from the input port with name 'in'
      throw maybe_value.error(); // or `return;`
    }

    auto& value = maybe_value.value();
    HOLOSCAN_LOG_INFO("Message received (value: {})", value->data());
  }
};
```

Internally, message passing in Holoscan is implemented using the `Message` class, which wraps a `std::any` object and provides a type-safe interface to access the input data. The `std::any` class is a type-safe container for single values of any type and is used to store the input and output data of operators. The `std::any` class is part of the C++ standard library and is defined in the `any` header file.

Since the Holoscan SDK uses GXF as an execution engine, the `holoscan::Message` object is also encapsulated in a `nvidia::gxf::Entity` object when passing data among Holoscan native operators and GXF operators. This ensures that the data is compatible with the GXF framework.

If the input data is expected to be from a GXF operator or a tensor (in both cases, the data is an instance of `nvidia::gxf::Entity`), the `holoscan::gxf::Entity` class can be used in the template argument of the `receive` method to access the input data. The `holoscan::gxf::Entity` class is a wrapper around the `nvidia::gxf::Entity` class (which is like a dictionary object) and provides a way to get a tensor and to add a tensor to the entity.

The Holoscan SDK provides built-in data types called **Domain Objects**, defined in the `include/holoscan/core/domain` directory. For example, the `holoscan::Tensor` is a Domain Object class that represents a multi-dimensional array of data, which is interoperable with the underlying GXF class (`nvidia::gxf::Tensor`). The `holoscan::Tensor` class provides methods to access the tensor data, shape, and other properties. Passing `holoscan::Tensor` objects to/from *GXF operators* is supported.

Tip: The `holoscan::Tensor` class is a wrapper around the `DLManagedTensorContext` struct holding a DLManagedTensor object. As such, it provides a primary interface to access tensor data and is interoperable with other frameworks that support the DLPack interface.

See the *interoperability section* for more details.

In the example below, the TensorRx operator receives input on a port called "in" with data type `holoscan::gxf::Entity`.

```
// ...

class TensorRxOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(TensorRxOp)
  TensorRxOp() = default;

  void setup(holoscan::OperatorSpec& spec) override {
    spec.input<holoscan::gxf::Entity>("in");
  }

  void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
               holoscan::ExecutionContext&) override {
    // Type of 'maybe_entity' is holoscan::expected<holoscan::gxf::Entity,␣
↪holoscan::RuntimeError>
    auto maybe_entity = op_input.receive<holoscan::gxf::Entity>("in");
    if (maybe_entity) {
      auto& entity = maybe_entity.value();  // holoscan::gxf::Entity&
      // Get a tensor from the entity if it exists.
      // Can pass a tensor name as an argument to get a specific tensor.
      auto tensor = entity.get<holoscan::Tensor>();  // std::shared_ptr<holoscan::Tensor>
      if (tensor) {
        HOLOSCAN_LOG_INFO("tensor nbytes: {}", tensor->nbytes());
      }
    }
  }
};
```

If the entity contains a tensor, the `get` method of the `holoscan::gxf::Entity` class can be used to retrieve the tensor. The `get` method returns a `std::shared_ptr<holoscan::Tensor>` object, which can be used to access the tensor data. The `nbytes` method of the `holoscan::Tensor` class is used to get the number of bytes in the tensor.

By using the `holoscan::TensorMap` class, which stores a map of tensor names to tensors (`std::unordered_map<std::string, std::shared_ptr<holoscan::Tensor>>`), the code that receives an entity object containing one or more tensor objects can be updated to receive a `holoscan::TensorMap` object instead of a `holoscan::gxf::Entity` object. The `holoscan::TensorMap` class provides a way to access the tensor data by name, using a `std::unordered_map`-like interface.

```
// ...

class TensorRxOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(TensorRxOp)
  TensorRxOp() = default;

  void setup(holoscan::OperatorSpec& spec) override {
    spec.input<holoscan::TensorMap>("in");
  }

  void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
               holoscan::ExecutionContext&) override {
    // Type of 'maybe_entity' is holoscan::expected<holoscan::TensorMap,␣
↪holoscan::RuntimeError>
```

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```cpp
    auto maybe_tensor_map = op_input.receive<holoscan::TensorMap>("in");
    if (maybe_tensor_map) {
      auto& tensor_map = maybe_tensor_map.value();  // holoscan::TensorMap&
      for (const auto& [name, tensor] : tensor_map) {
        HOLOSCAN_LOG_INFO("tensor name: {}", name);
        HOLOSCAN_LOG_INFO("tensor nbytes: {}", tensor->nbytes());
      }
    }
  }
};
```

In the above example, the `TensorRxOp` operator receives input on a port called "in" with data type `holoscan::TensorMap`. The `receive` method of the `InputContext` object is used to access the input data. The `receive` method returns an `expected` object that can hold either a `holoscan::TensorMap` object or a `holoscan::RuntimeError` object. The `holoscan::TensorMap` class is a wrapper around the `std::unordered_map<std::string, std::shared_ptr<holoscan::Tensor>>` class and provides a way to access the tensor data. The `nbytes` method of the `holoscan::Tensor` class is used to get the number of bytes in the tensor.

If the type std::any is used for the template argument of the `receive` method, the `receive()` method will return a `std::any` object containing the input of the specified name. In the example below, the `PingRxOp` operator receives input on a port called "in" with data type `std::any`. The `type()` method of the `std::any` object is used to determine the actual type of the input data, and the std::any_cast() function is used to retrieve the value of the input data.

```cpp
// ...

class AnyRxOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS_SUPER(AnyRxOp, holoscan::ops::GXFOperator)
  AnyRxOp() = default;
  void setup(holoscan::OperatorSpec& spec) override {
    spec.input<std::any>("in");
  }
  void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,␣
↪holoscan::ExecutionContext&) override {
    auto maybe_any = op_input.receive<std::any>("in");
    if (!maybe_any) {
      HOLOSCAN_LOG_ERROR("Failed to receive message - {}", maybe_any.error().what());
      return;
    }

    auto& in_any = maybe_any.value();
    const auto& in_any_type = in_any.type();

    try {
      if (in_any_type == typeid(holoscan::gxf::Entity)) {
        auto in_entity = std::any_cast<holoscan::gxf::Entity>(in_any);
        auto tensor = in_entity.get<holoscan::Tensor>();  // std::shared_ptr
↪<holoscan::Tensor>
        if (tensor) {
          HOLOSCAN_LOG_INFO("tensor nbytes: {}", tensor->nbytes());
        }
      } else if (in_any_type == typeid(std::shared_ptr<ValueData>)) {
```

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```cpp
        auto in_value = std::any_cast<std::shared_ptr<ValueData>>(in_any);
        HOLOSCAN_LOG_INFO("Received value: {}", in_value->data());
      } else {
        HOLOSCAN_LOG_ERROR("Invalid message type: {}", in_any_type.name());
      }
    } catch (const std::bad_any_cast& e) {
      HOLOSCAN_LOG_ERROR("Failed to cast message - {}", e.what());
    }
  }
};
```

Receiving any number of inputs (C++)

Instead of assigning a specific number of input ports, it may be preferable to allow the ability to receive any number of objects on a port in certain situations.

Using `IOSpec::kAnySize` for variable input handling

One way to achieve this is to define a multi-receiver input port by calling `spec.input<std::vector<T>>("port_name", IOSpec::kAnySize)` with `IOSpec::kAnySize` as the second argument in the `setup()` method of the operator, where `T` is the type of the input data (as done for `PingRxOp` in the *native operator ping example*).

```cpp
  void setup(OperatorSpec& spec) override {
    spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers", IOSpec::kAnySize);
  }
```

Listing 12.3: examples/ping_multi_port/cpp/ping_multi_port.cpp

```cpp
class PingRxOp : public Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(PingRxOp)

  PingRxOp() = default;

  void setup(OperatorSpec& spec) override {
    // // Since Holoscan SDK v2.3, users can define a multi-receiver input port using
↪'spec.input()'
    // // with 'IOSpec::kAnySize'.
    // // The old way is to use 'spec.param()' with 'Parameter<std::vector<IOSpec*>>␣
↪receivers_;'.
    // spec.param(receivers_, "receivers", "Input Receivers", "List of input receivers.",
↪ {});
    spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers", IOSpec::kAnySize);
  }

  void compute(InputContext& op_input, OutputContext&, ExecutionContext&) override {
    auto value_vector =
        op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();

```

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```
    HOLOSCAN_LOG_INFO("Rx message received (count: {}, size: {})", count_++, value_
↪vector.size());

    HOLOSCAN_LOG_INFO("Rx message value1: {}", value_vector[0]->data());
    HOLOSCAN_LOG_INFO("Rx message value2: {}", value_vector[1]->data());
  };

 private:
  // // Since Holoscan SDK v2.3, the following line is no longer needed.
  // Parameter<std::vector<IOSpec*>> receivers_;
  int count_ = 1;
};

}  // namespace holoscan::ops

class MyPingApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
    auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
    auto mx = make_operator<ops::PingMxOp>("mx", Arg("multiplier", 3));
    auto rx = make_operator<ops::PingRxOp>("rx");

    // Define the workflow
    add_flow(tx, mx, {{"out1", "in1"}, {"out2", "in2"}});
    add_flow(mx, rx, {{"out1", "receivers"}, {"out2", "receivers"}});
  }
};
```

Then, once the following configuration is provided in the `compose()` method,

```
    add_flow(mx, rx, {{"out1", "receivers"}, {"out2", "receivers"}});
```

the `PingRxOp` will receive two inputs on the `receivers` port in the `compute()` method:

```
    auto value_vector =
        op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();
```

Tip: When an input port is defined with `IOSpec::kAnySize`, the framework creates a new input port for each input object received on the port. The input ports are named using the format `<port_name>:<index>`, where `<port_name>` is the name of the input port and `<index>` is the index of the input object received on the port. For example, if the `receivers` port receives two input objects, the input ports will be named `receivers:0` and `receivers:1`.

The framework internally creates a parameter (`receivers`) with the type `std::vector<holoscan::IOSpec*>`, implicitly creates input ports (`receivers:0` and `receivers:1`), and connects them (adding references of the input ports to the `receivers` vector). This way, when the `receive()` method is called, the framework can return the input data from the corresponding input ports as a vector.

```
auto value_vector =
        op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();
```

If you add `HOLOSCAN_LOG_INFO(rx->description());` at the end of the `compose()` method, you will see the description of the `PingRxOp` operator as shown below:

```
id: -1
name: rx
fragment: ""
args:
  []
type: kNative
conditions:
  []
resources:
  []
spec:
  fragment: ""
  params:
    - name: receivers
      type: std::vector<holoscan::IOSpec*>
      description: ""
      flag: kNone
  inputs:
    - name: receivers:1
      io_type: kInput
      typeinfo_name: N8holoscan3gxf6EntityE
      connector_type: kDefault
      conditions:
        []
    - name: receivers:0
      io_type: kInput
      typeinfo_name: N8holoscan3gxf6EntityE
      connector_type: kDefault
      conditions:
        []
    - name: receivers
      io_type: kInput
      typeinfo_name: St6vectorISt10shared_ptrI9ValueDataESaIS2_EE
      connector_type: kDefault
      conditions:
        []
  outputs:
    []
```

Configuring input port queue size and message batch condition (C++)

If you want to receive multiple objects on a port and process them in batches, you can increase the queue size of the input port and set the `min_size` parameter of the `MessageAvailableCondition` condition to the desired batch size. This can be done by calling the `connector()` and `condition()` methods with the desired arguments, using the batch size as the `capacity` and `min_size` parameters, respectively.

Setting `min_size` to `N` will ensure that the operator receives `N` objects before the `compute()` method is called.

```
void setup(holoscan::OperatorSpec& spec) override {
  spec.input<std::shared_ptr<ValueData>>("receivers")
      .connector(holoscan::IOSpec::ConnectorType::kDoubleBuffer,
                 holoscan::Arg("capacity", static_cast<uint64_t>(2)))
      .condition(holoscan::ConditionType::kMessageAvailable,
                 holoscan::Arg("min_size", static_cast<uint64_t>(2)));
}
```

Then, the `receive()` method can be called with the `receivers` port name to receive input data in batches.

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
             holoscan::ExecutionContext&) override {
  std::vector<std::shared_ptr<ValueData>> value_vector;
  auto maybe_value = op_input.receive<std::shared_ptr<ValueData>>("receivers");
  while (maybe_value) {
    value_vector.push_back(maybe_value.value());
    maybe_value = op_input.receive<std::shared_ptr<ValueData>>("receivers");
  }

  HOLOSCAN_LOG_INFO("Rx message received (size: {})", value_vector.size());
}
```

In the above example, the operator receives input on a port called "receivers" with a queue size of 2 and a `min_size` of 2. The `receive()` method is called in a loop to receive the input data in batches of 2. Since the operator does not know the number of objects to be received in advance, the `receive()` method is called in a loop until it returns an error. The input data is stored in a vector, and the size of the vector is logged after all the input data is received.

To simplify the above code, the Holoscan SDK provides a `IOSpec::kPrecedingCount` constant as a second argument to the OperatorSpec's `input()` method to specify the number of preceding connections to the input port (in this case, the number of connections to the `receivers` port is 2) as the batch size. This can be used to receive the input data in batches without the need to call the `receive()` method in a loop.

```
void setup(holoscan::OperatorSpec& spec) override {
  spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers",␣
↪holoscan::IOSpec::kPrecedingCount);
}
```

Then, the `receive()` method can be called with the `receivers` port name to receive the input data in batches.

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
             holoscan::ExecutionContext&) override {
  auto value_vector =
      op_input.receive<std::vector<std::shared_ptr<ValueData>>>("receivers").value();

  HOLOSCAN_LOG_INFO("Rx message received (size: {})", value_vector.size());

  HOLOSCAN_LOG_INFO("Rx message value1: {}", value_vector[0]->data());
  HOLOSCAN_LOG_INFO("Rx message value2: {}", value_vector[1]->data());
}
```

In the above example, the operator receives input on a port called "receivers" with a batch size of 2. The `receive()` method is called with the `receivers` port name to receive the input data in batches of 2. The input data is stored in a vector, and the size of the vector is logged after all the input data has been received.

If you want to use a specific batch size, you can use `holoscan::IOSpec::IOSize(int64_t)` instead of holoscan::IOSpec::kPrecedingCount to specify the batch size. Using IOSize in this way is equivalent to the more verbose condition() and connector() calls to update the capacity and min_size arguments shown near the start of this section.

The main reason to use condition() or connector() methods instead of the shorter IOSize is if additional parameter changes, such as the queue policy, need to be made. See more details on the use of the condition() and connector() methods in the advanced topics section below (*Further customizing inputs and outputs*).

```
void setup(holoscan::OperatorSpec& spec) override {
  spec.input<std::vector<std::shared_ptr<ValueData>>>("receivers",␣
↪holoscan::IOSpec::IOSize(2));
}
```

If you want to receive the input data one by one, you can call the receive() method without using the std::vector<T> template argument.

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
             holoscan::ExecutionContext&) override {
  while (true) {
    auto maybe_value = op_input.receive<std::shared_ptr<ValueData>>("receivers");
    if (!maybe_value) { break; }
    auto& value = maybe_value.value();
    // Process the input data
    HOLOSCAN_LOG_INFO("Rx message received (value: {})", value->data());
  }
}
```

The above code will receive input data one by one from the receivers port. The receive() method is called in a loop until it returns an error. The input data is stored in a variable, and the value of the input data is logged.

Note: This approach (receiving the input data one by one) is not applicable for the holoscan::IOSpec::kAnySize case. With the holoscan::IOSpec::kAnySize argument, the framework creates a new input port for each input object received on the port internally. Each implicit input port (named using the format <port_name>:<index>) is associated with a MessageAvailableCondition condition that has a min_size of 1. Therefore, the receive() method needs to be called with the std::vector<T> template argument to receive the input data in batches at once.

If you really need to receive the input data one by one for holoscan::IOSpec::kAnySize case (though it is not recommended), you can receive the input data from each implicit input port (named <port_name>:<index>) one by one using the receive() method without the std::vector<T> template argument. (e.g., op_input.receive<std::shared_ptr<ValueData>>("receivers:0"), op_input.receive<std::shared_ptr<ValueData>>("receivers:1"), etc.). To avoid the error message (such as The operator does not have an input port with label 'receivers:X') when calling the receive() method for the implicit input port, you need to calculate the number of connections to the receivers port in advance and call the receive() method for each implicit input port accordingly.

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext&,
             holoscan::ExecutionContext&) override {
  int input_count = spec()->inputs().size() - 1;  // -1 to exclude the 'receivers'␣
↪input port
  for (int i = 0; i < input_count; i++) {
    auto maybe_value =
        op_input.receive<std::shared_ptr<ValueData>>(fmt::format("receivers:{}", i).c_
↪str());
    if (!maybe_value) { break; }
```

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```
      auto& value = maybe_value.value();
      // Process the input data
      HOLOSCAN_LOG_INFO("Rx message received (value: {})", value->data());
    }
  }
```

Attention: Using IOSpec::kPrecedingCount or IOSpec::IOSize(int64_t) appears to show the same behavior as IOSpec::kAnySize in the above example. However, the difference is that since IOSpec::kPrecedingCount or IOSpec::IOSize(int64_t) doesn't use separate MessageAvailableCondition conditions for each (internal) input port, it is not guaranteed that the operator will receive the input data in order.

This means the operator may receive the input data in a different order than the order in which the connections are made in the compose() method. Additionally, with the multithread scheduler, it is not guaranteed that the operator will receive the input data from each of the connections uniformly. The operator may receive more input data from one connection than from another.

If the order of the input data is important, it is recommended to use IOSpec::kAnySize and call the receive() method with the std::vector<T> template argument to receive the input data in batches at once.

Please see the C++ system test cases for more examples of receiving multiple inputs in C++ operators.

Configuring OR-combination of port conditions (C++)

When the operator has multiple input or output ports, each of which has its own condition, the default behavior of Holoscan SDK is an AND combination of all conditions. In some scenarios, it may be desirable to set some subset of ports to have instead OR combination of their conditions (e.g., an OR condition across two input ports can be used to allow an operator to execute if a message arrives on either port). Additional details of condition combination logic and the set of conditions provided by Holoscan are provided in the *condition components section*.

The OperatorSpec::or_combine_port_conditions method can be called from within Operator::setup to specify that a subset of ports should have OR combination of their conditions. The only argument that must be provided is a vector containing the names of the ports whose conditions should be OR combined.

For a concrete example of OR combination, see the multi_port_or_combiner example. The relevant setup method from that example for the configuration of OR combination of the input ports is:

```
void setup(OperatorSpec& spec) override {
  // Using size argument to explicitly set the receiver message queue size for each␣
↪input.
  spec.input<int>("in1");
  spec.input<int>("in2");

  // configure Operator to execute if an input is on "in1" OR "in2"
  // (without this, the default is "in1" AND "in2")
  spec.or_combine_port_conditions({"in1", "in2"});
}
```

General combination of conditions (C++)

For condition types which are not associated with an input or output port, the user creates them via `Fragment::make_condition` which returns a `std::shared_ptr<Condition>`. Any number of such conditions can be passed as positional arguments to `Fragment::make_operator` and the resulting status of the operator is the AND combination of these conditions. For example, the following would cause an operator to only execute of (condition1 AND condition2 AND condition3) are all ready.

```
// passing multiple conditions to make_operator AND combines the conditions
auto my_cond1 = make_condition<MyCondition1>("condition1");
auto my_cond2 = make_condition<MyCondition2>("condition2");
auto my_cond3 = make_condition<MyCondition3>("condition3");
auto my_op = make_operator<MyOperator>("my_op", my_cond1, my_cond2, my_cond3);
```

If we instead want to allow OR combination of some subset of these conditions, then instead of passing all of these conditions directly to `make_operator`, we first create an `OrConditionCombiner` for the terms we want OR logic to apply to and then pass that OR combiner object to `make_operator`. The following shows how one would configure ((condition1 OR condition2) AND condition3).

```
// using generic MyCondition1, MyOperator, etc. class names for this example
auto my_cond1 = make_condition<MyCondition1>("condition1");
auto my_cond2 = make_condition<MyCondition2>("condition2");

// define an OR combination of the above two conditions
std::vector<std::shared_ptr<Condition>> terms({my_cond1, my_cond2});
auto or_combiner = make_resource<OrConditionCombiner>("or_combiner",  Arg{"terms", terms}
↪);

// create a third condition that will be AND combined
auto my_cond3 = make_condition<MyCondition3>("condition3");

// pass both the OR combiner and the conditions to be AND combined to MyOperator
auto my_op = make_operator<MyOperator>("my_op", or_combiner, my_cond3);
```

Note that for the above `MyOperator` example, if the operator also had input and/or output ports, then any port conditions (e.g. the default `MessageAvailableCondition` for input ports) would also be AND combined in addition to `condition3`.

Additional details of condition combination logic and the set of conditions provided by Holoscan is provided in the *condition components section*.

Note: Only conditions which the user has explicitly created via `make_condition` can be passed to `OrConditionCombiner`. To instead use OR combination across **implicitly** created conditions on input or output ports, see the section above regarding `OperatorSpec::or_combine_port_conditions`. A current limitation of the API is that there is not currently a way to use the input/output port conditions with the same `OrConditionCombiner` combiner as conditions explicitly created via `make_condition`.

Configuring multi-port conditions (C++)

A subset of `Condition` types apply to multiple input ports of an operator (e.g. `MultiMessageAvailableCondition` and `MultiMessageAvailableTimeoutCondition`). In this case, rather than using the `IOSpec::condition` method as demonstrated above for setting a condition on a single port, the `OperatorSpec::multi_port_condition` method should be used to configure a condition across multiple input ports. If an input port's name was included in a `multi_port_condition` call, this will automatically disable the default `MessageAvailableCondition` that would otherwise have been assigned to that port (This means it is not required to explicitly set a `ConditionType::kNone` condition on the input port via `IOSpec::condition` in order to be able to use the port with `multi_port_condition`).

Examples of use of multi-port conditions are given in the examples/conditions/multi_message/ folder of the repository. An example of `Operator::setup` for a multi-message condition from `multi_message_sum_of_all.cpp` is shown below:

```
  void setup(OperatorSpec& spec) override {
    // Using size argument to explicitly set the receiver message queue size for each␣
↪input.
    spec.input<std::shared_ptr<std::string>>("in1", IOSpec::IOSize(10));
    spec.input<std::shared_ptr<std::string>>("in2", IOSpec::IOSize(10));
    spec.input<std::shared_ptr<std::string>>("in3", IOSpec::IOSize(10));

    // Use kMultiMessageAvailableTimeout to consider all three ports together. In this
    // "SumOfAll" mode, it only matters that `min_sum` messages have arrived across all␣
↪the ports
    // {"in1", "in2", "in3"}, but it does not matter which ports the messages arrived on.
↪ The
    // "execution_frequency" is set to 30ms, so the operator can run once 30 ms has␣
↪elapsed even
    // if 20 messages have not arrived. Use ConditionType::kMultiMessageAvailable␣
↪instead if the
    // timeout interval is not desired.
    ArgList multi_message_args{
        holoscan::Arg("execution_frequency", std::string{"30ms"}),
        holoscan::Arg("min_sum", static_cast<size_t>(20)),
        holoscan::Arg("sampling_mode",␣
↪MultiMessageAvailableTimeoutCondition::SamplingMode::kSumOfAll)};
    spec.multi_port_condition(
        ConditionType::kMultiMessageAvailableTimeout, {"in1", "in2", "in3"}, multi_
↪message_args);
  }
```

Here, three input ports are defined, each of which has a queue size of 10. A `MultiMessageAvailableTimeoutCondition` is applied across all three of these ports via the `multi_port_condition` method. The condition is configured to allow the operator to execute when either a total of 20 messages have arrived across the three ports OR a time-out interval of 30 ms has elapsed.

Building your C++ operator

You can build your C++ operator using CMake, by calling `find_package(holoscan)` in your `CMakeLists.txt` to load the SDK libraries. Your operator will need to link against `holoscan::core`:

Listing 12.4: <src_dir>/CMakeLists.txt

```
# Your CMake project
cmake_minimum_required(VERSION 3.20)
project(my_project CXX)

# Finds the holoscan SDK
find_package(holoscan REQUIRED CONFIG PATHS "/opt/nvidia/holoscan")

# Create a library for your operator
add_library(my_operator SHARED my_operator.cpp)

# Link your operator against holoscan::core
target_link_libraries(my_operator
    PUBLIC holoscan::core
)
```

Once your `CMakeLists.txt` is ready in `<src_dir>`, you can build in `<build_dir>` with the command line below. You can optionally pass `Holoscan_ROOT` if the SDK installation you'd like to use differs from the `PATHS` given to `find_package(holoscan)` above.

```
# Configure
cmake -S <src_dir> -B <build_dir> -D Holoscan_ROOT="/opt/nvidia/holoscan"
# Build
cmake --build <build_dir> -j
```

Using your C++ Operator in an Application

- **If the application is configured in the same CMake project as the operator**, you can simply add the operator CMake target library name under the application executable `target_link_libraries` call, as the operator CMake target is already defined.

```
  # operator
  add_library(my_op my_op.cpp)
  target_link_libraries(my_operator PUBLIC holoscan::core)

  # application
  add_executable(my_app main.cpp)
  target_link_libraries(my_operator
    PRIVATE
    holoscan::core
    my_op
  )
```

- **If the application is configured in a separate project as the operator**, you need to export the operator in its own CMake project, and import it in the application CMake project, before being able to list it under `target_link_libraries` also. This is the same as what is done for the SDK *built-in operators*, available under the `holoscan::ops` namespace.

You can then include the headers to your C++ operator in your application code.

12.1.2 GXF Operators

With the Holoscan C++ API, we can also wrap *GXF Codelets* from GXF extensions as Holoscan Operators.

Note: If you do not have an existing GXF extension, we recommend developing native operators using the *C++* or *Python* APIs to skip the need for wrapping GXF codelets as operators. If you do need to create a GXF Extension, follow the *Creating a GXF Extension* section for a detailed explanation of the GXF extension development process.

Tip: The manual codelet wrapping mechanism described below is no longer necessary in order to make use of a GXF Codelet as a Holoscan operator. There is a new `GXFCodeletOp` which allows directly using an existing GXF codelet via `Fragment::make_operator` without having to first create a wrapper class for it. Similarly there is now also a `GXFComponentResource` class which allows a GXF Component to be used as a Holoscan resource via `Fragment::make_resource`. A detailed example of how to use each of these is provided for both C++ and Python applications in the **examples/import_gxf_components** folder.

Given an existing GXF extension, we can create a simple "identity" application consisting of a replayer, which reads contents from a file on disk, and our recorder from the last section, which will store the output of the replayer exactly in the same format. This allows us to see whether the output of the recorder matches the original input files.

The `MyRecorderOp` Holoscan Operator implementation below will wrap the `MyRecorder` GXF Codelet shown *here*.

Operator definition

Listing 12.5: my_recorder_op.hpp

```cpp
#ifndef APPS_MY_RECORDER_APP_MY_RECORDER_OP_HPP
#define APPS_MY_RECORDER_APP_MY_RECORDER_OP_HPP

#include "holoscan/core/gxf/gxf_operator.hpp"

namespace holoscan::ops {

class MyRecorderOp : public holoscan::ops::GXFOperator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS_SUPER(MyRecorderOp, holoscan::ops::GXFOperator)

  MyRecorderOp() = default;

  const char* gxf_typename() const override { return "MyRecorder"; }

  void setup(OperatorSpec& spec) override;

  void initialize() override;

 private:
  Parameter<holoscan::IOSpec*> receiver_;
  Parameter<std::shared_ptr<holoscan::Resource>> my_serializer_;
```

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```cpp
  Parameter<std::string> directory_;
  Parameter<std::string> basename_;
  Parameter<bool> flush_on_tick_;
};

}  // namespace holoscan::ops

#endif /* APPS_MY_RECORDER_APP_MY_RECORDER_OP_HPP */
```

The `holoscan::ops::MyRecorderOp` class wraps a `MyRecorder` GXF Codelet by inheriting from the `holoscan::ops::GXFOperator` class. The HOLOSCAN_OPERATOR_FORWARD_ARGS_SUPER macro is used to forward the arguments of the constructor to the base class.

We first need to define the fields of the `MyRecorderOp` class. You can see that fields with the same names are defined in both the `MyRecorderOp` class and the `MyRecorder` GXF codelet .

Listing 12.6: Parameter declarations in gxf_extensions/my_recorder/my_recorder.hpp

```cpp
  nvidia::gxf::Parameter<nvidia::gxf::Handle<nvidia::gxf::Receiver>> receiver_;
  nvidia::gxf::Parameter<nvidia::gxf::Handle<nvidia::gxf::EntitySerializer>> my_
↪serializer_;
  nvidia::gxf::Parameter<std::string> directory_;
  nvidia::gxf::Parameter<std::string> basename_;
  nvidia::gxf::Parameter<bool> flush_on_tick_;
```

Comparing the `MyRecorderOp` holoscan parameter to the `MyRecorder` gxf codelet:

Holoscan Operator	GXF Codelet
`holoscan::Parameter`	`nvidia::gxf::Parameter`
`holoscan::IOSpec*`	`nvidia::gxf::Handle<nvidia::gxf::Receiver>>` or `nvidia::gxf::Handle<nvidia::gxf::Transmitter>>`
`std::shared_ptr<holoscan::Resource>`	`nvidia::gxf::Handle<T>>` example: `T` is `nvidia::gxf::EntitySerializer`

We then need to implement the following functions:

- `const char* gxf_typename() const override`: return the GXF type name of the Codelet. The fully-qualified class name (`MyRecorder`) for the GXF Codelet is specified.
- `void setup(OperatorSpec& spec) override`: setup the OperatorSpec with the inputs/outputs and parameters of the Operator.
- `void initialize() override`: initialize the Operator.

Setting up parameter specifications

The implementation of the `setup(OperatorSpec& spec)` function is as follows:

Listing 12.7: my_recorder_op.cpp

```cpp
#include "./my_recorder_op.hpp"

#include "holoscan/core/fragment.hpp"
#include "holoscan/core/gxf/entity.hpp"
#include "holoscan/core/operator_spec.hpp"

#include "holoscan/core/resources/gxf/video_stream_serializer.hpp"

namespace holoscan::ops {

void MyRecorderOp::setup(OperatorSpec& spec) {
  auto& input = spec.input<holoscan::gxf::Entity>("input");
  // Above is same with the following two lines (a default condition is assigned to the input port if not specified):
  //
  //   auto& input = spec.input<holoscan::gxf::Entity>("input")
  //                     .condition(ConditionType::kMessageAvailable, Arg("min_size") = static_cast<uint64_t>(1));

  spec.param(receiver_, "receiver", "Entity receiver", "Receiver channel to log", &input);
  spec.param(my_serializer_,
             "serializer",
             "Entity serializer",
             "Serializer for serializing input data");
  spec.param(directory_, "out_directory", "Output directory path", "Directory path to store received output");
  spec.param(basename_, "basename", "File base name", "User specified file name without extension");
  spec.param(flush_on_tick_,
             "flush_on_tick",
             "Boolean to flush on tick",
             "Flushes output buffer on every `tick` when true",
             false);
}

void MyRecorderOp::initialize() {...}

}  // namespace holoscan::ops
```

Here, we set up the inputs/outputs and parameters of the Operator. Note how the content of this function is very similar to the `MyRecorder` GXF codelet's *registerInterface* function.

- In the C++ API, GXF `Receiver` and `Transmitter` components (such as `DoubleBufferReceiver` and `DoubleBufferTransmitter`) are considered as input and output ports of the Operator so we register the inputs/outputs of the Operator with `input<T>` and `output<T>` functions (where `T` is the data type of the port).
- Compared to the pure *GXF application* that does the same job, the *SchedulingTerm* of an Entity in the *GXF Application YAML* are specified as `Conditions`

on the input/output ports (e.g., `holoscan::MessageAvailableCondition` and `holoscan::DownstreamMessageAffordableCondition`).

The highlighted lines in `MyRecorderOp::setup` above match the following highlighted statements of *GXF Application YAML*:

Listing 12.8: A part of apps/my_recorder_app_gxf/my_recorder_gxf.yaml

```yaml
name: recorder
components:
 - name: input
   type: nvidia::gxf::DoubleBufferReceiver
 - name: allocator
   type: nvidia::gxf::UnboundedAllocator
 - name: component_serializer
   type: nvidia::gxf::StdComponentSerializer
   parameters:
     allocator: allocator
 - name: entity_serializer
   type: nvidia::gxf::StdEntitySerializer
   parameters:
     component_serializers: [component_serializer]
 - type: MyRecorder
   parameters:
     receiver: input
     serializer: entity_serializer
     out_directory: "/tmp"
     basename: "tensor_out"
 - type: nvidia::gxf::MessageAvailableSchedulingTerm
   parameters:
     receiver: input
     min_size: 1
```

In the same way, if we had a `Transmitter` GXF component, we would have the following statements (Please see available constants for `holoscan::ConditionType`):

```cpp
  auto& output = spec.output<holoscan::gxf::Entity>("output");
  // Above is same with the following two lines (a default condition is assigned to the␣
↪output port if not specified):
  //
  //   auto& output = spec.output<holoscan::gxf::Entity>("output")
  //                      .condition(ConditionType::kDownstreamMessageAffordable, Arg(
↪"min_size") = static_cast<uint64_t>(1));
```

Initializing the operator

Next, the implementation of the `initialize()` function is as follows:

Listing 12.9: my_recorder_op.cpp

```cpp
#include "./my_recorder_op.hpp"

#include "holoscan/core/fragment.hpp"
```

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```cpp
#include "holoscan/core/gxf/entity.hpp"
#include "holoscan/core/operator_spec.hpp"

#include "holoscan/core/resources/gxf/video_stream_serializer.hpp"

namespace holoscan::ops {

void MyRecorderOp::setup(OperatorSpec& spec) {...}

void MyRecorderOp::initialize() {
  // Set up prerequisite parameters before calling GXFOperator::initialize()
  auto frag = fragment();
  auto serializer =
      frag->make_resource<holoscan::StdEntitySerializer>("serializer");
  add_arg(Arg("serializer") = serializer);

  GXFOperator::initialize();
}

}  // namespace holoscan::ops
```

Here we set up the pre-defined parameters such as the `serializer`. The highlighted lines above matches the highlighted statements of *GXF Application YAML*:

Listing 12.10: Another part of apps/my_recorder_app_gxf/my_recorder_gxf.yaml

```yaml
name: recorder
components:
 - name: input
   type: nvidia::gxf::DoubleBufferReceiver
 - name: allocator
   type: nvidia::gxf::UnboundedAllocator
 - name: component_serializer
   type: nvidia::gxf::StdComponentSerializer
   parameters:
     allocator: allocator
 - name: entity_serializer
   type: nvidia::gxf::StdEntitySerializer
   parameters:
     component_serializers: [component_serializer]
 - type: MyRecorder
   parameters:
     receiver: input
     serializer: entity_serializer
     out_directory: "/tmp"
     basename: "tensor_out"
 - type: nvidia::gxf::MessageAvailableSchedulingTerm
   parameters:
     receiver: input
     min_size: 1
```

Note: The Holoscan C++ API already provides the `holoscan::StdEntitySerializer` class which wraps the `nvidia::gxf::StdEntitySerializer` GXF component, used here as `serializer`.

Building your GXF operator

There are no differences in CMake between building a GXF operator and *building a native C++ operator*, since the GXF codelet is actually loaded through a GXF extension as a plugin, and does not need to be added to `target_link_libraries(my_operator ...)`.

Using your GXF Operator in an Application

There are no differences in CMake between using a GXF operator and *using a native C++ operator in an application*. However, the application will need to load the GXF extension library which holds the wrapped GXF codelet symbols, so the application needs to be configured to find the extension library in its yaml configuration file, as documented *here*.

12.1.3 Interoperability between GXF and native C++ operators

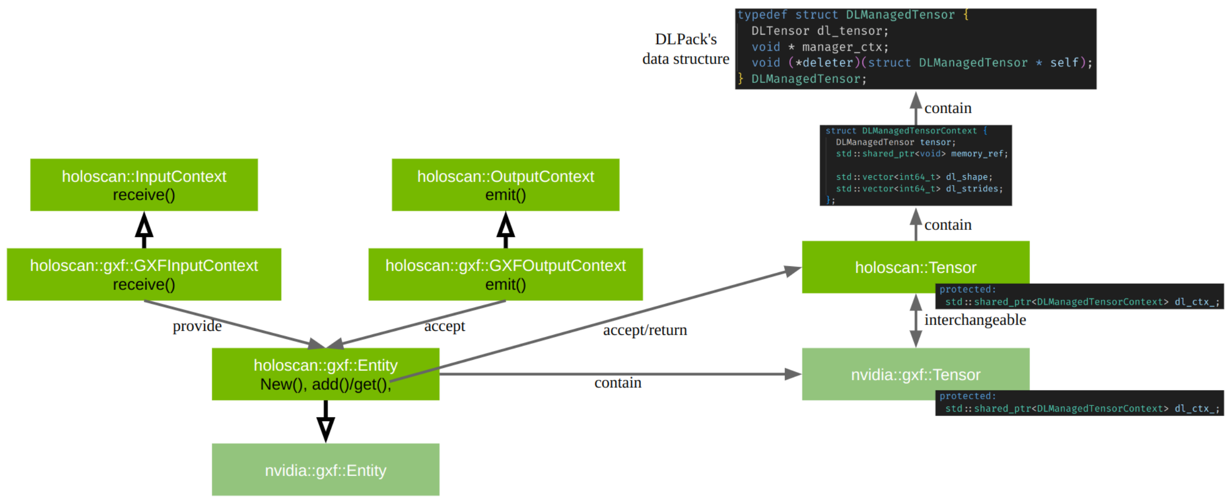
To support sending or receiving tensors to and from operators (both GXF and native C++ operators), the Holoscan SDK provides the C++ classes below:

- A class template called `holoscan::Map` which inherits from `std::unordered_map<std::string, std::shared_ptr<T>>`. The template parameter `T` can be any type, and it is used to specify the type of the `std::shared_ptr` objects stored in the map.
- A `holoscan::TensorMap` class defined as a specialization of `holoscan::Map` for the `holoscan::Tensor` type.

When a message with a `holoscan::TensorMap` is emitted from a native C++ operator, the message object is always converted to a `holoscan::gxf::Entity` object and sent to the downstream operator.

Then, if the sent GXF Entity object holds only Tensor object(s) as its components, the downstream operator can receive the message data as a `holoscan::TensorMap` object instead of a `holoscan::gxf::Entity` object.

Fig. 12.2 shows the relationship between the `holoscan::gxf::Entity` and `nvidia::gxf::Entity` classes and the relationship between the `holoscan::Tensor` and `nvidia::gxf::Tensor` classes.



```
typedef struct DLManagedTensor {
  DLTensor dl_tensor;
  void * manager_ctx;
  void (*deleter)(struct DLManagedTensor * self);
} DLManagedTensor;
```

```
struct DLManagedTensorContext {
  DLManagedTensor tensor;
  std::shared_ptr<void> memory_ref;

  std::vector<int64_t> dl_shape;
  std::vector<int64_t> dl_strides;
};
```

```
protected:
 std::shared_ptr<DLManagedTensorContext> dl_ctx_;
```

```
protected:
 std::shared_ptr<DLManagedTensorContext> dl_ctx_;
```

Fig. 12.2: Supporting Tensor Interoperability

Both `holoscan::gxf::Tensor` and `nvidia::gxf::Tensor` are interoperable with each other because they are wrappers around the same underlying `DLManagedTensorContext` struct holding a DLManagedTensor object.

The `holoscan::TensorMap` class is used to store multiple tensors in a map, where each tensor is associated with a unique key. The `holoscan::TensorMap` class is used to pass multiple tensors between operators, and it is used in the same way as a `std::unordered_map<std::string, std::shared_ptr<holoscan::Tensor>>` object.

Since both `holoscan::TensorMap` and `holoscan::gxf::Entity` objects hold tensors which are interoperable, the message data between GXF and native C++ operators are also interoperable.

Fig. 12.3 illustrates the use of the `holoscan::TensorMap` class to pass multiple tensors between operators. The `GXFSendTensorOp` operator sends a `nvidia::gxf::Entity` object (containing a `nvidia::gxf::Tensor` object as a GXF component named "tensor") to the `ProcessTensorOp` operator, which processes the tensors and then forwards the processed tensors to the `GXFReceiveTensorOp` operator.

Consider the following example, where `GXFSendTensorOp` and `GXFReceiveTensorOp` are GXF operators, and where `ProcessTensorOp` is a Holoscan native operator in C++:

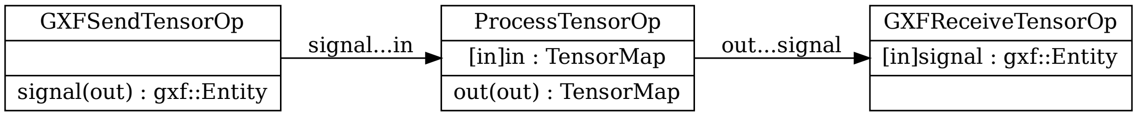


Fig. 12.3: The tensor interoperability between C++ native operator and GXF operator

The following code shows how to implement `ProcessTensorOp`'s `compute()` method as a C++ native operator communicating with GXF operators. Focus on the use of the `holoscan::gxf::Entity`:

Listing 12.11: examples/tensor_interop/cpp/tensor_interop.cpp

```cpp
void compute(InputContext& op_input, OutputContext& op_output,
             ExecutionContext& context) override {
  // The type of `in_message` is 'holoscan::TensorMap'.
  auto in_message = op_input.receive<holoscan::TensorMap>("in").value();
  // The type of out_message is TensorMap
  TensorMap out_message;

  for (auto& [key, tensor] : in_message) {  // Process with 'tensor' here.
    cudaError_t cuda_status;
    size_t data_size = tensor->nbytes();
    std::vector<uint8_t> in_data(data_size);
    CUDA_TRY(cudaMemcpy(in_data.data(), tensor->data(), data_size,␣
↪cudaMemcpyDeviceToHost));
    HOLOSCAN_LOG_INFO("ProcessTensorOp Before key: '{}', shape: ({}), data: [{}]",
                      key,
                      fmt::join(tensor->shape(), ","),
                      fmt::join(in_data, ","));
    for (size_t i = 0; i < data_size; i++) { in_data[i] *= 2; }
    HOLOSCAN_LOG_INFO("ProcessTensorOp After key: '{}', shape: ({}), data: [{}]",
                      key,
                      fmt::join(tensor->shape(), ","),
                      fmt::join(in_data, ","));
    CUDA_TRY(cudaMemcpy(tensor->data(), in_data.data(), data_size,␣
↪cudaMemcpyHostToDevice));
```

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```
      out_message.insert({key, tensor});
    }
    // Send the processed message.
    op_output.emit(out_message);
  };
```

- The input message is of type `holoscan::TensorMap` object.
- Every `holoscan::Tensor`in the `TensorMap` object is copied on the host as `in_data`.
- The data is processed (values multiplied by 2)
- The data is moved back to the `holoscan::Tensor` object on the GPU.
- A new `holoscan::TensorMap` object `out_message`is created to be sent to the next operator with `op_output.emit()`.

Note: A complete example of the C++ native operator that supports interoperability with GXF operators is available in the examples/tensor_interop/cpp directory.

12.2 Python Operators

When assembling a Python application, two types of operators can be used:

1. ***Native Python operators***: custom operators defined in Python, by creating a subclass of `holoscan.core.Operator`. These Python operators can pass arbitrary Python objects around between operators and are not restricted to the stricter parameter typing used for C++ API operators.
2. ***Python wrappings of C++ Operators***: operators defined in the underlying C++ library by inheriting from the `holoscan::Operator` class. These operators have Python bindings available within the `holoscan.operators` module. Examples are `VideoStreamReplayerOp` for replaying video files, `FormatConverterOp` for format conversions, and `HolovizOp` for visualization.

Note: It is possible to create an application using a mixture of Python wrapped C++ operators and native Python operators. In this case, some special consideration to cast the input and output tensors appropriately must be taken, as shown in *a section below*.

12.2.1 Native Python Operator

Operator Lifecycle (Python)

The lifecycle of a `holoscan.core.Operator` is made up of three stages:

- `start()` is called once when the operator starts, and is used for initializing heavy tasks such as allocating memory resources and using parameters.
- `compute()` is called when the operator is triggered, which can occur any number of times throughout the operator lifecycle between `start()` and `stop()`.
- `stop()` is called once when the operator is stopped, and is used for deinitializing heavy tasks such as deallocating resources that were previously assigned in `start()`.

All operators on the workflow are scheduled for execution. When an operator is first executed, the `start()` method is called, followed by the `compute()` method. When the operator is stopped, the `stop()` method is called. The `compute()` method is called multiple times between `start()` and `stop()`.

If any of the scheduling conditions specified by *Conditions* are not met (for example, the `CountCondition` would cause the scheduling condition to not be met if the operator has been executed a certain number of times), the operator is stopped and the `stop()` method is called.

We will cover how to use `Conditions` in the *Specifying operator inputs and outputs (Python)* section of the user guide.

Typically, the `start()` and the `stop()` functions are only called once during the application's lifecycle. However, if the scheduling conditions are met again, the operator can be scheduled for execution, and the `start()` method will be called again.

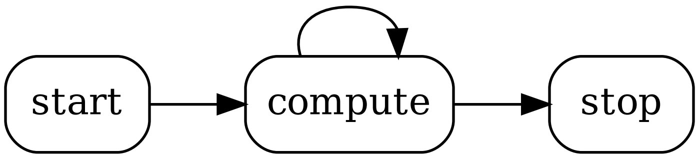

Fig. 12.4: The sequence of method calls in the lifecycle of a Holoscan Operator

We can override the default behavior of the operator by implementing the above methods. The following example shows how to implement a custom operator that overrides start, stop and compute methods.

Listing 12.12: The basic structure of a Holoscan Operator (Python)

```python
from holoscan.core import (
    ExecutionContext,
    InputContext,
    Operator,
    OperatorSpec,
    OutputContext,
)


class MyOp(Operator):

    def __init__(self, fragment, *args, **kwargs):
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: OperatorSpec):
        pass

    def start(self):
        pass

    def compute(self, op_input: InputContext, op_output: OutputContext, context:␣
↪ExecutionContext):
```

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```
        pass

    def stop(self):
        pass
```

`setup()` method vs `initialize()` vs `__init__()`

The `setup()` method aims to get the "operator's spec" by providing a `OperatorSpec` object as a spec param. When `__init__()` is called, it calls C++'s `Operator::spec` method (and also sets the `self.spec` class member) and calls the `setup` method so that the Operator's `spec` property holds the operator's specification. (See the source code for more details.)

Since the `setup()` method can be called multiple times with other `OperatorSpec` objects (e.g., to enumerate the operator's description), in the `setup()` method, a user shouldn't initialize something. Such initialization needs to be done by overriding the `initialize()` method.

```
    def initialize(self):
        pass
```

The `__init__()` method is for creating the Operator object and can be used to initialize the operator object itself by passing various arguments. Note that it doesn't initialize the corresponding GXF entity object. The underlying GXF entity object is initialized when the operator is scheduled for execution.

Please do not forget to call the base class constructor (`super().__init__(fragment, *args, **kwargs)`) at the end of the `__init__` method.

Creating a custom operator (Python)

To create a custom operator in Python it is necessary to create a subclass of `holoscan.core.Operator`. A simple example of an operator that takes a time-varying 1D input array named "signal" and applies convolution with a boxcar (i.e. rect) kernel.

For simplicity, this operator assumes that the "signal" that will be received on the input is already a `numpy.ndarray` or is something that can be cast to one via (`np.asarray`). We will see more details in a later section on how we can interoperate with various tensor classes, including the GXF Tensor objects used by some of the C++-based operators.

Code Snippet: **examples/numpy_native/convolve.py**

Listing 12.13: examples/numpy_native/convolve.py

```python
import os

from holoscan.conditions import CountCondition
from holoscan.core import Application, Operator, OperatorSpec
from holoscan.logger import LogLevel, set_log_level

import numpy as np


class SignalGeneratorOp(Operator):
    """Generate a time-varying impulse.

    Transmits an array of zeros with a single non-zero entry of a
```

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```
    specified `height`. The position of the non-zero entry shifts
    to the right (in a periodic fashion) each time `compute` is
    called.

    Parameters
    ----------
    fragment : holoscan.core.Fragment
        The Fragment (or Application) the operator belongs to.
    height : number
        The height of the signal impulse.
    size : number
        The total number of samples in the generated 1d signal.
    dtype : numpy.dtype or str
        The data type of the generated signal.
    """

    def __init__(self, fragment, *args, height=1, size=10, dtype=np.int32, **kwargs):
        self.count = 0
        self.height = height
        self.dtype = dtype
        self.size = size
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: OperatorSpec):
        spec.output("signal")

    def compute(self, op_input, op_output, context):

        # single sample wide impulse at a time-varying position
        signal = np.zeros((self.size,), dtype=self.dtype)
        signal[self.count % signal.size] = self.height
        self.count += 1

        op_output.emit(signal, "signal")


class ConvolveOp(Operator):
    """Apply convolution to a tensor.

    Convolves an input signal with a "boxcar" (i.e. "rect") kernel.

    Parameters
    ----------
    fragment : holoscan.core.Fragment
        The Fragment (or Application) the operator belongs to.
    width : number
        The width of the boxcar kernel used in the convolution.
    unit_area : bool, optional
        Whether or not to normalize the convolution kernel to unit area.
        If False, all samples have implitude one and the dtype of the
        kernel will match that of the signal. When True the sum over
        the kernel is one and a 32-bit floating point data type is used
```

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```
        for the kernel.
    """

    def __init__(self, fragment, *args, width=4, unit_area=False, **kwargs):
        self.count = 0
        self.width = width
        self.unit_area = unit_area
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: OperatorSpec):
        spec.input("signal_in")
        spec.output("signal_out")

    def compute(self, op_input, op_output, context):

        signal = op_input.receive("signal_in")
        assert isinstance(signal, np.ndarray)

        if self.unit_area:
            kernel = np.full((self.width,), 1/self.width, dtype=np.float32)
        else:
            kernel = np.ones((self.width,), dtype=signal.dtype)

        convolved = np.convolve(signal, kernel, mode='same')

        op_output.emit(convolved, "signal_out")


class PrintSignalOp(Operator):
    """Print the received signal to the terminal."""

    def setup(self, spec: OperatorSpec):
        spec.input("signal")

    def compute(self, op_input, op_output, context):
        signal = op_input.receive("signal")
        print(signal)


class ConvolveApp(Application):
    """Minimal signal processing application.

    Generates a time-varying impulse, convolves it with a boxcar kernel, and
    prints the result to the terminal.

    A `CountCondition` is applied to the generate to terminate execution
    after a specific number of steps.
    """

    def compose(self):
        signal_generator = SignalGeneratorOp(
            self,
```

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```python
            CountCondition(self, count=24),
            name="generator",
            **self.kwargs("generator"),
        )
        convolver = ConvolveOp(self, name="conv", **self.kwargs("convolve"))
        printer = PrintSignalOp(self, name="printer")
        self.add_flow(signal_generator, convolver)
        self.add_flow(convolver, printer)


def main(config_file):
    app = ConvolveApp()
    # if the --config command line argument was provided, it will override this config_
↪file`
    app.config(config_file)
    app.run()


if __name__ == "__main__":
    config_file = os.path.join(os.path.dirname(__file__), 'convolve.yaml')
    main(config_file=config_file)
```

Code Snippet: examples/numpy_native/convolve.yaml

Listing 12.14: examples/numpy_native/convolve.yaml

```yaml
signal_generator:
  height: 1
  size: 20
  dtype: int32

convolve:
  width: 4
  unit_area: false
```

In this application, three native Python operators are created: `SignalGeneratorOp`, `ConvolveOp` and `PrintSignalOp`. The `SignalGeneratorOp` generates a synthetic signal such as `[0, 0, 1, 0, 0, 0]` where the position of the non-zero entry varies each time it is called. `ConvolveOp` performs a 1D convolution with a boxcar (i.e. rect) function of a specified width. `PrintSignalOp` just prints the received signal to the terminal.

As covered in more detail below, the inputs to each operator are specified in the `setup()` method of the operator. Then inputs are received within the `compute` method via `op_input.receive()` and outputs are emitted via `op_output.emit()`.

Note that for native Python operators as defined here, any Python object can be emitted or received. When transmitting between operators, a shared pointer to the object is transmitted rather than a copy. In some cases, such as sending the same tensor to more than one downstream operator, it may be necessary to avoid in-place operations on the tensor in order to avoid any potential race conditions between operators.

Specifying operator parameters (Python)

In the example `SignalGeneratorOp` operator above, we added three keyword arguments in the operator's `__init__` method, used inside the `compose()` method of the operator to adjust its behavior:

```python
def __init__(self, fragment, *args, width=4, unit_area=False, **kwargs):
    # Internal counter for the time-dependent signal generation
    self.count = 0

    # Parameters
    self.width = width
    self.unit_area = unit_area

    # To forward remaining arguments to any underlying C++ Operator class
    super().__init__(fragment, *args, **kwargs)
```

Note: As an alternative closer to C++, these parameters can be added through the `OperatorSpec` attribute of the operator in its `setup()` method, where an associated string key must be provided as well as a default value.

```python
def setup(self, spec: OperatorSpec):
    spec.param("width", 4)
    spec.param("unit_area", False)
```

The parameters can then be accessed on the `self` object in the operator's methods (including `initialize()`, `start()`, `compute()`, `stop()`) as `self.width` and `self.unit_area`.

Other `kwargs` properties can also be passed to `spec.param`, such as `headline`, `description` (used by GXF applications), or `kind` (used when *Receiving any number of inputs (Python)*, which is deprecated since v2.3.0).

Note: Native operator parameters added via either of these methods must **not** have a name that overlaps with any of the existing attribute or method names of the base `Operator` class.

See the Configuring operator parameters *section to learn how an application can set these parameters.*

Specifying operator inputs and outputs (Python)

To configure the input(s) and output(s) of Python native operators, call the `spec.input()` and `spec.output()` methods within the `setup()` method of the operator.

The `spec.input()` and `spec.output()` methods should be called once for each input and output to be added. The `holoscan.core.OperatorSpec` object and the `setup()` method will be initialized and called automatically by the `Application` class when its `run()` method is called.

These methods (`spec.input()` and `spec.output()`) return an `IOSpec` object that can be used to configure the input/output port.

By default, the `holoscan.conditions.MessageAvailableCondition` and `holoscan.conditions.DownstreamMessageAffordableCondition` conditions are applied (with a `min_size` of `1`) to the input/output ports. This means that the operator's `compute()` method will not be invoked until a message is available on the input port and the downstream operator's input port (queue) has enough capacity to receive the message.

```
    def setup(self, spec: OperatorSpec):
        spec.input("in")
        # Above statement is equivalent to:
        #   spec.input("in")
        #       .condition(ConditionType.MESSAGE_AVAILABLE, min_size = 1)
        spec.output("out")
        # Above statement is equivalent to:
        #   spec.output("out")
        #       .condition(ConditionType.DOWNSTREAM_MESSAGE_AFFORDABLE, min_size = 1)
```

In the above example, the `spec.input()` method is used to configure the input port to have the `holoscan.conditions.MessageAvailableCondition` with a minimum size of 1. This means that the operator's `compute()` method will not be invoked until a message is available on the input port of the operator. Similarly, the `spec.output()` method is used to configure the output port to have a `holoscan.conditions.DownstreamMessageAffordableCondition` with a minimum size of 1. This means that the operator's `compute()` method will not be invoked until the downstream operator's input port has enough capacity to receive the message.

If you want to change this behavior, use the `IOSpec.condition()` method to configure the conditions. For example, to configure the input and output ports to have no conditions, you can use the following code:

```
from holoscan.core import ConditionType, OperatorSpec
#   ...
    def setup(self, spec: OperatorSpec):
        spec.input("in").condition(ConditionType.NONE)
        spec.output("out").condition(ConditionType.NONE)
```

The example code in the `setup()` method configures the input port to have no conditions, which means that the `compute()` method will be called as soon as the operator is ready to compute. Since there is no guarantee that the input port will have a message available, the `compute()` method should check if there is a message available on the input port before attempting to read it.

The `receive()` method of the `InputContext` object can be used to access different types of input data within the `compute()` method of your operator class. This method takes the name of the input port as an argument (which can be omitted if your operator has a single input port).

For standard Python objects, `receive()` will directly return the Python object for input of the specified name.

The Holoscan SDK also provides built-in data types called **Domain Objects**, defined in the `include/holoscan/core/domain` directory. For example, the `Tensor` is a Domain Object class that is used to represent a multi-dimensional array of data, which can be used directly by `OperatorSpec`, `InputContext`, and `OutputContext`.

Tip: This `holoscan.core.Tensor` class supports both DLPack and NumPy's array interface (`__array_interface__` and `__cuda_array_interface__`) so that it can be used with other Python libraries such as CuPy, PyTorch, JAX, TensorFlow, and Numba. See the *interoperability section* for more details.

In both cases, it will return `None` if there is no message available on the input port:

```
#   ...
    def compute(self, op_input, op_output, context):
        msg = op_input.receive("in")
        if msg:
            # Do something with msg
```

Receiving any number of inputs (Python)

Instead of assigning a specific number of input ports, it may be preferable to allow the ability to receive any number of objects on a port in certain situations.

Using `IOSpec.ANY_SIZE` for variable input handling

One way to achieve this is to define a multi-receiver input port by calling `spec.input("port_name", IOSpec.ANY_SIZE)` with `IOSpec.ANY_SIZE` as the second argument in the `setup()` method of the operator (as done for `PingRxOp` in the *native operator ping example*).

```python
    def setup(self, spec: OperatorSpec):
        spec.input("receivers", size=IOSpec.ANY_SIZE)
```

Code Snippet: examples/ping_multi_port/python/ping_multi_port.py

Listing 12.15: examples/ping_multi_port/python/ping_multi_port.py

```python
class PingRxOp(Operator):
    """Simple receiver operator.

    This operator has:
        input: "receivers"

    This is an example of a native operator that can dynamically have any
    number of inputs connected to is "receivers" port.
    """

    def __init__(self, fragment, *args, **kwargs):
        self.count = 1
        # Need to call the base class constructor last
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: OperatorSpec):
        # # Since Holoscan SDK v2.3, users can define a multi-receiver input port using
        # # 'spec.input()' with 'size=IOSpec.ANY_SIZE'.
        # # The old way is to use 'spec.param()' with 'kind="receivers"'.
        # spec.param("receivers", kind="receivers")
        spec.input("receivers", size=IOSpec.ANY_SIZE)

    def compute(self, op_input, op_output, context):
        values = op_input.receive("receivers")
        print(f"Rx message received (count: {self.count}, size: {len(values)})")
        self.count += 1
        print(f"Rx message value1: {values[0].data}")
        print(f"Rx message value2: {values[1].data}")


# Now define a simple application using the operators defined above


class MyPingApp(Application):
    def compose(self):
```

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```
        # Define the tx, mx, rx operators, allowing the tx operator to execute 10 times
        tx = PingTxOp(self, CountCondition(self, 10), name="tx")
        mx = PingMxOp(self, name="mx", multiplier=3)
        rx = PingRxOp(self, name="rx")

        # Define the workflow
        self.add_flow(tx, mx, {("out1", "in1"), ("out2", "in2")})
        self.add_flow(mx, rx, {("out1", "receivers"), ("out2", "receivers")})
```

Then, once the following configuration is provided in the `compose()` method,

```
self.add_flow(mx, rx, {("out1", "receivers"), ("out2", "receivers")})
```

the `PingRxOp` will receive two inputs on the `receivers` port in the `compute()` method:

```
values = op_input.receive("receivers")
```

Tip: When an input port is defined with `IOSpec.ANY_SIZE`, the framework creates a new input port for each input object received on the port. The input ports are named using the format `<port_name>:<index>`, where `<port_name>` is the name of the input port and `<index>` is the index of the input object received on the port. For example, if the `receivers` port receives two input objects, the input ports will be named `receivers:0` and `receivers:1`.

The framework internally creates a parameter (`receivers`) with the type `std::vector<holoscan::IOSpec*>`, implicitly creates input ports (`receivers:0` and `receivers:1`), and connects them (adding references of the input ports to the `receivers` vector). This way, when the `receive()` method is called, the framework can return the input data from the corresponding input ports as a tuple.

```
values = op_input.receive("receivers")
```

If you add `print(rx.description)` at the end of the `compose()` method, you will see the description of the `PingRxOp` operator as shown below:

```
id: -1
name: rx
fragment: ""
args:
  []
type: kNative
conditions:
  []
resources:
  []
spec:
  fragment: ""
  params:
    - name: receivers
      type: std::vector<holoscan::IOSpec*>
      description: ""
      flag: kNone
  inputs:
    - name: receivers:1
      io_type: kInput
```

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```
      typeinfo_name: N8holoscan3gxf6EntityE
      connector_type: kDefault
      conditions:
        []
    - name: receivers:0
      io_type: kInput
      typeinfo_name: N8holoscan3gxf6EntityE
      connector_type: kDefault
      conditions:
        []
    - name: receivers
      io_type: kInput
      typeinfo_name: N8holoscan3gxf6EntityE
      connector_type: kDefault
      conditions:
        []
  outputs:
    []
```

Configuring input port queue size and message batch condition (Python)

If you want to receive multiple objects on a port and process them in batches, you can increase the queue size of the input port and set the `min_size` parameter of the `MessageAvailableCondition` condition to the desired batch size. This can be done by calling the `connector()` and `condition()` methods with the desired arguments, using the batch size as the `capacity` and `min_size` parameters, respectively.

Setting `min_size` to `N` will ensure that the operator receives `N` objects before the `compute()` method is called.

```
    def setup(self, spec: OperatorSpec):
        spec.input("receivers").connector(IOSpec.ConnectorType.DOUBLE_BUFFER,␣
↪capacity=2).condition(
            ConditionType.MESSAGE_AVAILABLE, min_size=2
        )
```

Then, the `receive()` method can be called with the `receivers` port name to receive input data in batches.

```
    def compute(self, op_input, op_output, context):
        values = []
        value = op_input.receive("receivers")
        while value:
            values.append(value)
            value = op_input.receive("receivers")

        print(f"Rx message received (size: {len(values)})")
```

In the above example, the operator receives input on a port called "receivers" with a queue size of 2 and a `min_size` of 2. The `receive()` method is called in a loop to receive the input data in batches of 2. Since the operator does not know the number of objects to be received in advance, the `receive()` method is called in a loop until it returns a `None` value. The input data is stored in a list, and the size of the list is logged after all the input data is received.

To simplify the above code, the Holoscan SDK provides a `IOSpec.PRECEDING_COUNT` constant as a second argument to the `spec.input()` method to specify the number of preceding connections to the input port (in this case, the number of connections to the `receivers` port is 2) as the batch size. This can be used to receive the input data in batches without the need to call the `receive()` method in a loop.

```
    def setup(self, spec: OperatorSpec):
        spec.input("receivers", size=IOSpec.PRECEDING_COUNT)
```

Then, the `receive()` method can be called with the `receivers` port name to receive the input data in batches.

```
    def compute(self, op_input, op_output, context):
        values = op_input.receive("receivers")

        print(f"Rx message received (size: {len(values)})")

        print(f"Rx message value1: {values[0].data}")
        print(f"Rx message value2: {values[1].data}")
```

In the above example, the operator receives input on a port called "receivers" with a batch size of 2. The `receive()` method is called with the `receivers` port name to receive the input data in batches of 2. The input data is stored in a tuple, and the size of the tuple is logged after all the input data has been received.

If you want to use a specific batch size, you can use `holoscan.IOSpec.IOSize(size : int)` instead of `holoscan.IOSpec.PRECEDING_COUNT` to specify the batch size. Using `IOSize` in this way is equivalent to the more verbose `condition()` and `connector()` calls to update the `capacity` and `min_size` arguments shown near the start of this section.

The main reason to use `condition()` or `connector()` methods instead of the shorter `IOSize` is if additional parameter changes, such as the queue policy, need to be made. See more details on the use of the `condition()` and `connector()` methods in the advanced topics section below (*Further customizing inputs and outputs*).

```
    def setup(self, spec: OperatorSpec):
        spec.input("receivers", size=IOSpec.IOSize(2))
```

If you want to receive the input data one by one, you can call the `receive()` method with the `kind="single"` argument.

```
    def compute(self, op_input, op_output, context):
        while True:
            value = op_input.receive("receivers", kind="single")
            if value is None:
                break
            # Process the input data
            print(f"Rx message received (value: {value.data})")
```

The above code will receive the input data one by one from the `receivers` port. The `receive()` method is called in a loop until it returns a `None` value. The input data is stored in a variable, and the value of the input data is logged.

Note: This approach (receiving the input data one by one) is not applicable for the `IOSpec.ANY_SIZE` case. With the `IOSpec.ANY_SIZE` argument, the framework creates a new input port for each input object received internally. Each implicit input port (named using the format `<port_name>:<index>`) is associated with a `MessageAvailableCondition` condition that has a `min_size` of 1. Therefore, the `receive()` method **cannot** be called with the `kind="single"` keyword argument to receive the input data one by one. Instead, it can be called without any `kind` argument or with the `kind="multi"` argument for the `IOSpec.ANY_SIZE` case.

If you really need to receive the input data one by one for `IOSpec.ANY_SIZE` case (though it is not recommended), you can receive the input data from each implicit input port (named `<port_name>:<index>`) one by one using the receive() method without the kind argument. (e.g., op_input.receive("receivers:0"), op_input.receive("receivers:1"), etc.). To avoid the error message (such as The operator does not have an input port with label 'receivers:X') when calling the receive() method for the implicit input port, you need to calculate the number of connections to the receivers port in advance and call the receive() method for each implicit input port accordingly.

```
    def compute(self, op_input, op_output, context):
        input_count = len(self.spec.inputs) - 1  # -1 to exclude the 'receivers' input␣
↪port
        for i in range(input_count):
            value = op_input.receive(f"receivers:{i}")
            if value is None:
                break
            # Process the input data
            print(f"Rx message received (value: {value.data})")
```

Attention: Using IOSpec.PRECEDING_COUNT or IOSpec.IOSize(2) appears to show the same behavior as IOSpec.ANY_SIZE in the above example. However, the difference is that since IOSpec.PRECEDING_COUNT or IOSpec.IOSize(2) doesn't use separate MessageAvailableCondition conditions for each (internal) input port, it is not guaranteed that the operator will receive the input data in order.

This means the operator may receive the input data in a different order than the order in which the connections are made in the compose() method. Additionally, with the multithread scheduler, it is not guaranteed that the operator will receive the input data from each of the connections uniformly. The operator may receive more input data from one connection than from another.

If the order of the input data is important, it is recommended to use IOSpec.ANY_SIZE and call the receive() method to receive the input data in batches at once.

Please see the Python system test cases for more examples of receiving multiple inputs in Python operators.

Configuring OR-combination of port conditions (Python)

When an operator has multiple input or output ports, each of which has its own condition, the default behavior of Holoscan SDK is AND combination of all conditions. In some scenarios, it may be desirable to set some subset of ports to instead have OR combination of their conditions (e.g. an OR condition across two input ports can be used to allow an operator to execute if a message arrives on either port).

The OperatorSpec.or_combine_port_conditions method can be called from within Operator.setup to specify that a subset of ports should have OR combination of their conditions. The only argument that must be provided is a vector containing the names of the ports whose conditions should be OR combined.

For a concrete example of OR combination, see the multi_port_or_combiner example. The relevant setup method from that example for the configuration of OR combination of the input ports is:

```
def setup(self, spec: OperatorSpec):
  # Using size argument to explicitly set the receiver message queue size for each input.
  spec.input("in1")
  spec.input("in2")

  # configure Operator to execute if an input is on "in1" OR "in2"
```

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```
  # (without this, the default is "in1" AND "in2")
  spec.or_combine_port_conditions(("in1", "in2"))
```

General combination of conditions (Python)

For condition types which are not associated with an input or output port, the user creates them via construction of `Condition` objects provided via `holoscan.conditions` (or via a custom native Python `Condition` class). Any number of such conditions can be passed as positional arguments to an operator's constructor and the resulting status of the operator is the AND combination of these conditions. For example, the following would cause an operator to only execute of (condition1 AND condition2 AND condition3) are all ready.

```
# passing multiple conditions as positional arguments to an operator AND combines them
my_cond1 = MyCondition1(fragment=self, name="condition1")
my_cond2 = MyCondition2(fragment=self, name="condition2")
my_cond3 = MyCondition3(fragment=self, name="condition3")
my_op = MyOperator(fragment=self, my_cond1, my_cond2, my_cond3, name="my_op")
```

If we instead want to allow OR combination of some subset of these conditions, then instead of passing all of these conditions directly to the `MyOperator` constructor, we would first create an `OrConditionCombiner` for the terms we want OR logic to apply to and then pass that OR combiner object to the `MyOperator` constructor. The following shows how one would configure ((condition1 OR condition2) AND condition3).

```
from holoscan.resources import OrConditionCombiner

# ...

# using generic MyCondition1, MyOperator, etc. class names for this example
my_cond1 = MyCondition1(fragment=self, name="condition1")
my_cond2 = MyCondition2(fragment=self, name="condition2")

# define an OR combination of the above two conditions
or_combiner = OrConditionCombiner(
    fragment=self,
    name="or_combiner",
    terms=[my_cond1, my_cond2]
)

# create a third condition that will be AND combined
my_cond3 = MyCondition3(fragment=self, name="condition3")

# pass both the OR combiner and the conditions to be AND combined to MyOperator
my_op = MyOperator(fragment=self, or_combiner, my_cond3, name="my_op")
```

Note that for the above `MyOperator` example, if the operator also had input and/or output ports, then any port conditions (e.g. the default `MessageAvailableCondition` for input ports) would also be AND combined in addition to `condition3`.

Additional details of condition combination logic and the set of conditions provided by Holoscan is provided in the *condition components section*.

Note: Only conditions which the user has explicitly constructed with `Fragment.compose` can be passed to `OrConditionCombiner`. To instead use OR combination across **implicitly** created conditions on input or output ports, see the section above regarding `OperatorSpec.or_combine_port_conditions`. A current limitation of the API is that there is not currently a way to use the input/output port conditions with the same `OrConditionCombiner` combiner as conditions explicitly created via `make_condition`.

Configuring multi-port conditions (Python)

A subset of `Condition` types apply to multiple input ports of an operator (e.g. `MultiMessageAvailableCondition` and `MultiMessageAvailableTimeoutCondition`). In this case, rather than using the `IOSpec.condition` method as demonstrated above for setting a condition on a single port, the `OperatorSpec.multi_port_condition` method should be used to configure a condition across multiple input ports. If an input port's name was included in a `multi_port_condition` call, this will automatically disable the default `MessageAvailableCondition` that would otherwise have been assigned to that port (This means it is not required to explicitly set a `ConditionType.NONE` condition on the input port via `IOSpec.condition` in order to be able to use the port with `multi_port_condition`).

Examples of use of multi-port conditions are given in the examples/conditions/multi_message/ folder of the repository. An example of `Operator.setup` for a multi-message condition from `multi_message_sum_of_all.py` is shown below:

```
    def setup(self, spec):
        # Using size argument to explicitly set the receiver message queue size for each␣
↪input.
        spec.input("in1", size=IOSpec.IOSize(20))
        spec.input("in2", size=IOSpec.IOSize(20))
        spec.input("in3", size=IOSpec.IOSize(20))

        # Use kMultiMessageAvailableTimeout to consider all three ports together. In this
        # "SumOfAll" mode, it only matters that `min_sum` messages have arrived across␣
↪all the
        # ports that are listed in `input_port_names` below, but it does not matter which␣
↪ports the
        # messages arrived on. The "execution_frequency" is set to 30ms, so the operator␣
↪can run
        # once 30 ms has elapsed even if 20 messages have not arrived. Use
        # ConditionType.MULTI_MESSAGE_AVAILABLE instead if the timeout interval is not␣
↪desired.
        spec.multi_port_condition(
            kind=ConditionType.MULTI_MESSAGE_AVAILABLE_TIMEOUT,
            execution_frequency="30ms",
            port_names=["in1", "in2", "in3"],
            sampling_mode="SumOfAll",
            min_sum=20,
        )
```

Here, three input ports are defined, each of which has a queue size of 20. A `MultiMessageAvailableTimeoutCondition` is applied across all three of these ports via the `multi_port_condition` method. The condition is configured to allow the operator to execute when either a total of 20 messages have arrived across the three ports OR a time-out interval of 30 ms has elapsed.

12.2.2 Important note on sending tensor objects between Python and C++ operators

Holoscan's C++ API does not have any Python dependency and thus operators implemented in C++ will not be capable of directly receiving any Python objects. For a case such as a native Python operator that emits a CuPy or NumPy tensor, the default behavior is to emit that Python object type directly as that is preferable for a pure Python operator workflow. However, emitting the Python object is problematic if the downstream operator is a C+±based one like `PingTensorRxOp` as it will not be able to handle this Python object. For interoperability of tensors with C++ operators, the `emitter_name="holoscan::Tensor"` kwarg should be provided to the `op_output.emit` call in the Python operator's `compute` method so that any tensors emitted are compatible with downstream C+±based operators. In practice this "holoscan::Tensor" emitter is configured to emit a C++ `holoscan::TensorMap` containing the tensor (no data copy is required for this). This means that any downstream C++ operator can receive this tensor either as a `TensorMap`

```
    auto maybe_tensormap = op_input.receive<TensorMap>(port_name);
```

or (since Holoscan v3.1) directly as a `std::shared_ptr<holsocan::Tensor>`

```
    auto maybe_tensor = op_input.receive<Tensor>(port_name);
```

One exception to the above behavior is for the transmit of tensors between fragments of a distributed application. In this distributed case even for Python tensors like CuPy or NumPy arrays, the `emitter_name="holoscan::Tensor"` option will always automatically be used because the components used to serialize tensors over the network require a C++ tensor type.

One other important detail when `emitter_name="holoscan::Tensor"` is used is that the name of the key in the `TensorMap` that is transmitted will depend on whether the Python tensor-like object transmitted was a host tensor (any tensor-like object having `__array_interface__`) or device tensor (any tensor-like object having `__cuda_array_interface__`). This key name information is used by any downstream Python operator to automatically convert the received tensor to a NumPy or CuPy array for the host or device case, respectively. This behavior was originally introduced to make the behavior of sending tensors between fragments of a distributed application comparable to sending those same tensors within-fragment (i.e. if a CuPy array was sent a CuPy array is also received at the other end despite the intermediate representation as a C++ `holoscan::Tensor`). The one downside to the approach currently used for `emitter_name="holoscan::Tensor` is that a host or device array from some other third-party library like PyTorch will not preserve its original type. It will instead be received as a NumPy (for host data) or CuPy (for device data) array on receive.

For more information on compatibility with general C++ types for Python operators there is a dedicated section on *how to register emit/receive custom C++ types from Python*.

12.2.3 Python wrapping of a C++ operator

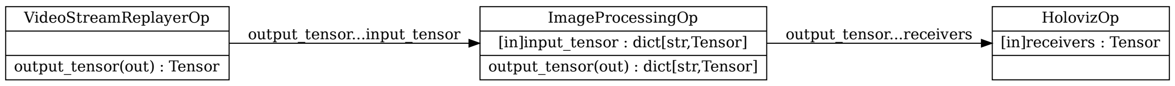
Wrapping an operator developed in C++ for use from Python is covered in a separate section on *creating C++ operator Python bindings*.

Tip: As of Holoscan 2.1, there is a `GXFCodeletOp` class which can be used to easily wrap an existing GXF codelet from Python without having to first write an underlying C++ wrapper class for it. Similarly there is now also a `GXFComponentResource` class which allows a GXF Component to be used as a Holoscan resource from Python applications. A detailed example of how to use each of these is provided for Python applications in the **examples/import_gxf_components** folder.

12.2.4 Interoperability between wrapped and native Python operators

As described in the *Interoperability between GXF and native C++ operators* section, `holoscan::Tensor` objects can be passed to GXF operators using a `holoscan::TensorMap` message that holds the tensor(s). In Python, this is done by sending `dict` type objects that have tensor names as the keys and holoscan Tensor or array-like objects as the values. Similarly, when a wrapped C++ operator that transmits a single `holoscan::Tensor` is connected to the input port of a Python native operator, calling `op_input.receive()` on that port will return a Python dict containing a single item. That item's key is the tensor name and its value is the corresponding `holoscan.core.Tensor`.

Consider the following example, where `VideoStreamReplayerOp` and `HolovizOp` are Python wrapped C++ operators, and where `ImageProcessingOp` is a Python native operator:



VideoStreamReplayerOp
output_tensor(out) : Tensor
output_tensor...input_tensor
ImageProcessingOp
[in]input_tensor : dict[str,Tensor]
output_tensor(out) : dict[str,Tensor]
output_tensor...receivers
HolovizOp
[in]receivers : Tensor

Fig. 12.5: The tensor interoperability between Python native operator and C++-based Python GXF operator

The following code shows how to implement `ImageProcessingOp`'s `compute()` method as a Python native operator communicating with C++ operators:

Listing 12.16: examples/tensor_interop/python/tensor_interop.py

```python
    def compute(self, op_input, op_output, context):
        # in_message is a dict of tensors
        in_message = op_input.receive("input_tensor")

        # smooth along first two axes, but not the color channels
        sigma = (self.sigma, self.sigma, 0)

        # out_message will be a dict of tensors
        out_message = dict()

        for key, value in in_message.items():
            print(f"message received (count: {self.count})")
            self.count += 1

            cp_array = cp.asarray(value)

            # process cp_array
            cp_array = ndi.gaussian_filter(cp_array, sigma)

            out_message[key] = cp_array

        op_output.emit(out_message, "output_tensor")
```

- The `op_input.receive()` method call returns a `dict` object.
- The `holoscan.core.Tensor` object is converted to a CuPy array by using `cupy.asarray()` method call.
- The CuPy array is used as an input to the `ndi.gaussian_filter()` function call with a parameter `sigma`. The result of the `ndi.gaussian_filter()` function call is a CuPy array.
- Finally, a new `dict` object is created ,`out_message`, to be sent to the next operator with `op_output.emit()`. The CuPy array, `cp_array`, is added to it where the key is the tensor name. CuPy arrays do not

have to explicitly be converted to a `holocan.core.Tensor` object first since they implement a DLPack (and `__cuda__array_interface__`) interface.

Note: A complete example of the Python native operator that supports interoperability with Python wrapped C++ operators is available in the examples/tensor_interop/python directory.

You can add multiple tensors to a single `dict` object , as in the example below:

Operator sending a message:

```
        out_message = {
         "video": output_array,
         "labels": labels,
         "bbox_coords": bbox_coords,
     }

     # emit the tensors
     op_output.emit(out_message, "outputs")
```

Operator receiving the message, assuming the `outputs` port above is connected to the `inputs` port below with `add_flow()`has the corresponding tensors:

```
in_message = op_input.receive("inputs")
# Tensors and tensor names
video_tensor = in_message["video"]
labels_tensor = in_message["labels"]
bbox_coords_tensor = in_message["bbox_coords"]
```

Note: Some existing operators allow *configuring* the name of the tensors they send/receive. An example is the `tensors` parameter of `HolovizOp`, where the name for each tensor maps to the names of the tensors in the `Entity` (see the `holoviz` entry in apps/endoscopy_tool_tracking/python/endoscopy_tool_tracking.yaml).

A complete example of a Python native operator that emits multiple tensors to a downstream C++ operator is available in the examples/holoviz/python directory.

There is a special serialization code for tensor types for emit/receive of tensor objects over a UCX connection that avoids copying the tensor data to an intermediate buffer. For distributed apps, we cannot just send the Python object as we do between operators in a single fragment app, but instead we need to cast it to `holoscan::Tensor` to use a special zero-copy code path. However, we also transmit a header indicating if the type was originally some other array-like object and attempt to return the same type again on the other side so that the behavior remains more similar to the non-distributed case.

Transmitted object	Received Object
holoscan.Tensor	holoscan.Tensor
dict of array-like	dict of holoscan.Tensor
host array-like object (with `__array_interface__`)	numpy.ndarray
device array-like object (with `__cuda_array_interface__`)	cupy.ndarray

This avoids NumPy or CuPy arrays being serialized to a string via cloudpickle so that they can efficiently be transmitted and the same type is returned again on the opposite side. Worth mentioning is that ,if the type emitted was e.g. a PyTorch host/device tensor on emit, the received value will be a numpy/cupy array since ANY object implementing the interfaces returns those types.

12.2.5 Automated operator class creation from a function using the `@create_op` decorator

Holoscan also provides a `holoscan.decorator` module which provides ways to autogenerate Operators by adding decorators to an existing function or class. Please see the separate section on *operator creation via holoscan.decorator.create_op*.

12.3 Advanced Topics

12.3.1 Further customizing inputs and outputs

This section complements the information above on basic input and output port configuration given separately in the C++ and Python operator creation guides. The concepts described here are the same for either the C++ or Python APIs.

By default, both the input and output ports of an Operator will use a double-buffered queue that has a capacity of one message and a policy that is set to error if a message arrives while the queue is already full. A single `MessageAvailableCondition` (`C++`/`Python`)) condition is automatically placed on the operator for each input port so that the `compute` method will not be called until a single message is available at each port. Similarly each output port has a `DownstreamMessageAffordableCondition` (`C++`/`Python`) condition that does not let the operator call `compute` until any operators connected downstream have space in their receiver queue for a single message. These default conditions ensure that messages never arrive at a queue when it is already full and that a message has already been received whenever the `compute` method is called. These default conditions make it relatively easy to connect a pipeline where each operator calls compute in turn, but may not be suitable for all applications. This section covers how the default behavior can be overridden on request.

It is possible to modify the global default queue policy via the `HOLOSCAN_QUEUE_POLICY` environment variable. Valid options (case insensitive) are:

- "pop": a new item that arrives when the queue is full replaces the oldest item
- "reject": a new item that arrives when the queue is discarded
- "fail": terminate the application if a new item arrives when the queue is full

The default behavior is "fail" when `HOLOSCAN_QUEUE_POLICY` is not specified. If an operator's `setup` method explicitly sets a receiver or transmitter via the `connector` (`C++`/`Python`) method as describe below, that connector's policy will not be overridden by the default. As of Holoscan 3.0, rather than specifying a custom policy via `connector`, it is preferred to just specify the `policy` argument to `OperatorSpec::input` or `OperatorSpec::output` directly and that policy will be applied to whichever connector type is assigned by the SDK (e.g. the receiver/transmitter class chosen by the SDK depends on whether connections are made within a fragment or across fragments of a distributed application). An `IOSpec::QueuePolicy` (`C++`/`Python`) enum is provided for specifying the policy.

Note: Overriding operator port properties is an advanced topic. Developers may want to skip this section until they come across a case where the default behavior is not sufficient for their application.

To override the properties of the queue used for a given port, the `connector` (`C++`/`Python`) method can be used as shown in the example below. This example also shows how the `condition` (`C++`/`Python`) method can be used to change the condition type placed on the Operator by a port. In general, when an operator has multiple conditions, they are AND combined, so the conditions on **all** ports must be satisfied before an operator can call `compute`.

C++ Example

Consider the following code from within the `holoscan::Operator::setup()` method of an operator.

```
spec.output<TensorMap>("out1")

spec.output<TensorMap>("out2").condition(ConditionType::kNone);

// specify a specific non-default capacity (2) and policy (reject) for the Receiver queue
spec.input<TensorMap>("in", IOSpec::IOSize(2), IOSpec::QueuePolicy::kReject)
      // can specify a specific connector type with capacity and policy arguments as in␣
↪the commented
      // code below, but it is better to just supply these arguments to the `input`␣
↪method instead.
      //  .connector(IOSpec::ConnectorType::kDoubleBuffer,
      //             Arg("capacity", static_cast<uint64_t>(2)),
      //             Arg("policy", static_cast<uint64_t>(1)))  // 0=pop, 1=reject,␣
↪2=fault (default)
        .condition(ConditionType::kMessageAvailable,
                   Arg("min_size", static_cast<uint64_t>(2)),
                   Arg("front_stage_max_size", static_cast<size_t>(2)));
```

This would define

- an output port named "out1" with the default properties
- an output port named "out2" that still has the default connector (a `holoscan::gxf::DoubleBufferTransmitter`), but the default condition of `ConditionType::kDownstreamMessageAffordable` is removed by setting `ConditionType::kNone`. This indicates that the operator will not check if any port downstream of "out2" has space available in its receiver queue before calling `compute`.
- an input port named "in" where both the connector and condition have parameters different from the default. For example, the queue size is increased to 2, and `policy=1` is "reject", indicating that if a message arrives when the queue is already full, that message will be rejected in favor of the message already in the queue. The actual default Receiver class type (e.g. `DoubleBufferReceiver` for local connections or `UcxReceiver` for distributed connections) will still be automatically determined by the SDK.

Note that if the `connector` method was **not** used to set a specific `Receiver` or `Transmitter` class, then it is also possible to change a port's queue policy after an operator has been constructed via the `Operator::queue_policy` method.

```
    // (from within Application.compose or Fragment.compose)

    op = make_operator<MyOperator>("my_op");

    // modify the queue policy that would be applied to the default Receiver for a␣
↪specific input port
    op->queue_policy("in", IOSpec::IOType::kInput, IOSpec::QueuePolicy::kReject);
```

Python Example

Consider the following code from within the `holoscan::Operator::setup()` method of an operator.

```
spec.output("out1")

spec.output("out2").condition(ConditionType.NONE)

# specify a specific non-default capacity (2) and policy (reject) for the Receiver queue
spec.input("in", capacity=2, policy=IOSpec.QueuePolicy.REJECT).condition(
    ConditionType.MESSAGE_AVAILABLE, min_size=2, front_stage_max_size=2
)
# Could specify a specific connector type with capacity and policy arguments as in the␣
↪commented
# code below, but it is better to just supply these arguments to the `input` method as␣
↪shown
# above instead.
#     .connector(
#         IOSpec.ConnectorType.DOUBLE_BUFFER,
#         capacity=2,
#         policy=1,  # 0=pop, 1=reject, 2=fault (default)
#     )
```

This would define

- an output port named "out1" with the default properties
- an output port named "out2" that still has the default connector (a `holoscan.resources.DoubleBufferTransmitter`), but the default condition of `ConditionType.DOWNSTREAM_MESSAGE_AFFORDABLE` is removed by setting `ConditionType.NONE`. This indicates that the operator will not check if any port downstream of "out2" has space available in its receiver queue before calling `compute`.
- an input port named "in1" where both the connector and condition have parameters different from the default. For example, the queue size is increased to 2, and `policy=1` is "reject", indicating that if a message arrives when the queue is already full, that message will be rejected in favor of the message already in the queue. The actual default Receiver class type (e.g. `DoubleBufferReceiver` for local connections or `UcxReceiver` for distributed connections) will still be automatically determined by the SDK.

Note that if the `connector` method was **not** used to set a specific `Receiver` or `Transmitter` class, then it is also possible to change a port's queue policy after an operator has been constructed via the `Operator.queue_policy`

```
    # (from within Application.compose or Fragment.compose)

    op = MyOperator(self, name="my_op")

    # modify the queue policy that would be applied to the default Receiver for a␣
↪specific input port
    op.queue_policy(port_name="in", port_type=IOSpec.IOType.INPUT, policy=IOSpec.
↪QueuePolicy.REJECT)
```

To learn more about overriding connectors and/or conditions there is a multi_branch_pipeline example which overrides default conditions to allow two branches of a pipeline to run at different frame rates. There is also an example of increasing the queue sizes available in this Python queue policy test application.

12.3.2 Using the Holoscan SDK with Other Libraries

The Holoscan SDK enables seamless integration with various powerful, GPU-accelerated libraries to build efficient, high-performance pipelines.

Please refer to the Best Practices to Integrate External Libraries into Holoscan Pipelines tutorial in the HoloHub repository for detailed examples and more information on Holoscan's tensor interoperability and handling CUDA libraries in the pipeline. This includes CUDA Python, CuPy, MatX for C++, cuCIM, CV-CUDA, and OpenCV for integration into Holoscan applications.

12.3.3 Operator Execution Control and Monitoring

Holoscan provides several APIs for controlling and monitoring operator execution at runtime. These APIs are particularly useful for implementing advanced control flow and dynamic behavior in your application.

Operator Execution Control

Operators can control their own execution using the following methods:

async_condition

The `async_condition()` (`C++`/`Python`) method allows an operator to get the internal asynchronous condition:

(Please refer to *AsynchronousCondition* for more information on the asynchronous condition.)

C++

```
std::shared_ptr<holoscan::AsynchronousCondition> async_condition()
```

This method returns the internal asynchronous condition that controls when the operator executes. This can be useful for custom scheduling logic or coordinating execution with other components.

Example usage:

```
// Example of using async_condition to control operator execution

class MyOperator : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(MyOperator)

  MyOperator() = default;

  void initialize() override {
    Operator::initialize();  // Always call the parent class initialize

    // Get the asynchronous condition for this operator
    auto condition = async_condition();

    // Set the initial state if needed
    if (condition) {
      // Set the AsynchronousCondition to 'WAIT' to block the operator from running.
```

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```
      condition->event_state(holoscan::AsynchronousEventState::WAIT);
    }

    // You could also share it with external components that need to control this␣
↪operator.
    // For example, you could set the condition to 'READY' to allow the operator to run:
    //
    //   condition->event_state(holoscan::AsynchronousEventState::READY);
  }
  ...
};
```

Python

```
Operator.async_condition  # property
```

This property returns the internal asynchronous condition that controls when the operator executes. This can be useful for custom scheduling logic or coordinating execution with other components.

Example usage:

```
class MyOperator(Operator):
    def __init__(self, *args, **kwargs):
        ...
        super().__init__(*args, **kwargs)

        # Note that `self.async_condition` is not set until the operator is initialized
        # so we need to check for it in the `initialize()` method

    def initialize(self):
        # `self.async_condition` is available inside `initialize()` method

        # Set the initial state if needed
        if self.async_condition:
            # Set the AsynchronousCondition to 'WAIT' to block the operator from running.
            self.async_condition.event_state = AsynchronousEventState.WAIT

        # You could also share it with external components that need to control this␣
↪operator
        # For example, you could set the condition to 'READY' to allow the operator to␣
↪run:
        #
        #   self.async_condition.event_state = AsynchronousEventState.READY
    ...
```

For a complete example of how to use these methods to implement advanced control over operator execution, see the async_operator_execution_control example.

stop_execution

The `stop_execution()` (C++/Python) method allows an operator to stop its own execution:

C++

```
void Operator::stop_execution();
```

This method can be called from within the `compute()` method to signal that the operator should stop executing. It works by modifying the internal asynchronous condition of the operator to prevent the operator from being scheduled again.

Example usage:

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext& op_output,
             holoscan::ExecutionContext& context) override {
  // Logic to determine if operator should stop
  if (should_stop_condition) {
    // Stop this operator from executing further
    stop_execution();
  }
  // ... rest of compute logic ...
}
```

Note: What it actually does is set the internal asynchronous condition of the operator to `EVENT_NEVER`, which is a special state that prevents the operator from being scheduled again.

```
async_condition()->event_state(holoscan::AsynchronousEventState::EVENT_NEVER);
```

Python

```
def stop_execution(self)
```

This method can be called from within the `compute()` method to signal that the operator should stop executing. It works by modifying the internal asynchronous condition of the operator to prevent the operator from being scheduled again.

Example usage:

```
def compute(self, op_input, op_output, context):
    # Logic to determine if operator should stop
    if should_stop_condition:
        # Stop this operator from executing further
        self.stop_execution()
    # ... rest of compute logic ...
```

execution_context

The `execution_context()` (C++/Python) property allows an operator to access its execution context:

C++

```
std::shared_ptr<holoscan::ExecutionContext> execution_context();
```

This method returns the execution context that the operator is running in. The execution context provides access to information about the execution environment and other operators in the application.

Example usage:

```
void initialize() override {
  Operator::initialize();

  auto context = execution_context();
  if (context) {
    // Use the execution context to find other operators
    auto other_op = context->find_operator("mx");
    if (other_op) {
      // Store a reference to the other operator for later use
      other_operator_ = other_op;
      HOLOSCAN_LOG_INFO("Found other operator: {}", other_op->name());
    }
  }
}

private:
  std::shared_ptr<holoscan::Operator> other_operator_;
```

Python

```
execution_context  # property
```

This property returns the execution context that the operator is running in. The execution context provides access to information about the execution environment and other operators in the application.

Example usage:

```
def initialize(self):
    # Note that unlike C++, you don't need to call super().initialize() in the␣
↪initialize() method
    # because it is called automatically by the Operator class constructor before calling
    # the initialize() method
    context = self.execution_context

    # Use the execution context to find other operators
    other_op = context.find_operator("other_operator")
    if other_op:
        # Store a reference to the other operator for later use
        self.other_operator = other_op
```

ExecutionContext Methods for Operator Monitoring

The `ExecutionContext` (C++/Python) provides an interface for operators to interact with the execution environment, including other operators in the application. The ExecutionContext object can be accessed by calling the `execution_context()` (C++/Python) method on the operator. Once the operator is initialized, the execution context object is available in various lifecycle methods such as `initialize()`, `start()`, and `stop()`. Additionally, the ExecutionContext object is directly passed as a parameter to the `compute()` method for convenience.

Using the ExecutionContext, operators can find other operators in the application, check their status, and interact with them, enabling complex coordination patterns between operators. This is particularly useful for implementing dynamic behaviors such as conditional processing branches, adaptive execution rates, or coordinated shutdowns.

The `ExecutionContext` object passed to the `compute()` method provides several methods for monitoring and manipulating other operators in the application:

find_operator

The `find_operator()` (C++/Python) method allows an operator to find another operator in the application by its name:

C++

```
virtual std::shared_ptr<Operator> find_operator(const std::string& op_name = "") = 0;
```

Returns a shared pointer to the operator with the given name, or `nullptr` if no such operator exists.

Example usage:

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext& op_output,
             holoscan::ExecutionContext& context) override {
  auto other_op = context.find_operator("other_operator");
  if (other_op) {
    // Interact with the other operator
  }
}
```

Python

```
def find_operator(self, op_name="")
```

Returns the operator with the given name, or `None` if no such operator exists.

Example usage:

```
def compute(self, op_input, op_output, context):
    other_op = context.find_operator("other_operator")
    if other_op:
        # Interact with the other operator
```

get_operator_status

The `get_operator_status()` (C++/Python) method allows an operator to check the current execution status of another operator:

C++

```
virtual expected<holoscan::OperatorStatus, RuntimeError> get_operator_status(const␣
↪std::string& op_name) = 0;
```

Returns an `expected` containing the `OperatorStatus` of the operator with the given name, or an error if no such operator exists.

The `OperatorStatus` enum includes the following values:

- `kNotStarted`: Operator is created but not started
- `kStartPending`: Operator is pending to start
- `kStarted`: Operator is started
- `kTickPending`: Operator is pending to tick
- `kTicking`: Operator is currently ticking
- `kIdle`: Operator is idle
- `kStopPending`: Operator is pending to stop

Example usage:

```
void compute(holoscan::InputContext& op_input, holoscan::OutputContext& op_output,
             holoscan::ExecutionContext& context) override {
  auto status = context.get_operator_status("other_operator");
  if (status && status.value() == holoscan::OperatorStatus::kIdle) {
    // React to the other operator being idle
  }
}
```

Python

```
def get_operator_status(self, op_name)
```

Returns the `OperatorStatus` of the operator with the given name, or raises an exception if no such operator exists.

The `OperatorStatus` enum includes the following values:

- `OperatorStatus.NOT_STARTED`: Operator is created but not started
- `OperatorStatus.START_PENDING`: Operator is pending to start
- `OperatorStatus.STARTED`: Operator is started
- `OperatorStatus.TICK_PENDING`: Operator is pending to tick (call Operator.compute)
- `OperatorStatus.TICKING`: Operator is currently ticking (running Operator.compute)
- `OperatorStatus.IDLE`: Operator is idle
- `OperatorStatus.STOP_PENDING`: Operator is pending to stop

Example usage:

```python
def compute(self, op_input, op_output, context):
    status = context.get_operator_status("other_operator")
    if status == OperatorStatus.IDLE:
        # React to the other operator being idle
```

Attention: Currently, there's no way to retrieve the computed SchedulingCondition status from the operator (i.e., whether the computed scheduling condition status is NEVER, which means the operator is terminated).

A better approach for checking an operator's computed scheduling condition will be available in a future release.

For a complete example of how to use these methods to implement advanced monitoring behavior, see the operator_status_tracking example.

CHAPTER

THIRTEEN

SIMPLIFIED PYTHON OPERATOR CREATION VIA THE CREATE_OP DECORATOR

Warning: The `holoscan.decorator.create_op()` decorator and the supporting `holoscan.decorator.Input` and `holoscan.decorator.Output` classes are new in Holoscan v2.2 and are still considered experimental. They are usable now, but it is possible that some backwards incompatible changes to the behavior or API may be made based on initial feedback.

For convenience, a `holoscan.decorator.create_op()` decorator is provided which can be used to automatically convert a simple Python function/generator or a class into a native Python `holoscan.core.Operator`. The wrapped function body (or the `__call__` method if `create_op` is applied to a class) will correspond to the computation to be done in the `holoscan.core.Operator.compute()` method, but without any need to explicitly make any calls to `holoscan.core.InputContext.receive()` to receive inputs or `holoscan.core.OutputContext.emit()` to transmit the output. Any necessary input or output ports will have been automatically generated.

Consider first a simple Python function named `mask_and_offset` that takes `image` and `mask` tensors as input and multiplies them, followed by adding some scalar `offset`.

```python
def mask_and_offset(image, mask, offset=1.5):
    return image * mask + offset
```

To turn this into an function that returns a corresponding operator we can add the `create_op` decorator like this:

```python
from holoscan.decorator import create_op


@create_op(
    inputs=("image", "mask"),
    outputs="out",
)
def mask_and_offset(image, mask, offset=1.5):
    return image * mask + offset
```

By supplying the `inputs` argument we are specifying that there are two input ports, named "image" and "mask". By setting `outputs="out"` we are indicating that the output will be transmitted on a port named "out". When `inputs` are specified by simple strings in this way, the names used must map to variable names in the wrapped function's signature. We will see later that it is possible to use the `holoscan.decorator.Input` class to provide more control over how inputs are mapped to function arguments. Similarly, we will see that the `holoscan.decorator.Output` class can be used to provide more control over how the function output is mapped to any output port(s).

There is also an optional, `cast_tensors` argument to `create_op`. For convenience, this defaults to `True`, which results in any tensor-like objects being automatically cast to a NumPy or CuPy array (for host or device tensors, respectively) before they are passed on to the function. If this is not desired (e.g. due to working with a different third party tensor framework than NumPy or CuPy), the user can set `cast_tensors=False`, and manually handle casting of any `holoscan.Tensor` objects to the desired form in the function body. This casting option applies to either single tensors or a tensor map (`dict[Tensor]`).

This decorated function can then be used within the `compose` method of an `Application` to create an operator corresponding to this computation:

```
from holoscan.core import Application, Operator


def MyApp(Application):

    def compose(self)
        mask_op = mask_and_offset(self, name="my_scaling_op", offset=0.0)

        # verify that an Operator was generated
        assert(isinstance(mask_op, Operator))

        # now add any additional operators and create the computation graph using add_
↪flow
```

Note that as for all other Operator classes, it is **required** to supply the application (or fragment) as the first argument (`self` here). The `name` kwarg is always supported and is the name that will be assigned to the operator. Due to the use of this `kwarg` to specify the operator name, the wrapped function (`mask_and_offset` in this case) should not use `name` as an argument name. In this case, we specified `offset=0.0` which would override the default value of `offset=1.5` in the function signature.

For completeness, the use of the `create_op` decorator on `mask_and_offset` is equivalent to if the user had defined the following `MaskAndOffsetOp` class and used it in `MyApp.compose`:

```
def MaskAndOffsetOp(Operator):
    def setup(self, spec):
        spec.input("image")
        spec.input("mask")
        spec.output("out")

    def compute(self, op_input, op_output, context):
        # Simplified logic here assumes received values are GPU tensors
        # create_op would add additional logic to handle the inputs
        image = op_input.receive("image")
        image = cp.asarray(image)

        mask = op_input.receive("mask")
        mask = cp.asarray(mask)

        out = image * mask + offset
        op_output.emit(out, "out")
```

13.1 Decorating a function that returns a tuple of arrays

Let's consider another example where function takes in multiple arrays, processes them, and returns a tuple of updated arrays:

```
def scale_and_offset(x1, x2, scale=2.0, offset=1.5):
    y1 = x1 * scale
    y2 = x2 + offset
    return y1, y2
```

To turn this into a corresponding operator we can add the `create_op` decorator like this:

```
@create_op(
    inputs=("x1", "x2"),
    outputs=("out1", "ou2"),
)
def scale_and_offset(x1, x2, scale=2.0, offset=1.5):
    y1 = x1 * scale
    y2 = x2 + offset
    return y1, y2
```

As before, the messages received through the ports defined by `inputs`, "x1" and "x2", will be mapped to respective variables `x1` and `x2`. Likewise, the elements of the output tuple, arrays `y1` and `y2`, will be emitted through ports "out1" and "out2", respectively. In contrast to input mapping, which is determined by the naming of ports and variables, the output mapping is determined by the ordering of output ports and elements in the tuple returned by the function.

13.2 Using the Input class for more control over input ports

This section will cover additional use cases where using a `str` or `Tuple[str]` for the `inputs` argument is insufficient.

Scenario 1: Assume that the upstream operator sends a tensormap to a given input port and we need to specify which tensor(s) in the tensormap will map to which input port.

For a concrete example, suppose we want to print a tensor's shape using a function like:

```
def print_shape(tensor):
    print(f"{tensor.shape = }")
```

but the upstream operator outputs a dictionary containing two tensors named "image" and "labels". We could use this operator by specifying which tensor name on a particular input port would map to the function's "tensor" argument. For example:

```
@create_op(inputs=Input("input_tensor", arg_map={"image": "tensor"}))
def print_shape(tensor):
    print(f"{tensor.shape = }")
```

would create an operator with a single input port named "input_tensor" and no output port. The input port may receive a tensormap with any number of tensors, but will only use the tensor named "image", mapping it to the "tensor" argument of the wrapped function. In general, the `arg_map` is a dictionary mapping tensor names found on the port to their corresponding function argument names.

Scenario 2: we want to override the scheduling condition present on a port. This can be done by specifying Input with the `condition` and optionally `condition_kwargs` arguments. For example, to override the MessageAvailableCondition that is added to the port by default and allow it to call `compute` even when no input message is available:

```
@create_op(inputs=Input("input_tensor", condition=ConditionType.NONE, condition_kwargs={}
↪))
```

Scenario 3: we want to override the parameters of the receiver present on a port. For example, we could specify a different policy for the double buffer receiver that is used by default (policy=1 corresponds to discarding incoming messages when the queue is already full)

```
@create_op(inputs=Input("input_tensor", connector=ConditionType.DOUBLE_BUFFER, connector_
↪kwargs=dict(capacity=1, policy=1)))
```

13.3 Using the Output class for more control over output ports

To support a case where multiple output ports should be present, the user must have the function return a `dict`. The `holoscan.decorator.Output` class then has a `tensor_names` keyword argument that can be specified to indicate which items in the dictionary are to be transmitted on a given output port.

For example, assume we have a function that generates three tensors, `x`, `y` and `z` and we want to transmit `x` and `y` on port "out1" while `z` will be transmitted on port "out2". This can be done by specifying `outputs` as follows in the `create_op` call:

```
@create_op(
    outputs=(
        Output("out1", tensor_names=("x", "y")),
        Output("out2", tensor_names=("z",)),
    ),
)
def xyz_generator(nx=32, ny=32, nz=16):
    x = cp.arange(nx, dtype=np.uint32)
    y = cp.arange(ny, dtype=np.uint32)
    z = cp.arange(nz, dtype=np.uint32)

    # must return a dict type when Output arg(s) with `tensor_names` is used
    return dict(x=x, y=y, z=z)
```

This operator has no input ports and three optional keyword arguments. It splits the output tensors across two ports as described above. All names used in `tensor_names` must correspond to keys present in the `dict` emitted by the object. Often the `dict` values are tensors, but that is not a requirement.

The `holoscan.decorator.Output` class also supports `condition`, `condition_kwargs`, `connector` and `connector_kwargs` that work in the same way as shown for `holoscan.decorator.Input` above. For example, to override the transmitter queue policy for a single output port named "output_tensor"

```
@create_op(outputs=Output("output_tensor",
                          connector=IOSpec.ConnectorType.DOUBLE_BUFFER,
                          connector_kwargs=dict(capacity=1, policy=1)))
```

note that `tensor_names` was not specified which means that the returned object does not need to be a `dict`. The object itself will be emitted on the "output_tensor" port.

Note: When specifying the `inputs` and `outputs` arguments to `create_op`, please make sure that all ports have unique names. As a concrete example, if an operator has a single input and output port that are used to send images, one should use unique port names like “image_in” and “image_out” rather than using “image” for both.

13.4 Configuring the queue size and policy for an input or output port

When using the decorator approach to create operators, you can configure the queue size and policy for input and output ports using the `Input` and `Output` classes. Here’s how to configure these parameters:

```python
from holoscan.core import ConditionType, IOSpec
from holoscan.decorator import Input, Output, create_op

# Example with input port configuration
@create_op(
    op_param="self",
    inputs=Input(
        "input",
        arg_map="value",
        size=IOSpec.SIZE_ONE,  # Set queue size to 1
        policy=IOSpec.QueuePolicy.POP  # Pop oldest item if queue is full
    ),
    outputs="output"
)
def my_operator(self, value):
    return value * 2

# Example with output port configuration
@create_op(
    op_param="self",
    inputs="input",
    outputs=Output(
        "output",
        size=2,  # Set queue size to 2
        policy=IOSpec.QueuePolicy.REJECT,  # Reject new items if queue is full
        condition_type=ConditionType.NONE
    )
)
def another_operator(self, value):
    return value
```

13.4.1 Queue Size Options

The `size` parameter can be set to:

- `IOSpec.SIZE_ONE`: Queue size of 1 (default)
- `IOSpec.ANY_SIZE`: Any size queue
- `IOSpec.PRECEDING_COUNT`: Size based on number of preceding connections
- An integer value: Custom queue size

13.4.2 Queue Policy Options

The `policy` parameter accepts these values:

- `IOSpec.QueuePolicy.POP`: Pop oldest item when queue is full
- `IOSpec.QueuePolicy.REJECT`: Reject new items when queue is full
- `IOSpec.QueuePolicy.FAULT`: Log warning and reject when queue is full

13.4.3 Example Use Cases

1. Throttling execution with POP policy:

```
@create_op(
    op_param="self",
    inputs=Input("input", arg_map="value"),
    outputs=Output(
        "output",
        policy=IOSpec.QueuePolicy.POP,
        condition_type=ConditionType.NONE
    )
)
def execution_throttler_op(self, value):
    if value is not None:
        return value
```

2. Multiple input handling:

```
@create_op(
    op_param="self",
    inputs=Input("input", arg_map="value", size=IOSpec.ANY_SIZE),
    outputs="output"
)
def multi_input_op(self, value):
    return value
```

13.5 Using the op_param argument to access the operator instance

The `op_param` argument to `create_op` can be used to access the operator instance within the function body. This is useful if the operator needs to access its own name or other attributes.

```
@create_op(op_param="self")
def simple_op(self, param1, param2=5):
    print(f"I am here - {self.name} (param1: {param1}, param2: {param2})")
```

The operator can then be used in an application like this:

```
class OpParamApp(Application):
    def compose(self):
        node1 = simple_op(self, param1=1, name="node1")
        node2 = simple_op(self, param1=2, name="node2")
```

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```
        node3 = simple_op(self, param1=3, name="node3")

        self.add_flow(self.start_op(), node1)
        self.add_flow(node1, node2)
        self.add_flow(node2, node3)
```

The output of this application will be:

```
I am here - node1 (param1: 1, param2: 5)
I am here - node2 (param1: 2, param2: 5)
I am here - node3 (param1: 3, param2: 5)
```

When this application runs, each operator instance will print its name along with its parameter values. The `op_param` argument allows the function to access operator attributes like `name` through the specified parameter (in this case `self`). This is particularly useful when you need to access operator-specific information or methods within your function's implementation.

13.6 Interoperability with wrapped C++ operators

The SDK includes a python_decorator example showing interoperability of wrapped C++ operators (`VideoStreamReplayerOp` and `HolovizOp`) alongside native Python operators created via the `create_op` decorator.

The start of this application imports a couple of the built in C+±based operators with Python bindings (`HolovizOp` and `VideoStreamReplayerOp`). In addition to these, two new operators are created via the `create_op` decorator APIs.

```
import os

from holoscan.core import Application
from holoscan.decorator import Input, Output, create_op
from holoscan.operators import HolovizOp, VideoStreamReplayerOp

sample_data_path = os.environ.get("HOLOSCAN_INPUT_PATH", "../data")


@create_op(
    inputs="tensor",
    outputs="out_tensor",
)
def invert(tensor):
    tensor = 255 - tensor
    return tensor


@create_op(inputs=Input("in", arg_map="tensor"), outputs=Output("out", tensor_names=(
↪"frame",)))
def tensor_info(tensor):
    print(f"tensor from 'in' port: shape = {tensor.shape}, " f"dtype = {tensor.dtype.
↪name}")
    return tensor
```

The first is created by adding the decorator to a function named `invert` which just inverts the (8-bit RGB) color space values. A second operator, is created by adding the decorator to a function named `tensor_info`, which assumes that the input is a CuPy or NumPy tensor, and prints its shape and data type. Note that `create_op`'s default `cast_tensors=True` option ensures that any host or device tensors are cast to NumPy or CuPy arrays, respectively. This is why it is safe to use NumPy APIs in the function bodies. If the user wants to receive the `holoscan.Tensor` object directly and manually handle the casting to a different type of object in the function body, then `cast_tensors=False` should be specified in the keyword arguments to `create_op`.

Now that we have defined or imported all of the operators, we can build an application in the usual way by inheriting from the `Application` class and implementing the `compose` method. The remainder of the code for this example is shown below.

```
class VideoReplayerApp(Application):
    """Example of an application that uses the operators defined above.

    This application has the following operators:

    - VideoStreamReplayerOp
    - HolovizOp
    - invert (created via decorator API)
    - tensor_info (created via decorator API)

    `VideoStreamReplayerOp` reads a video file and sends the frames to the HolovizOp.
    The `invert` operator inverts the color map (the 8-bit `value` in each color channel␣
↪is
    set to `255 - value`).
    The `tensor_info` operator prints information about the tensors shape and data type.
    `HolovizOp` displays the frames.
    """

    def compose(self):
        video_dir = os.path.join(sample_data_path, "racerx")
        if not os.path.exists(video_dir):
            raise ValueError(f"Could not find video data: {video_dir=}")

        # Define the replayer and holoviz operators
        replayer = VideoStreamReplayerOp(
            self,
            name="replayer",
            directory=video_dir,
            basename="racerx",
            frame_rate=0,  # as specified in timestamps
            repeat=False,  # default: false
            realtime=True,  # default: true
            count=40,  # default: 0 (no frame count restriction)
        )
        invert_op = invert(self, name="image_invert")
        info_op = tensor_info(self, name="tensor_info")
        visualizer = HolovizOp(
            self,
            name="holoviz",
            width=854,
            height=480,
            # name="frame" to match Output argument to create_op for tensor_info
```

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```
            tensors=[dict(name="frame", type="color", opacity=1.0, priority=0)],
        )
        # Define the workflow
        self.add_flow(replayer, invert_op, {("output", "tensor")})
        self.add_flow(invert_op, info_op, {("out_tensor", "in")})
        self.add_flow(info_op, visualizer, {("out", "receivers")})


def main():
    app = VideoReplayerApp()
    app.run()


if __name__ == "__main__":
    main()
```

The highlighted lines show how Operators corresponding to the `invert` and `tensor_info` functions are created by passing the application itself as the first argument. The `invert_op` and `info_op` variables now correspond to a `holsocan.core.Operator` class and can be connected in the usual way using `add_flow` to define the computation. Note that a name was provided for these operators, via the optional `name` keyword argument. In this case each operator is only used once, but if the same operator is to be used more than once in an application, each should be given a unique name.

13.7 Using create_op to turn a generator into an Operator

The `create_op` decorator can be applied to a generator in the same way as for a function. In this case, a `BooleanCondition` will automatically be added to the operator that will stop it from trying to call `compute` again once the generator is exhausted (has no more values to yield). The following is a basic example of decorating a generator for integers from 1 to `count`:

```
@create_op(outputs="out")
def source_generator(count):
    yield from range(1, count + 1)
```

The `compose` method can then create an operator from this decorated generator as follows

```
count_op = source_generator(self, count=100, name="int_source")
```

13.8 Using create_op to turn a class into an Operator

The `create_op` decorator can also be applied to a class implementing the `__call__` method, to turn it into an `Operator()`. One reason to choose a class vs. a function is if there is some internal state that needs to be maintained across calls. For example, the operator defined below casts the input data to 32-bit floating point and on even frames also negates the values.

```
@create_op
class NegateEven:
    def __init__(self, start_index=0):
        self.counter = start_index
```

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```
    def __call__(self, x):
        # cast tensor to 32-bit floating point
        x = x.astype('float32')

        # negate the values if the frame is even
        if self.counter % 2 == 0:
            x = -x
        return x
```

In this case, since there is only a single input and output for the function, we can omit the `inputs` and `outputs` arguments in the call to `create_op`. In this case the input port will have name `"x"`, as determined from the variable name in the function signature. The output port will be have an empty name `""`. To use different port names, the `inputs` and/or `outputs` arguments should be specified.

The `compose` method can then create an operator from this decorated generator as follows. Note that any positional or keyword arguments in the `__init__` method would be supplied during the `NegateEven` call. This returns a function (not yet an operator) that can then be called to generate the operator. This is shown below

```
negate_op_creation_func = NegateEven(start_index=0)              # `negate_op_
↪creation_func` is a function that returns an Operator
negate_even_op = negate_op_creation_func(self, name="negate_even")  # call the function␣
↪to create an instance of NegateEvenOp
```

or more concisely as just

```
negate_even_op = NegateEven(start_index=0)(self, name="negate_even")
```

Note that the operator class as defined above is approximately equivalent to the Python native operator defined below. We show it here explicitly for reference.

```
import cupy as cp
import numpy as np


class NegateEvenOp(Operator):

    def __init__(self, fragment, *args, start_index=0, **kwargs):
        self.counter = start_index
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec):
        spec.input("x")
        spec.output("")

    def compute(op_input, op_output, context):
        x = op_input.receive("x")

        # cast to CuPy or NumPy array
        # (validation that `x` is a holoscan.Tensor is omitted for simplicity)
        if hasattr(x, '__cuda_array_interface__'):
            x = cupy.asarray(x)
        else:
```

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```
            x = numpy.asarray(x)

        # cast tensor to 32-bit floating point
        x = x.astype('float32')

        # negate the values if the frame is even
        if self.counter % 2 == 0:
            x = -x

        op_output.emit(x, "")
```

The primary differences between this `NegateEvenOp` class and the decorated `NegateEven` above are:

- `NegateEven` does not need to define a `setup` method
- `NegateEven` does not inherit from `Operator` and so does not call its `__init__` from the constructor.
- The `NegateEven::__call__` method is simpler than the `NegateEvenOp::compute` method as `receive` and `emit` methods do not need to be explicitly called and casting to a NumPy or CuPy array is automatically handled for `NegateEven`.

CHAPTER

FOURTEEN

CREATING CONDITIONS

Tip: In most cases, applications will be built using one of several provided conditions documented in the *condition components section* of this user guide. This page illustrates the advanced use case of adding a user-defined condition to control when an operator can execute.

14.1 C++ Conditions

When assembling a C++ application, two types of conditions can be used:

1. ***Native C++ conditions***: custom conditions defined in C++ without using the GXF API, by creating a subclass of `holoscan::Condition`.
2. ***GXF Conditions***: conditions defined in the underlying C++ library by inheriting from the `holoscan::ops::GXFCondition` class. These conditions wrap GXF scheduling term components from GXF extensions. Examples are `CountCondition` for limiting operator execution to a specified count and `PeriodicCondition` for restricting the rate of execution of an operator to a specified period. Several additional built-in conditions are documented in the *condition components section*.

Note: It is possible to assign a mixture of GXF conditions and native conditions to an operator.

14.1.1 Native Conditions

Understanding operator scheduling

C++

The `holoscan::SchedulingStatusType` enum defines the current status of the condition.

Condition Scheduling Status	Description
kNever	Operator will never execute again
kReady	Operator is ready for execution
kWait	Operator may execute in the future
kWaitTime	Operator will be ready for execution after specified duration
kWaitEvent	Operator is waiting on an asynchronous event with unknown time interval

The overall readiness of an operator to execute will be determined by AND combination of the status of all of the individual conditions present on an operator. In other words, the operator will only be able to execute once all conditions are in a `kReady` state. If any condition is in `kNever` state, the operator will never execute again.

When multiple operators are ready to execute at the same time, the order in which they execute will depend on the specific `Scheduler` being used by the application. For example, the `GreedyScheduler` executes one operator at a time in a fixed, deterministic order while the `EventBasedScheduler` and `MultiThreadScheduler` can have multiple worker threads that allow operators to execute in parallel.

Python

The `holoscan.core.SchedulingStatusType` enum defines the current status of the condition.

Condition Scheduling Status	Description
NEVER	Operator will never execute again
READY	Operator is ready for execution
WAIT	Operator may execute in the future
WAIT_TIME	Operator will be ready for execution after specified duration
WAIT_EVENT	Operator is waiting on an asynchronous event with unknown time interval

The overall readiness of an operator to execute will be determined by AND combination of the status of all of the individual conditions present on an operator. In other words, the operator will only be able to execute once all conditions are in a `READY` state. If any condition is in `NEVER` state, the operator will never execute again.

When multiple operators are ready to execute at the same time, the order in which they execute will depend on the specific `Scheduler` being used by the application. For example, the `GreedyScheduler` executes one operator at a time in a fixed, deterministic order while the `EventBasedScheduler` and `MultiThreadScheduler` can have multiple worker threads that allow operators to execute in parallel.

Creating a custom condition (C++)

When creating a native `Condition` (C++/`Python`), one will typically need to override the following base component class methods

- `initialize` (C++/`Python`) is called once during initialization after the applications `run` (C++/`Python`) method is called. This can be used to setup any initial status for the member variables defined for the condition. It is important that this method call the base `initialize` (C++/`Python`) method prior to using any parameters defined by `setup` (C++/`Python`).
- `setup` (C++/`Python`) This method is used to configure any parameters defined for the condition. This method will be called automatically by the `Application` (C++/`Python`) class when its `run` (C++/`Python`) method is called.

It is also required to override the following three methods that will be used by the underlying GXF scheduler. Of these, the `check` method is the only one that is always required to have a non-empty implementation.

- `check` (C++/`Python`) is called by the underlying GXF scheduler in order to check whether the operator to which this condition is assigned is ready to execute. The operator will only execute when this check sets the `type` output argument to `holoscan::SchedulingStatusType::kReady` (C++) / `holoscan.core.SchedulingStatusType.READY` (Python).
- `on_execute` (C++/`Python`) is called immediately after an operator's `compute` method (C++/`Python`), just before any emitted messages are actually distributed to downstream receivers.

- `update_state` (C++/Python) is always called immediately before `check` (C++/Python) and is always passed the current timestamp as an input argument. This is used by operator whose status depends on the current timestamp.

To create a custom condition in C++, it is necessary to create a subclass of `Condition` (C++/Python). The following example demonstrates how to use native conditions (conditions that do not have an underlying, pre-compiled GXF SchedulingTerm).

C++

Code Snippet: examples/conditions/native/cpp/ping_periodic_native.cpp

Listing 14.1: examples/conditions/native/cpp/ping_periodic_native.cpp

```cpp
#include <optional>

#include "holoscan/holoscan.hpp"
#include "holoscan/operators/ping_rx/ping_rx.hpp"
#include "holoscan/operators/ping_tx/ping_tx.hpp"

namespace holoscan::conditions {

class NativePeriodicCondition : public Condition {
 public:
  HOLOSCAN_CONDITION_FORWARD_ARGS(NativePeriodicCondition)

  NativePeriodicCondition() = default;

  void initialize() override {
    // call parent initialize or parameters will not be registered
    Condition::initialize();
    recess_period_ns_ = recess_period_.get();
  };

  void setup(ComponentSpec& spec) override {
    spec.param(recess_period_,
               "recess_period",
               "Recess Period",
               "Recession period in nanoseconds",
               static_cast<int64_t>(0));
  }

  void check(int64_t timestamp, SchedulingStatusType* status_type,
             int64_t* target_timestamp) const override {
    if (status_type == nullptr) {
      throw std::runtime_error(
          fmt::format("Condition '{}' received nullptr for status_type", name()));
    }
    if (target_timestamp == nullptr) {
      throw std::runtime_error(
          fmt::format("Condition '{}' received nullptr for target_timestamp", name()));
    }
    if (!next_target_.has_value()) {
```

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```
      *status_type = SchedulingStatusType::kReady;
      *target_timestamp = timestamp;
      return;
    }
    *target_timestamp = next_target_.value();
    *status_type = timestamp > *target_timestamp ? SchedulingStatusType::kReady
                                                 : SchedulingStatusType::kWaitTime;
  };

  void on_execute(int64_t timestamp) override {
    if (next_target_.has_value()) {
      next_target_ = next_target_.value() + recess_period_ns_;
    } else {
      next_target_ = timestamp + recess_period_ns_;
    }
  };

  void update_state([[maybe_unused]] int64_t timestamp) override {
    // no-op for this condition
  };

 private:
  Parameter<int64_t> recess_period_;

  int64_t recess_period_ns_ = 0;
  std::optional<int64_t> next_target_ = std::nullopt;
};

}  // namespace holoscan::conditions

class App : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    auto tx = make_operator<ops::PingTxOp>(
        "tx",
        make_condition<CountCondition>("count-condition", 5),
        make_condition<conditions::NativePeriodicCondition>(
            "dummy-condition", Arg("recess_period", static_cast<int64_t>(200'000'000))));

    auto rx = make_operator<ops::PingRxOp>("rx");

    add_flow(tx, rx);
  }
};

int main([[maybe_unused]] int argc, char** argv) {
  auto app = holoscan::make_application<App>();

  app->run();

```

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```
  return 0;
}
```

Python

Code Snippet: examples/conditions/native/python/ping_periodic_native.py

Listing 14.2: examples/conditions/native/python/ping_periodic_native.py

```python
from holoscan.conditions import CountCondition
from holoscan.core import Application, ComponentSpec, Condition, SchedulingStatusType
from holoscan.operators import PingRxOp, PingTxOp

# Now define a simple application using the operators defined above


class NativePeriodicCondition(Condition):
    """Example native Python periodic condition

    This behaves like holoscan.conditions.PeriodicCondition (which wraps an
    underlying C++ class). It is simplified in that it does not support a
    separate `policy` kwarg.

    Parameters
    ----------
    fragment: holoscan.core.Fragment
        The fragment (or Application) to which this condition will belong.
    recess_period : int, optional
        The time to wait before an operator can execute again (units are in
        nanoseconds).
    """

    def __init__(self, fragment, *args, recess_period=0, **kwargs):
        self.recess_period_ns = recess_period
        self.next_target = -1
        super().__init__(fragment, *args, **kwargs)

    # Could add a `recess_period` Parameter via `setup` like in the following
    #
    #   def setup(self, ComponentSpec: spec):
    #       spec.param("recess_period", 0)
    #
    # and then configure that parameter in `initialize`, but for Python it is
    # easier to just add parameters to `__init__` as shown above.

    def setup(self, spec: ComponentSpec):
        print("** native condition setup method called **")

    def initialize(self):
        print("** native condition initialize method called **")

```

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```python
    def update_state(self, timestamp):
        print("** native condition update_state method called **")

    def check(self, timestamp):
        print("** native condition check method called **")
        # initially ready when the operator hasn't been called previously
        if self.next_target < 0:
            return (SchedulingStatusType.READY, timestamp)

        # return WAIT_TIME and the timestamp if the specified `recess_period` hasn't been␣
↪reached
        status_type = (
            SchedulingStatusType.READY
            if (timestamp > self.next_target)
            else SchedulingStatusType.WAIT_TIME
        )
        return (status_type, self.next_target)

    def on_execute(self, timestamp):
        print("** native condition on_execute method called **")
        if self.next_target > 0:
            self.next_target = self.next_target + self.recess_period_ns
        else:
            self.next_target = timestamp + self.recess_period_ns


class MyPingApp(Application):
    def compose(self):
        # Configure the operators. Here we use CountCondition to terminate
        # execution after a specific number of messages have been sent.
        # PeriodicCondition is used so that each subsequent message is
        # sent only after a period of 200 milliseconds has elapsed.
        tx = PingTxOp(
            self,
            CountCondition(self, 10),
            NativePeriodicCondition(self, recess_period=200_000_000),
            name="tx",
        )
        rx = PingRxOp(self, name="rx")

        # Connect the operators into the workflow:  tx -> rx
        self.add_flow(tx, rx)


def main():
    app = MyPingApp()
    app.run()


if __name__ == "__main__":
    main()
```

In this application, two operators are created: `PingTxOp` (C++ / Python).

1. The tx operator is a source operator that emits an integer value each time it is evoked.
2. The rx operator is a sink operator that receives one value from the tx operator.

One custom condition, NativePeriodicCondition is created by inheriting from the Condition (C++/Python) class. This condition is a simplified version of the provided PeriodicCondition (C++/Python) (it does not implement the policy argument and only accepts an integer valued recess_period). We only create this condition to have a simple case to illustrate how a custom condition can be created.

The setup method of NativePeriodicCondition defines a single parameter named "recess_period", which represents the amount of time in nanoseconds that an operator will have to wait after executing before it can execute again.

In defining the initialize method, note that we start by calling initialize (C++/Python) so that we can get the value for the built in "recess_period" parameter. This initialize method then sets the initial state of the private member variables for this operator.

The check method is implemented to set type to SchedulingStatusType::kReady (C++) / SchedulingStatusType.READY (Python) if the specified period has elapsed. Otherwise, it sets the target_timestamp and sets type to SchedulingStatusType::kWaitTime (C++) / SchedulingStatusType.WAIT_TIME (Python). In this case kWaitTime is used because we know specifically what the target timestamp is. Note that for other types of conditions, we may not know the specific time at which the condition will be satisfied. In such a case where a target timestamp isn't known, one should instead set the status to kWait (C++) / WAIT (Python) and would not need to set target_timestamp. There is also a kWaitEvent (C++) / WAIT_EVENT (Python) state which can be used, but this is less common. Currently only the built-in AsynchronousCondition uses this status type. Finally, if we wanted to indicate that an operator would never execute again, we would return kNever (C++) / NEVER (Python) (a concrete example that uses never is the CountCondition (C++/Python) which sets that state once the specified count has been reached).

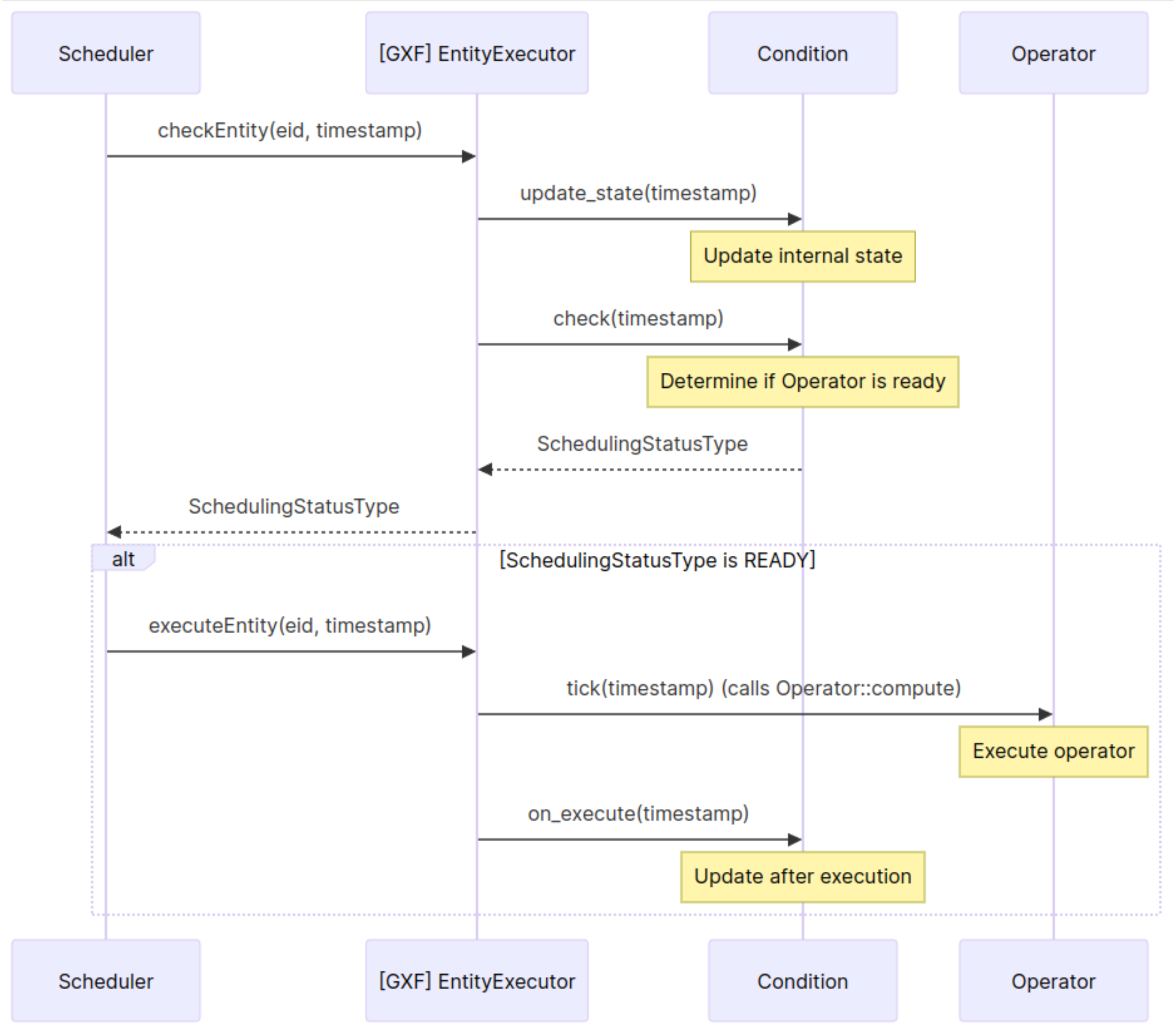
The on_execute method sets the internal next_target_ timestamp to the timestamp passed in. Because the underlying GXF framework calls this method immediately after Operator::compute, this is setting the period waited by this condition to be from the time when the prior call to compute completed.

The update_state method was not needed for this operator. This method is always called immediately prior to check and sometimes conditions choose to call it from the on_execute method. It is intended to perform some update of the internal state of the condition based on the timestamp at the time it is called.

For the C++ API, we can construct a shared pointer to an instance of the condition using the make_condition method. That condition can then be passed to the make_operator method for the operator the condition will apply to (in this case PingTxOp). For the Python API, we instead directly pass the constructed NativePeriodicCondition as a positional argument to the tx operator.

Condition Evaluation Timing Diagram

To better understand when a condition's `check`, `update_state` and `on_execute` methods would be called by the underlying GXF entity executor, please see the following diagram.



It can be seen that when checking if an operator is ready to execute the `Condition::update_state` method will be called immediately before `Condition::check`. If the check was successful (across the combination of all conditions on the operator), then the compute method would be called for that operator. The `Condition::on_execute` method is only called once compute completes.

Creating a custom condition involving transmitter or receiver queues

Some condition types depend on the state of the receiver or transmitter queues corresponding to an input or output port of an operator. This type of condition can also be created as a native condition. An illustration of this for an equivalent of `MessageAvailableCondition` is given in a second example. See **C++:** **examples/conditions/native/cpp/message_available_native.cpp**, **Python:** **examples/conditions/native/python/message_available_native.py**.

The primary additional consideration in designing such a message-based condition is how to retrieve the `Receiver` (`C++`/`Python`) or `Transmitter` (`C++`/`Python`) object for use in the native Condition's methods.

C++

In the case of a native C++ condition, a parameter of type `Parameter<std::shared_ptr<holoscan::Receiver>> receiver_` should be defined as shown on lines 114 and 67-71. Methods to query the queue size can then be used as demonstrated for the `check_min_size` method on lines 109-112.

Code Snippet: **examples/conditions/native/cpp/message_available_native.cpp**

Listing 14.3: examples/conditions/native/cpp/message_available_native.cpp

```
55 class NativeMessageAvailableCondition : public Condition {
56  public:
57   HOLOSCAN_CONDITION_FORWARD_ARGS(NativeMessageAvailableCondition)
58 
59   NativeMessageAvailableCondition() = default;
60 
61   void initialize() override {
62     // call parent initialize or parameters will not be registered
63     Condition::initialize();
64   };
65 
66   void setup(ComponentSpec& spec) override {
67     spec.param(receiver_,
68                "receiver",
69                "Receiver",
70                "The scheduling term permits execution if this channel has at least a␣
↪given "
71                "number of messages available.");
72     spec.param(min_size_,
73                "min_size",
74                "Minimum size",
75                "The condition permits execution if the given receiver has at least the␣
↪given "
76                "number of messages available",
77                static_cast<uint64_t>(1));
78   }
79 
80   void check(int64_t timestamp, SchedulingStatusType* type,
81              int64_t* target_timestamp) const override {
82     if (type == nullptr) {
83       throw std::runtime_error(fmt::format("Condition '{}' received nullptr for type",␣
↪name()));
84     }
```

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```cpp
    if (target_timestamp == nullptr) {
      throw std::runtime_error(
          fmt::format("Condition '{}' received nullptr for target_timestamp", name()));
    }
    *type = current_state_;
    *target_timestamp = last_state_change_;
  };

  void on_execute(int64_t timestamp) override { update_state(timestamp); };

  void update_state(int64_t timestamp) override {
    const bool is_ready = check_min_size();
    if (is_ready && current_state_ != SchedulingStatusType::kReady) {
      current_state_ = SchedulingStatusType::kReady;
      last_state_change_ = timestamp;
    }

    if (!is_ready && current_state_ != SchedulingStatusType::kWait) {
      current_state_ = SchedulingStatusType::kWait;
      last_state_change_ = timestamp;
    }
  };

 private:
  bool check_min_size() {
    auto recv = receiver_.get();
    return recv->back_size() + recv->size() >= min_size_.get();
  }

  Parameter<std::shared_ptr<holoscan::Receiver>> receiver_;
  Parameter<uint64_t> min_size_;

  SchedulingStatusType current_state_ =
      SchedulingStatusType::kWait;  // The current state of the scheduling term
  int64_t last_state_change_ = 0;   // timestamp when the state changed the last time
};
```

Python

In the case of a native Python condition, the name of the input or output port corresponding to the receiver or transmitter of interest should be passed to the constructor as shown on lines 78-79. The `holoscan.core.Condition.receiver()` (or `holoscan.core.Condition.transmitter()`) method can then be used to retrieve the actual `Receiver` (or `Transmitter`) object corresponding to a specific port name as shown on lines 94-98. Once that object has been retrieved, methods to query the queue size can be used as shown for the `check_min_size` method.

Code Snippet: examples/conditions/native/python/message_available_native.py

Listing 14.4: examples/conditions/native/python/message_available_native.py

```python
59 class NativeMessageAvailableCondition(Condition):
60     """Example native Python periodic condition
61 
```

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```
    This behaves like holoscan.conditions.MessageAvailableCondition (which
    wraps an underlying C++ class). It is simplified in that it does not
    support a separate `policy` kwarg.

    Parameters
    ----------
    fragment : holoscan.core.Fragment
        The fragment (or Application) to which this condition will belong.
    port_name : str
        The name of the input port on the operator whose Receiver queue this condition␣
↪will apply
        to.
    min_size : int, optional
        The number of messages that must be present on the specified input port before␣
↪the
        operator is allowed to execute.
    """

    def __init__(self, fragment, port_name: str, *args, min_size: int = 1, **kwargs):
        self.port_name = port_name

        if not isinstance(min_size, int) or min_size <= 0:
            raise ValueError("min_size must be a positive integer")
        self.min_size = min_size

        # The current state of the scheduling term
        self.current_state = SchedulingStatusType.WAIT
        # timestamp when the state changed the last time
        self.last_state_change_ = 0
        super().__init__(fragment, *args, **kwargs)

    def setup(self, spec: ComponentSpec):
        print("** native condition setup method called **")

    def initialize(self):
        print("** native condition initialize method called **")
        self.receiver_obj = self.receiver(self.port_name)
        if self.receiver_obj is None:
            raise RuntimeError(f"Receiver for port '{self.port_name}' not found")

    def check_min_size(self):
        return self.receiver_obj.back_size + self.receiver_obj.size >= self.min_size

    def update_state(self, timestamp):
        print("** native condition update_state method called **")
        is_ready = self.check_min_size()
        if is_ready and self.current_state != SchedulingStatusType.READY:
            self.current_state = SchedulingStatusType.READY
            self.last_state_change = timestamp
        if not is_ready and self.current_state != SchedulingStatusType.WAIT:
            self.current_state = SchedulingStatusType.WAIT
            self.last_state_change = timestamp
```

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```python

    def check(self, timestamp):
        print("** native condition check method called **")
        return self.current_state, self.last_state_change

    def on_execute(self, timestamp):
        print("** native condition on_execute method called **")
        self.update_state(timestamp)
```

Override behavior for default Operator port conditions

The *section on customizing input and output ports*, explains that when a user adds a port without specifying any condition in `Operator::setup`, a default one is added. This default is a `MessageAvailableCondition` for input ports or a `DownstreamMessageAffordableCondition` for output ports).

If the user has supplied their own `Condition` to `make_operator` (C++) or as a positional argument to the operator constructor (Python) and that condition has a “receiver” or “transmitter” argument corresponding to an Operator port name, then a default condition should **not** be added to that port. This is done to avoid having multiple, potentially conflicting conditions on the same port. However, if the `Operator::setup` method **explicitly** specifies a condition via a call to `IOSpec::condition`, then that explicit condition would still be added to the port in addition to any other user-supplied one.

Creating Python bindings for a custom C++ condition

To expose a custom C++ condition to Python, it can be wrapped using pybind11 just like any other `Condition` class. For several examples, see the bindings for built-in conditions. The only difference for binding a custom condition vs. the examples in that folder is that custom conditions should use `holoscan::Condition` instead of `holoscan::gxf::GXFCondition` in the list of classes passed to the `py::class_` call.

CHAPTER

FIFTEEN

DYNAMIC FLOW CONTROL

Dynamic Flow Control is a feature introduced in Holoscan SDK v3.0 that allows operators to modify their connections with other operators at runtime. This enables creating complex workflows with conditional branching, loops, and dynamic routing patterns.

15.1 Overview

Traditional static workflows in Holoscan define fixed connections between operators at application composition time. Dynamic Flow Control extends this by allowing operators to:

- Modify their connections during execution
- Route data conditionally to different operators
- Create loops and iterative patterns
- Implement complex branching logic

Common use cases include:

- Conditional processing pipelines
- Adaptive workflow routing
- Iterative processing with dynamic termination
- Error handling and recovery flows

15.2 Quick Start

Here's a simple example to get started with Dynamic Flow Control in Holoscan:

15.2.1 1. Basic Sequential Flow

The simplest use of dynamic flow control is creating a sequential chain of operators that doesn't have any input or output ports:

C++

```
#include <holoscan/holoscan.hpp>

// Define a simple operator
class SimpleOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(SimpleOp)
  SimpleOp() = default;

  void compute(holoscan::InputContext&, holoscan::OutputContext&,
               holoscan::ExecutionContext&) override {
    // Simple computation
    HOLOSCAN_LOG_INFO("Executing {}", name());
  }
};

// Define the application
class SimpleSequentialApp : public holoscan::Application {
 public:
  void compose() override {
    // Create operators
    auto op1 = make_operator<SimpleOp>("op1");
    auto op2 = make_operator<SimpleOp>("op2");

    // Connect operators sequentially
    add_flow(start_op(), op1);  // Start with op1
    add_flow(op1, op2);         // Then op2
  }
};

int main(int argc, char** argv) {
  auto app = holoscan::make_application<SimpleSequentialApp>();
  app->run();
  return 0;
}
```

Python

```
from holoscan.core import Application, Operator


class SimpleOp(Operator):
    def compute(self, op_input, op_output, context):
        # Simple computation
        print(f"Executing {self.name}")


class SimpleSequentialApp(Application):
    def compose(self):
        # Create operators
```

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```
        op1 = SimpleOp(self, name="op1")
        op2 = SimpleOp(self, name="op2")

        # Connect operators sequentially
        self.add_flow(self.start_op(), op1)  # Start with op1
        self.add_flow(op1, op2)  # Then op2


def main():
    app = SimpleSequentialApp()
    app.run()


if __name__ == "__main__":
    main()
```

15.2.2 2. Basic Conditional Flow

Here's a simple example of conditional routing between operators:

C++

```
#include <holoscan/holoscan.hpp>

// Define a simple operator with a value
class SimpleOp : public holoscan::Operator {
 public:
  HOLOSCAN_OPERATOR_FORWARD_ARGS(SimpleOp)

  SimpleOp() = default;

  void setup(holoscan::OperatorSpec& spec) override {}

  void compute(holoscan::InputContext&, holoscan::OutputContext&,
               holoscan::ExecutionContext&) override {
    value_++;  // Increment value each time
    HOLOSCAN_LOG_INFO("Executing {} with value {}", name(), value_);
  }

  int get_value() const { return value_; }

 private:
  int value_ = 0;
};

// Define the application
class SimpleConditionalApp : public holoscan::Application {
 public:
  void compose() override {
    // Create operators
```

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```cpp
    auto op1 = make_operator<SimpleOp>("op1", make_condition<holoscan::CountCondition>
↪(3));
    auto path_a = make_operator<SimpleOp>("path_a");
    auto path_b = make_operator<SimpleOp>("path_b");

    // Define possible flows
    add_flow(op1, path_a);
    add_flow(op1, path_b);

    // Set dynamic flow based on condition
    set_dynamic_flows(op1, [path_a, path_b](const std::shared_ptr<holoscan::Operator>&␣
↪op) {
      auto simple_op = std::static_pointer_cast<SimpleOp>(op);
      if (simple_op->get_value() % 2 == 0) {
        simple_op->add_dynamic_flow(path_a);  // Even values go to path_a
      } else {
        simple_op->add_dynamic_flow(path_b);  // Odd values go to path_b
      }
    });
  }
};

int main(int argc, char** argv) {
  auto app = holoscan::make_application<SimpleConditionalApp>();
  app->run();
  return 0;
}
```

Python

```python
from holoscan.conditions import CountCondition
from holoscan.core import Application, Operator


class SimpleOp(Operator):
    def __init__(self, *args, **kwargs):
        self.value = 0
        super().__init__(*args, **kwargs)

    def compute(self, op_input, op_output, context):
        self.value += 1  # Increment value each time
        print(f"Executing {self.name} with value {self.value}")


class SimpleConditionalApp(Application):
    def compose(self):
        # Create operators
        op1 = SimpleOp(self, CountCondition(self, count=3), name="op1")
        path_a = SimpleOp(self, name="path_a")
        path_b = SimpleOp(self, name="path_b")
```

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```python
        # Define possible flows
        self.add_flow(op1, path_a)
        self.add_flow(op1, path_b)

        # Set dynamic flow based on condition
        def route_flow(op):
            if op.value % 2 == 0:
                op.add_dynamic_flow(path_a)  # Even values go to path_a
            else:
                op.add_dynamic_flow(path_b)  # Odd values go to path_b

        self.set_dynamic_flows(op1, route_flow)


def main():
    app = SimpleConditionalApp()
    app.run()


if __name__ == "__main__":
    main()
```

15.2.3 Key Points to Remember:

1. Optionally use `start_op()` (C++/`Python`) to get the initial operator in your flow
2. Connect operators with `add_flow()`
3. Use `set_dynamic_flows()` (C++/`Python`) to define runtime routing logic
4. Implement flow control logic in the callback function passed to `set_dynamic_flows()` (C++/`Python`)

- The callback function takes an operator as input and returns void
- The callback function can add dynamic flows using the operator's `add_dynamic_flow()` (C++/`Python`) methods

For more complex patterns and detailed explanations, see the sections below.

15.3 Key Concepts

15.3.1 Input and Output Execution Ports

Before Holoscan SDK v3.0, operators needed input and output ports to be connected via `add_flow()` and there is no way to specify the execution dependency if the operator does not have any input or output ports.

However, in some cases, the requirements were different:

- An 'execution order dependency' was needed instead of a 'data flow dependency'.
- Execution control was required rather than keeping a node running continuously.
- The pipeline should run only once unless explicitly specified to loop.

To address these needs, Holoscan SDK v3.0 introduced implicit input/output 'execution ports' (`__input_exec__` / `__output_exec__`), inspired by Unreal Engine's Blueprints (particularly execution pins).

The output execution port (`__output_exec__`. `holoscan::Operator::kOutputExecPortName` in C++ and `holoscan.core.Operator.OUTPUT_EXEC_PORT_NAME` in Python) of a source operator and the input execution port (`__input_exec__`, `holoscan::Operator::kInputExecPortName` in C++ and `holoscan.core.Operator.INPUT_EXEC_PORT_NAME` in Python) of a target operator are implicitly added when **both** of the following are true:

- Two operators are connected using `add_flow()` without specifying a port map.
- The target operator does not have an explicit input port.

Note: Both the source and target operators must be native Holoscan operators. Attempting to connect a *GXF Operator* to a native Holoscan operator, or vice versa, with an empty port map will result in an error.

During execution, after the source operator's `compute()` method is called, the Holoscan executor emits an empty message (`Entity`) to the implicit output execution port as a signal. This can then trigger the target operator's execution, as the Holoscan executor attaches a `MessageAvailableCondition` to the target operator's implicit input execution port. Before the target operator's `compute()` method runs, the executor collects (pops) all messages from the implicit input execution port, enabling execution dependencies without requiring explicit input and output execution ports.

Starting with Holoscan SDK v3.0, operators can be connected via `add_flow()` without the need for explicit input and output execution ports, allowing for more flexible and dynamic operator connections.

15.3.2 Start Operator

In Holoscan, when the workflow graph is executed, root operators who do not have any input ports are first executed, and unless any condition is specified to the root operator (such as `CountCondition` or `PeriodicCondition`), it will execute continuously.

Inspired by LangGraph's start node (langgraph.graph.START), Holoscan SDK v3.0 introduces a new concept of the **start operator**.

The **start operator** is the first operator in an application fragment, serving as the entry point to the workflow. It is simply the first operator added to the fragment.

This operator is named `<|start|>` and has a condition of `CountCondition(1)`, ensuring it executes only once. Other entry operators that initiate fragment execution should connect to this operator.

In Holoscan, you can retrieve the start operator by calling `start_op()` (C++/Python) within the `compose()` method. If this method is called multiple times, it will return the same start operator

This API is available in both C++ and Python (see flow_control/sequential for an example):

C++

```
class SequentialExecutionApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the operators
    auto node1 = make_operator<SimpleOp>("node1");
    auto node2 = make_operator<SimpleOp>("node2");
    auto node3 = make_operator<SimpleOp>("node3");
```

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```
    // Define the three-operator workflow
    add_flow(start_op(), node1);
    add_flow(node1, node2);
    add_flow(node2, node3);
  }
};
```

Python

```python
class SequentialExecutionApp(Application):
    def compose(self):
        # Define the operators
        node1 = SimpleOp(self, name="node1")
        node2 = SimpleOp(self, name="node2")
        node3 = SimpleOp(self, name="node3")

        # Define the three-operator workflow
        self.add_flow(self.start_op(), node1)
        self.add_flow(node1, node2)
        self.add_flow(node2, node3)
```

In this example, the start operator is connected to `node1`, making `node1` the first operator to execute. Since the start operator has a condition of `CountCondition(1)`, it will only trigger once, ensuring `node1` runs a single time.

In this example, each node (operator) is executed sequentially and executed only once. The `start_op()` method retrieves the start operator, which is connected to `node1`. This makes `node1` the first operator to execute. After `node1` completes its execution, `node2` is triggered, followed by `node3`. The `CountCondition(1)` in the `start_op()` method ensures that each operator in the sequence runs a single time, maintaining a clear and predictable flow of execution.

15.3.3 Setting Dynamic Flows

The `set_dynamic_flows()` (`C++`/`Python`) method allows for dynamic flow control in a Holoscan application. This method sets a callback function that determines the flow of execution based on the state of the operator at runtime.

In the example from flow_control/conditional, the `set_dynamic_flows()` method is used to dynamically control the flow between `node1`, `node2`, and `node4` based on the value of `node1`. The callback function checks the value of `node1` and adds a dynamic flow to either `node2` or `node4`:

```
Node Graph:

      node1 (launch twice)
      /   \
  node2   node4
    |       |
  node3   node5
```

C++

```cpp
class ConditionalExecutionApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the operators
    auto node1 = make_operator<SimpleOp>("node1", make_condition<CountCondition>(2));
    auto node2 = make_operator<SimpleOp>("node2");
    auto node3 = make_operator<SimpleOp>("node3");
    auto node4 = make_operator<SimpleOp>("node4");
    auto node5 = make_operator<SimpleOp>("node5");

    add_flow(node1, node2);
    add_flow(node2, node3);
    add_flow(node1, node4);
    add_flow(node4, node5);

    set_dynamic_flows(node1, [node2, node4](const std::shared_ptr<Operator>& op) {
      auto simple_op = std::static_pointer_cast<SimpleOp>(op);
      if (simple_op->get_value() % 2 == 1) {
        simple_op->add_dynamic_flow(node2);
      } else {
        simple_op->add_dynamic_flow(node4);
      }
    });
  }
};
```

Python

```python
class ConditionalExecutionApp(Application):
    def compose(self):
        # Define the operators
        node1 = SimpleOp(self, CountCondition(self, count=2), name="node1")
        node2 = SimpleOp(self, name="node2")
        node3 = SimpleOp(self, name="node3")
        node4 = SimpleOp(self, name="node4")
        node5 = SimpleOp(self, name="node5")

        self.add_flow(node1, node2)
        self.add_flow(node2, node3)
        self.add_flow(node1, node4)
        self.add_flow(node4, node5)

        def dynamic_flow_callback(op):
            if op.value % 2 == 1:
                op.add_dynamic_flow(node2)
            else:
                op.add_dynamic_flow(node4)
```

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```
        self.set_dynamic_flows(node1, dynamic_flow_callback)
```

In the above example, the `set_dynamic_flows()` (C++/Python) methods are used to define and manage dynamic workflows in the application.

The `set_dynamic_flows()` (C++/Python) method takes an operator and a callback function as arguments. The callback function is called with the operator as an argument. Inside the callback function, the `add_dynamic_flow()` (C++/Python) method is used to add a dynamic flow to the operator.

In the example, the callback function checks the value of `node1` and adds a dynamic flow to either `node2` or `node4`.

The `add_dynamic_flow()` (C++/Python) method has several overloads to support different ways of adding dynamic flows:

C++

```
/// Basic connection using default output port. This is the simplest form for connecting
/// two operators when you only need to specify the destination.
void add_dynamic_flow(const std::shared_ptr<Operator>& next_op,
                      const std::string& next_input_port = "");

/// Connection with explicit output port specification. Use this when the source operator
/// has multiple output ports and you need to specify which one to use.
void add_dynamic_flow(const std::string& curr_output_port,
                      const std::shared_ptr<Operator>& next_op,
                      const std::string& next_input_port = "");

/// Connection using a FlowInfo object, which encapsulates all connection details␣
↪including:
/// - Source operator and its output port specification
/// - Destination operator and its input port specification
/// - Port names and associated IOSpecs
void add_dynamic_flow(const std::shared_ptr<FlowInfo>& flow);

/// Batch connection using multiple FlowInfo objects. Use this to set up multiple
/// connections in a single call, which is more efficient than making multiple
/// individual connections.
void add_dynamic_flow(const std::vector<std::shared_ptr<FlowInfo>>& flows);
```

Python

```
# 1. Basic connection using default output port. This is the simplest form for connecting
#    two operators when you only need to specify the destination.
op.add_dynamic_flow(next_op: Operator, next_input_port_name: str = '')

# 2. Connection with explicit output port specification. Use this when the source␣
↪operator
#    has multiple output ports and you need to specify which one to use.
op.add_dynamic_flow(curr_output_port_name: str, next_op: Operator, next_input_port_name:␣
↪str = '')
```

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```
# 3. Connection using a FlowInfo object, which encapsulates all connection details␣
↪including:
#   - Source operator and its output port specification
#   - Destination operator and its input port specification
#   - Port names and associated IOSpecs
#
# This is useful for complex connections or when reusing connection patterns.
op.add_dynamic_flow(flow: FlowInfo)

# 4. Batch connection using multiple FlowInfo objects. Use this to set up multiple
#    connections in a single call, which is more efficient than making multiple
#    individual connections.
op.add_dynamic_flow(flows: list[FlowInfo])
```

The simple form of `add_dynamic_flow()` (C++/Python) is passing just the next operator (and optionally the next input port name).

If the next operator does not have any explicit input, you can omit the next input port name. In this case, current operator's implicit output execution port will be connected to the next operator's implicit input execution port.

15.3.4 Flow Information

The `FlowInfo` (C++/Python) class represents information about a connection between operators and takes the following arguments in the constructor:

- `curr_operator`: The source operator of the flow connection
- `curr_output_port`: The name of the output port on the source operator
- `next_operator`: The destination operator of the flow connection
- `next_input_port`: The name of the input port on the destination operator

Inside the callback function, you can use the `find_flow_info()` (C++/Python) method and `find_all_flow_info()` (C++/Python) method to find the `FlowInfo` object(s) that matches the predicate.

The following example shows how to find the `FlowInfo` object(s) that matches the predicate:

C++

```cpp
class ConditionalExecutionApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Define the operators
    auto node1 = make_operator<SimpleOp>("node1", make_condition<CountCondition>(2));
    auto node2 = make_operator<SimpleOp>("node2");
    auto node3 = make_operator<SimpleOp>("node3");
    auto node4 = make_operator<SimpleOp>("node4");
    auto node5 = make_operator<SimpleOp>("node5");

    add_flow(node1, node2);
```

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```
    add_flow(node2, node3);
    add_flow(node1, node4);
    add_flow(node4, node5);

    // // If you want to add all the next flows, you can use the following code:
    // set_dynamic_flows(
    //     node1, [](const std::shared_ptr<Operator>& op) { op->add_dynamic_flow(op->
↪next_flows());
    //     });

    set_dynamic_flows(node1, [](const std::shared_ptr<Operator>& op) {
      auto simple_op = std::static_pointer_cast<SimpleOp>(op);
      static const auto& node2_flow = op->find_flow_info(
          [](const auto& flow) { return flow->next_operator->name() == "node2"; });
      static const auto& node4_flow = op->find_flow_info(
          [](const auto& flow) { return flow->next_operator->name() == "node4"; });
      //static const auto& all_next_flows = op->find_all_flow_info(
      //    [](const auto& flow) { return true; });

      //std::cout << "All next flows: ";
      //for (const auto& flow : all_next_flows) {
      //  std::cout << flow->next_operator->name() << " ";
      //}
      //std::cout << std::endl;

      if (simple_op->get_value() % 2 == 1) {
        simple_op->add_dynamic_flow(node2_flow);
      } else {
        simple_op->add_dynamic_flow(node4_flow);
      }
    });
  }
};
```

Python

```python
class ConditionalExecutionApp(Application):
    def compose(self):
        # Define the operators
        node1 = SimpleOp(self, CountCondition(self, count=2), name="node1")
        node2 = SimpleOp(self, name="node2")
        node3 = SimpleOp(self, name="node3")
        node4 = SimpleOp(self, name="node4")
        node5 = SimpleOp(self, name="node5")

        self.add_flow(node1, node2)
        self.add_flow(node2, node3)
        self.add_flow(node1, node4)
        self.add_flow(node4, node5)
```

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```
        # # If you want to add all the next flows, you can use the following code:
        # self.set_dynamic_flows(node1, lambda op: op.add_dynamic_flow(op.next_flows))

        # This is another way to add dynamic flows based on the next operator name
        def dynamic_flow_callback(op):
            node2_flow = op.find_flow_info(lambda flow: flow.next_operator.name == "node2
↪")
            node4_flow = op.find_flow_info(lambda flow: flow.next_operator.name == "node4
↪")

            # all_next_flows = op.find_all_flow_info(lambda flow: True)
            # print(f"All next flows: {[flow.next_operator.name for flow in all_next_
↪flows]}")

            if op.value % 2 == 1:
                op.add_dynamic_flow(node2_flow)
            else:
                op.add_dynamic_flow(node4_flow)

        self.set_dynamic_flows(node1, dynamic_flow_callback)
```

In the above example, instead of using `op.add_dynamic_flow(node2)` or `op.add_dynamic_flow(node4)`, we use `op.add_dynamic_flow(node2_flow)` or `op.add_dynamic_flow(node4_flow)`. And the `node2_flow` and `node4_flow` are `FlowInfo` objects that are found using the `find_flow_info()` method.

The `find_flow_info()` (`C++`/`Python`) method takes a predicate as an argument and returns a `FlowInfo` object that matches the predicate.

The `find_all_flow_info()` (`C++`/`Python`) method takes a predicate as an argument and returns a vector (list) of `FlowInfo` objects that match the predicate.

If you want to get a vector of all the next flows, you can use `op->next_flows()` in C++ or `op.next_flows` in Python.

15.4 Flow Control Pattern Selection Guide

Here's when to choose different flow control patterns:

start_op() + Cyclic Flow

- Best for: Dynamic routing, feedback loops, runtime-adaptive flows
- Use when: Flow patterns depend on data content or need to change during execution
- Advantages: Flexible, handles complex routing
- Trade-offs: More complex to debug, slightly higher runtime overhead

Generator (root operator) with condition (CountCondition, PeriodicCondition, etc.)

- Best for: Fixed iteration counts, simple linear flows
- Use when: Number of iterations is known in advance (or infinite), static flow patterns
- Advantages: Simple to implement, better performance, easier to debug
- Trade-offs: Less flexible, cannot adapt to runtime conditions

15.5 Examples

Please see full examples under the `examples/flow_control` folder in the Holoscan SDK repository for more detailed implementations and use cases.

Note that the execution control examples are also related to the dynamic behavior of operators, and are available in the execution_control directory.

15.6 Best Practices

1. **Clear Flow Logic**: Keep dynamic flow logic clear and well-documented. Use meaningful names for operators and document the conditions that trigger different flow paths.
2. **Error Handling**: Handle edge cases in flow callbacks. Consider what happens if expected operators are not available or if flow conditions are invalid.
3. **State Management**: Be careful with shared state in dynamic flows. Ensure thread safety when multiple operators access shared resources.
4. **Performance**: Consider the overhead of frequent flow changes. Cache flow information when possible and avoid unnecessary flow modifications.
5. **Testing**: Test all possible flow paths thoroughly. Create unit tests that verify both normal operation and edge cases for each flow pattern.

15.7 Limitations

The dynamic flow control feature has the following limitations:

- It can only be used to connect operators within the same fragment. For inter-fragment flows (connecting operators across different fragments), explicit non-execution ports must be used instead of dynamic flows.
- Both the source and target operators must be native Holoscan operators (not *GXF Operators*).

CHAPTER

SIXTEEN

CUDA STREAM HANDLING IN HOLOSCAN APPLICATIONS

CUDA provides the concept of streams to allow for asynchronous concurrent execution on the GPU. Each stream is a sequence of commands that execute in order, but work launched on separate streams can potentially operate concurrently. Examples are running multiple kernels in separate streams or overlapping data transfers and kernel execution. See the Asynchronous Concurrent Execution section of the CUDA programming guide.

The `CudaStreamPool` class (`C++`/`Python`) is a resource that provides a mechanism for allocating CUDA streams from a pool of streams whose lifetime is managed by Holoscan. As of Holoscan v2.8, new APIs are provided to make use of dedicated CUDA streams easier for application authors. These APIs are intended as a replacement of the legacy `CudaStreamHandler` utility described in the note below.

Note: There is a legacy `CudaStreamHandler` utility class (provided via `#include "holoscan/utils/cuda_stream_handler.hpp"`) that made it possible to write a C++ operator that could make use of a `CudaStreamPool`. This class had some limitations:

- It required receiving messages as type `holoscan::gxf::Entity`.
- It required using `nvidia::gxf::Entity` and `nvidia::gxf::Handle` methods from the underlying GXF library.
- It was not available for native Python operators.

This existing utility is still provided for backwards compatibility and operators using it can continue to interoperate with those using the new APIs. However, we encourage operator authors to migrate to using the new APIs going forward.

16.1 Configuring a CUDA stream pool for an operator's internal use

---

Note: Starting from Holoscan v2.9, a default `CudaStreamPool` is added to all operators if the user did not otherwise provide one. This means that in most cases, it will not be necessary for the user to explicitly add a strea pool. The default stream pool has unbounded size, no flags set and a priority value of 0. In cases when the user wants to allocate streams with different flags or priority, the section below can be followed to add a customized stream pool to the operator.

The only case when a default stream pool would not be added is if the application (fragment) is running on a node without any CUDA-capable devices. In that case, since use of CUDA is not possible a default stream pool would not be added.

To enable an operator to allocate a CUDA stream, the user can pass a `CudaStreamPool` as in the following examples. The general pattern used for stream handling in Holoscan SDK is to have each Operator that wants to use a non-default stream have a `CudaStreamPool` assigned. That operator will then reserve a dedicated stream from the stream pool for use by any kernels launched by it. Multiple operators are allowed to use the same stream pool, with "max_size" of the shared pool equal to at least the number of Operators that are sharing it.

Note that the `CudaStreamPool` will manage the lifetimes of any CUDA streams used by the SDK. The user does not need typically need to explicitly call any CUDA APIs to create or destroy streams. Note that all streams from a single `CudaStreamPool` are on a single device (with CUDA id as passed to the "dev_id" argument). If the workflow involves operators that run on separate CUDA devices, those operators must use separate stream pools configured for the corresponding device.

C++

```
// The code below would appear within `Application::compose` (or `Fragment::compose`)

// Create a stream pool with a 5 streams capacity (5 operators could share the same pool)
const auto cuda_stream_pool = make_resource<CudaStreamPool>("stream_pool",
                                                            Arg("dev_id", 0),
                                                            Arg("stream_flags", 0u),
                                                            Arg("stream_priority", 0),
                                                            Arg("reserved_size", 1u),
                                                            Arg("max_size", 5u));

auto my_op = make_operator<MyOperator>("my_op", cuda_stream_pool, arg_list);

// Alternatively, the argument can be added via `add_arg` after operator construction
// auto my_op = make_operator<MyOperator>("my_op", arg_list);
// my_op->add_arg(cuda_stream_pool);
```

Note that the the legacy `CudaStreamHandler` utility did not support passing the stream pool in this way, but instead required that the user explicitly add a parameter to the operator's private data members.

```
private:
  // The legacy CudaStreamHandler required a "cuda_stream_pool" parameter.
  // The spec.param call in the Operator's `setup` method would use the name "cuda_stream_
↪pool"
  // for it
  Parameter<std::shared_ptr<CudaStreamPool>> cuda_stream_pool_{};
```

For backwards compatibility with prior releases, the built-in operators that were previously using the `CudaStreamHandler` utility class still offer this explicitly defined "cuda_stream_pool" parameter. It is not necessary for the user to add it to their own operators unless they prefer to explicitly use an `Arg` named "cuda_stream_pool" parameter when initializing the operator.

```
auto visualizer = make_operator<HolovizOp>(
    "visualizer",
    from_config("holoviz"),
    Arg("cuda_stream_pool", make_resource<CudaStreamPool>(0, 0, 0, 1, 5)));
```

Python

```python
# The code below would appear within `Application.compose` (or `Fragment.compose`)

# Create a stream pool with a 5 streams capacity (5 operators could share the same pool)
cuda_stream_pool = CudaStreamPool(
    self,
    name="stream_pool",
    dev_id=0,
    stream_flags=0,
    stream_priority=0,
    reserved_size=1,
    max_size=5,
)
my_op = MyOperator(self, cuda_stream_pool, name="my_op", **my_kwargs)

# Alternatively, the argument can be added via `add_arg` after operator construction
# auto my_op = MyOperator(self, name="my_op", **my_kwargs)
# my_op.add_arg(cuda_stream_pool)
```

The above is the recommended way for user-defined operators to add a `CudaStreamPool`. For purposes of backwards compatibility, the built-in operators of the SDK that already had a keyword-based `cuda_stream_pool` parameter continue to also allow passing the stream pool as in the following example:

```python
visualizer = HolovizOp(
  self,
  name="holoviz",
  cuda_stream_pool=CudaStreamPool(self, 0, 0, 0, 1, 5),
  **self.kwargs("holoviz"))
```

16.2 Sending stream information between operators

Because CUDA kernels are launched asynchronously by the host (CPU), it is possible for the `compute` method to return before the underlying computation on the GPU is complete (see a related warning regarding benchmarking in this scenario below). In this scenario, information about the stream that was used must be sent along with the data so that a downstream operator can handle any stream synchronization that is needed. For example, if an upstream kernel emitted a `Tensor` object immediately after launching a CUDA kernel, the downstream operator needs to be sure the kernel has completed before accessing the tensor's data.

The `CudaStreamPool` (C++/Python) class allocates `nvidia::gxf::CudaStream` objects behind the scenes. These stream objects exist as components in the entity-component system of the underlying GXF library. GXF defines an `nvidia::gxf::CudaStreamId` struct which contains the "component ID" corresponding to the stream. It is this `CudaStreamId` struct that actually gets transmitted along with each message emitted from an output port. The Holoscan application author is not expected to need to interact with either the `CudaStream` or `CudaStreamId` classes directly, but instead use the standard CUDA Runtime API `cudaStream_t` type that is returned by Holoscan's public stream handling methods described in the sections below. Methods like `receive_cuda_stream` (C++/Python) or `allocate_cuda_stream` (C++/Python) return a `cudaStream_t` that corresponds to an underlying `CudaStream` object. Similarly methods like `set_cuda_stream` (C++/Python) and `device_from_stream` (C++/Python) take a `cudaStream_t` as input, but only accept a `cudaStream_t` that corresponds to underlying `CudaStream` objects whose lifetime can be managed by the SDK.

The SDK provides several publicly accessible methods for working with streams that can be called from the `compute` method of an operator. These are described in detail below.

16.3 Simplified CUDA streams handling via `receive_cuda_stream`

In many cases, users will only need to use the `receive_cuda_stream` (C++/Python) method provided by `InputContext` in their `compute` method. This is because the method automatically manages multiple aspects of stream handling:

1. It automatically synchronizes any streams found on the named input port to the operator's internal CUDA stream

- The first time `compute` is called, an operator's internal CUDA stream would be allocated from the assigned `CudaStreamPool`. The same stream is then reused on all subsequent `compute` calls.
- There is a boolean flag which can also force synchronization to the default stream (false by default)

2. It returns the `cudaStream_t` corresponding to the operator's internal stream.

- The user should use this returned stream for any kernels or memory copy operations to be run on a non-default stream.

3. It sets the CUDA device corresponding to the stream returned in step 2 as the active CUDA device
4. This method automatically configures all output ports to emit the stream returned by step 2 as a component in each message sent.

- This ID will allow downstream operators to know what stream was used for any data received in this message.

Attention: Please insure that, for a given input port, `receive` is always called **before** `receive_cuda_stream`. This is necessary because the `receive` call is what actually receives the messages and allows the operator to know about any stream IDs found in messages on the input port. That `receive` method only records information internally about any streams that were found. The subsequent `receive_cuda_stream` call is needed to perform synchronization and return the `cudaStream_t` to which any input streams were synchronized.

Here is an example of the typical usage of this method from the built-in `BayerDemosaicOp`

C++

```cpp
// The code below would appear within `Operator::compute`

// Process input message
auto maybe_message = op_input.receive<gxf::Entity>("receiver");
if (!maybe_message || maybe_message.value().is_null()) {
  throw std::runtime_error("No message available");
}
auto in_message = maybe_message.value();

// Get the CUDA stream from the input message if present, otherwise generate one.
// This stream will also be transmitted on the "tensor" output port.
cudaStream_t cuda_stream = op_input.receive_cuda_stream("receiver", // input port name
                                                        true,       // allocate
                                                        false);     // sync_to_default

// assign the CUDA stream to the NPP stream context
npp_stream_ctx_.hStream = cuda_stream;
```

Python

Note that BayerDemosaicOp is implemented in C++ using code shown in the C++ tab, but this shows how the equivalent code would look in the Python API.

```python
# The code below would appear within `Operator.compute`

# Process input message
in_message = op_input.receive("receiver")
if in_message is None:
  raise RuntimeError("No message available")

# Get the CUDA stream from the input message if present, otherwise generate one.
# This stream will also be transmitted on the "tensor" output port.
cuda_stream_ptr = op_input.receive_cuda_stream("receiver", allocate=True, sync_to_
↪default=False)

# can then use cuda_stream_ptr to create a `cupy.cuda.ExternalStream` context, for example
```

It can be seen that the call to `receive` occurs prior to the call to `receive_cuda_stream` for the "receiver" input port as required. Also note that unlike for the legacy `CudaStreamHandler` utility class, it is not required to use `gxf::Entity` in the "receive" call. That type is use by some built-in operators like `BayerDemosaicOp` as a way to support both the `nvidia::gxf::VideoBuffer` type and the usual `Tensor` type as inputs. If only `Tensor` was supported we could have used `receive<std::shared_ptr<Tensor>>` or `receive<TensorMap>` instead.

The second boolean argument to `receive_cuda_stream` defaults to true and indicates that the operator should allocate its own internal stream. This could be set to false to not allow the operator to allocate its own internal stream from the stream pool. See the note below on the details of how `receive_cuda_stream` behaves in that case.

There is also an optional third argument to `receive_cuda_stream` which is a boolean specifying whether synchronization of the input streams (and internal stream) to CUDA's default stream should also be performed. This option is `false` by default.

The above description of `receive_cuda_stream` is accurate when a `CudaStreamPool` has been passed to the operator in one of the ways *described above*. See the note below for additional detail on how this method operates if the operator is unable to allocate an internal stream because a `CudaStreamPool` was unavailable.

16.3.1 Avoiding additional synchronization from Python's CUDA Array Interface

Python applications converting between Holoscan's Tensor and 3rd party tensor objects often use the CUDA Array Interface. This interface by default performs its own explicit synchronization (described here). This may be unnecessary when using `receive_cuda_stream` which already synchronizes streams found on the input with the operator's internal stream. The environment variable `CUPY_CUDA_ARARAY_INTERFACE_SYNC` can be set to 0 to disable an additional synchronization by CuPy when creating a CUDA array from a holoscan Tensor via the array interface. Similarly, `HOLOSCAN_CUDA_ARRAY_INTERFACE_SYNC` can be set to 0 to disable synchronization by the array interface on the Holoscan side when creating a Holoscan tensor from a 3rd party tensor.

16.3.2 Using receive_cuda_stream without a stream pool available

This section describes the behavior of receive_cuda_stream in the case where no streams are available in the operator's CudaStreamPool (or the allocate argument of receive_cuda_stream was set to false). In this case, receive_cuda_stream will not be able to allocate a dedicated internal stream for the operator's own use. Instead, the cudaStream_t corresponding to the **first** stream found on the named input port will be returned and any additional streams on that input port would be synchronized to it. If a subsequent receive_cuda_stream call was made for another input port, any streams found on that second port are synchronized to the cudaStream_t that was returned by the first receive_cuda_stream call and the stream returned is that same cudaStream_t. In other words, the first stream found on the initial call to receive_cuda_stream will be repurposed as the operator's internal stream to which any other input streams are synchronized. This same stream will also be the one automatically emitted on the output ports.

In the case that there is no CudaStreamPool and there is no stream found for the input port (or by any prior receive_cuda_stream calls for another port), then receive_cuda_stream will return the default stream (cudaStreamDefault). No stream would be emitted on the output ports in this case.

16.4 InputContext: additional stream handling methods

The receive_cuda_streams (C++/Python) method is designed for advanced use cases where the application author needs to manually manage all aspects of stream synchronization, allocation, and emission of CUDA streams. Unlike receive_cuda_stream, this method does not perform synchronization, does not automatically allocate an internal CUDA stream, does not update the active CUDA device, and does not configure any stream to be emitted on output ports. Instead, it simply returns a std::vector<std::optional<cudaStream_t>>, which is a vector of size equal to the number of messages on the input port. Each value in the vector corresponds to the cudaStream_t specified by the message (or std::nullopt if no stream ID is found).

Note that as for receive_cuda_stream, it is important that any receive_cuda_streams call for a port is **after** the corresponding receive call for that same port. An example is given below

C++

```cpp
// The code below would appear within `Operator::compute`

// Process a "receivers" port (e.g. one having IOSpec::kAnySize) that may
// have an arbitrary number of connections, each of which may have sent a
// TensorMap.
auto maybe_tensors = op_input.receive<std::vector<Tensor>>("receivers");
if (!maybe_tensors) { throw std::runtime_error("No message available"); }
auto tensormaps = maybe_tensors.value();

// Get a length two vector of std::option<CudaStream_t> containing any streams
// found by the any of the above receive calls.
auto cuda_streams = op_input.receive_cuda_streams("receivers");
```

Python

```
# The code below would appear within `Operator.compute`

auto tensors = op_input.receive("receivers")
if tensors is None:
    raise RuntimeError("No message available on 'receivers' input")

cuda_stream_ptrs = op_input.receive_cuda_streams("receivers")
```

16.5 ExecutionContext: additional stream handling methods

The `allocate_cuda_stream` (`C++`/`Python`) method can be used to allocate additional CUDA streams from the Operator's `CudaStreamPool`. An `unexpected` (or `None` in Python) will be returned if there is no stream pool associated with the operator or if all streams in the stream pool were already in used. A user-provided stream name is given for the allocation so that for a given name, a new stream is only allocated the first time the method is called. The same stream is then reused on on any subsequent calls using the same name. Streams allocated in this way are not automatically emitted on the output ports. If this is needed, the user must specifically emit the stream IDs by calling `set_cuda_stream` for the output port **prior** to the call to `emit` for that port.

C++

```
// The code below would appear within `Operator::compute`

cudaStream_t my_stream = context.allocate_cuda_stream("my_stream");

// some custom code using the CUDA stream here

// emit the allocated stream on the "out" port
op_output.set_cuda_stream(my_stream, "out");
```

Python

```
# The code below would appear within `Operator.compute`

my_stream_ptr = context.allocate_cuda_stream("my_stream")

# some custom code using the CUDA stream here

# emit the allocated stream on the "out" port
op_output.set_cuda_stream(my_stream, "out")
```

The `synchronize_streams` (`C++`/`Python`) method takes a vector of (optional) `cudaStream_t` values and synchronizes all of these streams to the specified `target_cuda_stream`. It is okay for the target stream to also appear in the vector of streams to synchronize (synchronization will be skipped for any element in the vector that is the same as the target stream). If the application author is using the `receive_cuda_stream` API described above, that will typically take care of any needed synchronization and this method does not need to be called. It is provided for manual stream handling use cases.

The `device_from_stream` (`C++`/`Python`) method takes a `cudaStream_t` value and returns the integer CUDA device id corresponding to that stream. This method only supports querying the device in this way for streams managed by Holoscan SDK (i.e. it only supports streams that were returned by `receive_cuda_stream`, `receive_cuda_streams` or `allocate_cuda_stream`).

16.6 OutputContext: stream handling methods

The `set_cuda_stream` (`C++`/`Python`) method is used to indicate that the stream ID corresponding to a specific `cudaStream_t` should be emitted on the specified CUDA output port. This typically does not need to be explicitly called when using `receive_cuda_stream` as that method would have already configured the stream ID returned to be output on all ports. It is needed for cases where the user has allocated some additional stream via `allocate_cuda_stream` or is doing manual stream handling with `receive_cuda_streams`. An example of usage was given in the *section above* on `allocate_cuda_stream`.

16.7 Using CudaStreamCondition to require stream work to complete before an operator executes

It is mentioned above that `receive_cuda_stream` automatically handles synchronization of streams found on an input port. If work on the stream was not already complete and the `compute` method is going to perform an operation which requires synchronization such as device->host memory copy, then some time will be spent waiting for work launched on an input stream by an upstream operator to complete. It may be beneficial to explicitly specify that work on the stream found on a given input port must be complete **before** the scheduler would execute the operator (call its `compute` method).

To require work on an input stream to complete before an operator is ready to schedule, a `CudaStreamCondition` (`C++`/`Python`) can be added to the operator. When a message is sent to the port to which a `CudaStreamCondition` has been assigned, this condition sets an internal host callback function on the CUDA stream found on this input port. The callback function will set the operator's status to READY once other work on the stream has completed. This will then allow the scheduler to execute the operator.

One limitation of `CudaStreamCondition` is that it only looks for a stream on the first message in the input port's queue. It does not currently support handling ports with multiple different input stream components within the same message (entity) or across multiple messages in the queue. The behavior of `CudaStreamCondition` is sufficient for Holoscan's default queue size of one and for use with `receive_cuda_stream` which places just a single CUDA stream component in an upstream operator's outgoing messages. Cases where it is not appropriate are:

- The input port's *queue size was explicitly set* with capacity greater than one and it is not known that all messages in the queue correspond to the same CUDA stream.
- The input port is a multi-receiver port (i.e. `IOSpec::kAnySize`) that any number of upstream operators could connect to.

In cases where no stream is found in the input message, this condition will allow execution of the operator.

Example usage is as follows

C++

```
// The code below would appear within `Application::compose` (or `Fragment::compose`)

// assuming the Operator has a port named "in", we can create the condition
auto stream_cond = make_condition<CudaStreamCondition>(name="stream_sync", receiver="in")

// it can then be passed as an argument to `make_operator`
auto my_op = make_operator<ops::MyOperator>("my_op",
                                            stream_cond,
                                            from_config("my_operator"));
)
```

Python

```
# The code below would appear within `Application.compose` (or `Fragment.compose`)

# assuming the Operator has a port named "in", we can create the condition
stream_cond = CudaStreamCondition(self, receiver="in", name="stream_sync")

# the condition is then passed as a positional argument to an Operator's constructor
visualizer = MyOperator(
    self,
    stream_cond,
    **my_kwargs,
    name="my_op",
)
```

16.8 Sharp edges related to Operators launching asynchronous work

This section describes a couple of scenarios where application authors may encounter surprising behavior when using operators that launch kernels asynchronously. As mentioned above, once a CUDA kernel has launched, control immediately returns to the host and the `compute` method may exit before all work on the GPU has completed. This is desirable for application performance, but raises some additional considerations that application authors should be aware of.

Tip: Tools like the built-in `{ref}Data Flow Tracking<holoscan-flow-tracking>` or `{ref}GXF JobStatistics<gxf-job-satistics>` measures report the times spent in the `compute` method for operators. This can be misleadingly short when the actual GPU kernels complete at some later time after the `compute` call has ended. A concrete example is when an upstream operator launches a CUDA kernel asynchronously and then a downstream operator needs to do a device->host transfer (which requires synchronization). In that scenario the downstream operator will need to wait for the kernel launched by the upstream operator to complete, so the time for that upstream kernel would be reflected in the downstream operator's `compute` duration (assuming no `CudaStreamCondition` was used to force the upstream kernel to have completed before the downstream `compute` method was called).

In such scenarios it is recommended to perform profiling with *Nsight Systems* to get a more detailed view of the application timing. The Nsight Systems UI will have per-stream traces of CUDA calls as well as separate traces for any scheduler worker threads that show the durations of Operator `compute` calls.

Tip: When an operator uses an `Allocator` (e.g. `UnboundedAllocator`, `BlockMemoryPool`, `RMMAllocator` or `StreamOrderedAllocator`) to dynamically allocate memory on each `compute` call, it is possible that more memory will be required than initially estimated. For example, if a kernel is launched but `compute` returns while computation is still being done on a tensor, an upstream operator is then free to be scheduled again. If that upstream operator was using an `Allocator`, the memory from the prior compute call would still be in use. Thus the operator needs space to allocate a second tensor on top of the original one. This means the author has to set a larger number of required bytes (or blocks) than they would have otherwise estimated (e.g. 2x as many).

CHAPTER

SEVENTEEN

LOGGING

17.1 Overview

The Holoscan SDK uses the Logger module to convey messages to the user. These messages are categorized into different severity levels (see below) to inform users of the severity of a message and as a way to control the number and verbosity of messages that are printed to the terminal. There are two settings which can be used for this purpose:

- Logger level
- Logger format

17.1.1 Logger Level

Messages that are logged using the Logger module have a severity level, e.g., messages can be categorized as INFO, WARN, ERROR, etc.

The default logging level for an application is to print out messages with severity INFO or above, i.e., messages that are categorized as INFO, WARN, ERROR, and CRITICAL. You can modify this default by calling `set_log_level()` (`C++`/`Python`) in the application code to override the SDK default logging level and give it one of the following log levels.

- TRACE
- DEBUG
- INFO
- WARN
- ERROR
- CRITICAL
- OFF

CPP

```cpp
#include <holoscan/holoscan.hpp>

int main() {
  holoscan::set_log_level(holoscan::LogLevel::WARN);
  // ...
  return 0;
}
```

PYTHON

```python
from holoscan.logger import set_log_level

def main():
    set_log_level(LogLevel::WARN)
    # ...

if __name__ == "__main__":
    main()
```

Additionally, at runtime, the user can set the `HOLOSCAN_LOG_LEVEL` environment variable to one of the values listed above. This provides users with the flexibility to enable printing of diagnostic information for debugging purposes when an issue occurs.

```
export HOLOSCAN_LOG_LEVEL=TRACE
```

Note: Under the hood, Holoscan SDK uses GXF to execute the computation graph. By default, this GXF layer uses the same logging level as Holoscan SDK. If it is desired to override the logging level of this executor independently of the Holoscan SDK logging level, environment variable `HOLOSCAN_EXECUTOR_LOG_LEVEL` can be used. It supports the same levels as `HOLOSCAN_LOG_LEVEL`.

Note: For distributed applications, it can sometimes be useful to also enable additional logging for the UCX library used to transmit data between fragments. This can be done by setting the UCX environment variable `UCX_LOG_LEVEL` to one of: fatal, error, warn, info, debug, trace, req, data, async, func, poll. These have the behavior as described here: UCX log levels.

17.2 Logger Format

When a message is printed out, the default message format shows the message severity level, filename:linenumber, and Sthe message to be printed.

For example:

```
[info] [ping_multi_port.cpp:114] Rx message value1: 51
[info] [ping_multi_port.cpp:115] Rx message value2: 54
```

You can modify this default by calling `set_log_pattern()` (`C++`/`Python`) in the application code to override the SDK default logging format.

The pattern string can be one of the following pre-defined values

- **SHORT** : prints message severity level, and message
- **DEFAULT** : prints message severity level, filename:linenumber, and message
- **LONG** : prints timestamp, application, message severity level, filename:linenumber, and message
- **FULL** : prints timestamp, thread id, application, message severity level, filename:linenumber, and message

CPP

```cpp
#include <holoscan/holoscan.hpp>

int main() {
  holoscan::set_log_pattern("SHORT")
  // ...
  return 0;
}
```

PYTHON

```python
from holoscan.logger import set_log_pattern

def main():
    set_log_pattern("SHORT")
    # ...

if __name__ == "__main__":
    main()
```

With this logger format, the above application would display messages with the following format:

```
[info] Rx message value1: 51
[info] Rx message value2: 54
```

Alternatively, the pattern string can be a custom pattern to customize the logger format. Using this string pattern:

```
"[%Y-%m-%d %H:%M:%S.%e] [%n] [%^%l%$] [%s:%#] %v";
```

The following format will be displayed:

```
[2023-06-27 14:22:36.073] [holoscan] [info] [ping_multi_port.cpp:114] Rx message value1:␣
↪51
[2023-06-27 14:22:36.073] [holoscan] [info] [ping_multi_port.cpp:115] Rx message value2:␣
↪54
```

For more details on custom formatting and details of each flag, please see the spdlog wiki page.

Additionally, at runtime, the user can also set the `HOLOSCAN_LOG_FORMAT` environment variable to modify the logger format. The accepted string pattern is the same as the string pattern for the `set_log_pattern()` api mentioned above.

17.2.1 Precedence of Logger Level and Logger Format

The HOLOSCAN_LOG_LEVEL environment variable takes precedence and overrides the application settings, such as Logger::set_log_level() (C++/Python).

When HOLOSCAN_LOG_LEVEL is set, it determines the logging level. If this environment variable is unset, the application settings are used if they are available. Otherwise, the SDK's default logging level of INFO is applied.

Similarly, the HOLOSCAN_LOG_FORMAT environment variable takes precedence and overrides the application settings, such as Logger::set_log_pattern() (C++/Python).

When HOLOSCAN_LOG_FORMAT is set, it determines the logging format. If this environment variable is unset, the application settings are used if they are available. Otherwise, the SDK's default logging format depending on the current log level (FULL format for DEBUG and TRACE log levels. DEFAULT format for other log levels) is applied.

17.3 Calling the Logger in Your Application

The **C++ API** uses the HOLOSCAN_LOG_XXX() macros to log messages in the application. These macros use the fmtlib format string syntax for their format strings.

Note: Holoscan automatically checks HOLOSCAN_LOG_LEVEL environment variable and sets the log level when the Application class instance is created. However, those log level settings are for Holoscan core or C++ operator (C++)'s logging message (such as HOLOSCAN_LOG_INFO macro), not for Python's logging. Users of the **Python API** should use the built-in logging module to log messages. You must configure the logger before use (logging.basicConfig(level=logging.INFO)):

```
>>> import logging
>>> logger = logging.getLogger("main")
>>> logger.info('hello')
>>> logging.basicConfig(level=logging.INFO)
>>> logger.info('hello')
INFO:main:hello
```

CHAPTER

EIGHTEEN

DEBUGGING

18.1 Overview

The Holoscan SDK is designed to streamline the debugging process for developers working on advanced applications.

This comprehensive guide covers the SDK's debugging capabilities, with a focus on Visual Studio Code integration, and provides detailed instructions for various debugging scenarios.

It includes methods for debugging both the C++ and Python components of applications, utilizing tools like GDB, UCX, and Python-specific debuggers.

18.2 Visual Studio Code Integration

18.2.1 VSCode Dev Container

The Holoscan SDK can be effectively developed using Visual Studio Code, leveraging the capabilities of a development container. This container, defined in the `.devcontainer` folder, is pre-configured with all the necessary tools and libraries, as detailed in Visual Studio Code's documentation on development containers.

18.2.2 Launching VSCode with the Holoscan SDK

- **Local Development**: Use the `./run vscode` command to launch Visual Studio Code in a development container (`-j <# of workers>` or `--parallel <# of workers>` can be used to specify the number of parallel jobs to run during the build process). For more information, refer to the instructions from `./run vscode -h`.
- **Remote Development**: For attaching to an existing dev container from a remote machine, use `./run vscode_remote`. Additional instructions can be accessed via `./run vscode_remote -h`.

Upon launching Visual Studio Code, the development container will automatically be built. This process also involves the installation of recommended extensions and the configuration of CMake.

18.2.3 Configuring CMake

For manual adjustments to the CMake configuration:

1. Open the command palette in VSCode (`Ctrl + Shift + P`).
2. Execute the `CMake: Configure` command.

18.2.4 Building the Source Code

To build the source code within the development container:

- Either press `Ctrl + Shift + B`.
- Or use the command palette (`Ctrl + Shift + P`) and run `Tasks: Run Build Task`.

18.2.5 Debugging Workflow

For debugging the source code:

1. Open the `Run and Debug` view in VSCode (`Ctrl + Shift + D`).
2. Select an appropriate debug configuration from the dropdown.
3. Press `F5` to start the debugging session.

The launch configurations are defined in `.vscode/launch.json`(link).

Please refer to Visual Studio Code's documentation on debugging for more information.

18.2.6 Integrated Debugging for C++ and Python in Holoscan SDK

The Holoscan SDK facilitates seamless debugging of both C++ and Python components within your applications. This is achieved through the integration of the `Python C++ Debugger` extension in Visual Studio Code, which can be found here.

This powerful extension is specifically designed to enable effective debugging of Python operators that are executed within the C++ runtime environment. Additionally, it provides robust capabilities for debugging C++ operators and various SDK components that are executed via the Python interpreter.

To utilize this feature, debug configurations for `Python C++ Debug` should be defined within the `.vscode/launch.json` file, available here.

Here's how to get started:

1. Open a Python file within your project, such as `examples/ping_vector/python/ping_vector.py`.
2. In the `Run and Debug` view of Visual Studio Code, select the `Python C++ Debug` debug configuration.
3. Set the necessary breakpoints in both your Python and C++ code.
4. Initiate the debugging session by pressing `F5`.

Upon starting the session, two separate debug terminals will be launched; one for Python and another for C++. In the C++ terminal, you will encounter a prompt regarding superuser access:

```
Superuser access is required to attach to a process. Attaching as superuser can␣
↪potentially harm your computer. Do you want to continue? [y/N]
```

Respond with y to proceed.

Following this, the Python application initiates, and the C++ debugger attaches to the Python process. This setup allows you to simultaneously debug both Python and C++ code. The `CALL STACK` tab in the `Run and Debug` view will display `Python: Debug Current File` and `(gdb) Attach`, indicating active debugging sessions for both languages.

By leveraging this integrated debugging approach, developers can efficiently troubleshoot and enhance applications that utilize both Python and C++ components within the Holoscan SDK.

18.3 Debugging an Application Crash

This section outlines the procedures for debugging an application crash.

18.3.1 Core Dump Analysis

In the event of an application crash, you might encounter messages like `Segmentation fault (core dumped)` or `Aborted (core dumped)`. These indicate the generation of a core dump file, which captures the application's memory state at the time of the crash. This file can be utilized for debugging purposes.

Enabling Core Dump

There are instances where core dumps might be disabled or not generated despite an application crash.

To activate core dumps, it's necessary to configure the `ulimit` setting, which determines the maximum size of core dump files. By default, `ulimit` is set to 0, effectively disabling core dumps. Setting `ulimit` to unlimited enables the generation of core dumps.

```
ulimit -c unlimited
```

Additionally, configuring the `core_pattern` value is required. This value specifies the naming convention for the core dump file. To view the current `core_pattern` setting, execute the following command:

```
cat /proc/sys/kernel/core_pattern
# or
sysctl kernel.core_pattern
```

To modify the `core_pattern` value, execute the following command:

```
echo "coredump_%e_%p" | sudo tee /proc/sys/kernel/core_pattern
# or
sudo sysctl -w kernel.core_pattern=coredump_%e_%p
```

In this case, we have requested that both the executable name (`%e`) and the process id (`%p`) be present in the generated file's name. The various options available are documented in the core documentation.

If you encounter errors like `tee: /proc/sys/kernel/core_pattern: Read-only file system` or `sysctl: setting key "kernel.core_pattern", ignoring: Read-only file system` within a Docker container, it's advisable to set the `kernel.core_pattern` parameter on the host system instead of within the container.

As `kernel.core_pattern` is a system-wide kernel parameter, modifying it on the host should impact all containers. This method, however, necessitates appropriate permissions on the host machine.

Furthermore, when launching a Docker container using `docker run`, it's often essential to include the `--cap-add=SYS_PTRACE` option to enable core dump creation inside the container. Core dump generation typically requires elevated privileges, which are not automatically available to Docker containers.

Using GDB to Debug a Core Dump File

After the core dump file is generated, you can utilize GDB to debug the core dump file.

Consider a scenario where a segmentation fault is intentionally induced at line 29 in `examples/ping_simple/cpp/ping_simple.cpp` by adding the line `*(int*)0 = 0;` to trigger the fault.

```
--- a/examples/ping_simple/cpp/ping_simple.cpp
+++ b/examples/ping_simple/cpp/ping_simple.cpp
@@ -19,7 +19,6 @@
 #include <holoscan/operators/ping_tx/ping_tx.hpp>
 #include <holoscan/operators/ping_rx/ping_rx.hpp>

-
 class MyPingApp : public holoscan::Application {
  public:
   void compose() override {
@@ -27,6 +26,7 @@ class MyPingApp : public holoscan::Application {
     // Define the tx and rx operators, allowing the tx operator to execute 10 times
     auto tx = make_operator<ops::PingTxOp>("tx", make_condition<CountCondition>(10));
     auto rx = make_operator<ops::PingRxOp>("rx");
+    *(int*)0 = 0;
```

Upon running `./examples/ping_simple/cpp/ping_simple`, the following output is observed:

```
$ ./examples/ping_simple/cpp/ping_simple
Segmentation fault (core dumped)
```

It's apparent that the application has aborted and a core dump file has been generated.

```
$ ls coredump*
coredump_ping_simple_2160275
```

The core dump file can be debugged using GDB by executing `gdb <application> <coredump_file>`.

```
$ gdb ./examples/ping_simple/cpp/ping_simple coredump_ping_simple_2160275
```

gives

```
GNU gdb (Ubuntu 12.1-0ubuntu1~22.04) 12.1
Copyright (C) 2022 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "x86_64-linux-gnu".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<https://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
    <http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from ./examples/ping_simple/cpp/ping_simple...
```

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```
[New LWP 2160275]
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/usr/lib/x86_64-linux-gnu/libthread_db.so.1".
Core was generated by `./examples/ping_simple/cpp/ping_simple'.
Program terminated with signal SIGSEGV, Segmentation fault.
#0  MyPingApp::compose (this=0x563bd3a3de80) at ../examples/ping_simple/cpp/ping_simple.
↪cpp:29
29          *(int*)0 = 0;
(gdb)
```

It is evident that the application crashed at line 29 of `examples/ping_simple/cpp/ping_simple.cpp`.

To display the backtrace, the `bt` command can be executed.

```
(gdb) bt
#0  MyPingApp::compose (this=0x563bd3a3de80) at ../examples/ping_simple/cpp/ping_simple.
↪cpp:29
#1  0x00007f2a76cdb5ea in holoscan::Application::compose_graph (this=0x563bd3a3de80) at .
↪./src/core/application.cpp:325
#2  0x00007f2a76c3d121 in holoscan::AppDriver::check_configuration (this=0x563bd3a42920)␣
↪at ../src/core/app_driver.cpp:803
#3  0x00007f2a76c384ef in holoscan::AppDriver::run (this=0x563bd3a42920) at ../src/core/
↪app_driver.cpp:168
#4  0x00007f2a76cda70c in holoscan::Application::run (this=0x563bd3a3de80) at ../src/
↪core/application.cpp:207
#5  0x0000563bd2ec4002 in main (argc=1, argv=0x7ffea82c4c28) at ../examples/ping_simple/
↪cpp/ping_simple.cpp:38
```

18.3.2 UCX Segmentation Fault Handler

In cases where a distributed application using the UCX library encounters a segmentation fault, you might see stack traces from UCX. This is a default configuration of the UCX library to output stack traces upon a segmentation fault. However, this behavior can be modified by setting the `UCX_HANDLE_ERRORS` environment variable:

- `UCX_HANDLE_ERRORS=bt` prints a backtrace during a segmentation fault (default setting).
- `UCX_HANDLE_ERRORS=debug` attaches a debugger if a segmentation fault occurs.
- `UCX_HANDLE_ERRORS=freeze` freezes the application on a segmentation fault.
- `UCX_HANDLE_ERRORS=freeze,bt` both freezes the application and prints a backtrace upon a segmentation fault.
- `UCX_HANDLE_ERRORS=none` disables backtrace printing during a segmentation fault.

While the default action is to print a backtrace on a segmentation fault, it may not always be helpful.

For instance, if a segmentation fault is intentionally caused at line 139 near the start of `PingTensorTxOp::compute` in `/workspace/holoscan-sdk/src/operators/ping_tensor_tx/ping_tensor_tx.cpp` (by adding `*(int*)0 = 0;`), running `./examples/ping_distributed/cpp/ping_distributed` will result in the following output:

```
[holoscan:2097261:0:2097311] Caught signal 11 (Segmentation fault: address not mapped to␣
↪object at address (nil))
==== backtrace (tid:2097311) ====
 0  /opt/ucx/1.15.0/lib/libucs.so.0(ucs_handle_error+0x2e4) [0x7f18db865264]
 1  /opt/ucx/1.15.0/lib/libucs.so.0(+0x3045f) [0x7f18db86545f]
```

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```
 2  /opt/ucx/1.15.0/lib/libucs.so.0(+0x30746) [0x7f18db865746]
 3  /usr/lib/x86_64-linux-gnu/libc.so.6(+0x42520) [0x7f18da9ee520]
 4  ./examples/ping_distributed/cpp/ping_distributed(+0x103d2b) [0x5651dafc7d2b]
 5  /workspace/holoscan-sdk/build-debug-x86_64/lib/libholoscan_core.so.1(_
↪ZN8holoscan3gxf10GXFWrapper4tickEv+0x13d) [0x7f18dcbfaafd]
 6  /workspace/holoscan-sdk/build-debug-x86_64/lib/libgxf_core.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem11tickCodeletERKNS0_6HandleINS0_
↪7CodeletEEE+0x127) [0x7f18db2cb487]
 7  /workspace/holoscan-sdk/build-debug-x86_64/lib/libgxf_core.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem4tickElPNS0_6RouterE+0x444) [0x7f18db2cde44]
 8  /workspace/holoscan-sdk/build-debug-x86_64/lib/libgxf_core.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem7executeElPNS0_6RouterERl+0x3e9)␣
↪[0x7f18db2ce859]
 9  /workspace/holoscan-sdk/build-debug-x86_64/lib/libgxf_core.so(_
↪ZN6nvidia3gxf14EntityExecutor13executeEntityEll+0x41b) [0x7f18db2cf0cb]
10  /workspace/holoscan-sdk/build-debug-x86_64/lib/libgxf_serialization.so(_
↪ZN6nvidia3gxf20MultiThreadScheduler20workerThreadEntranceEPNS0_10ThreadPoolEl+0x3c0)␣
↪[0x7f18daf0cc50]
11  /usr/lib/x86_64-linux-gnu/libstdc++.so.6(+0xdc253) [0x7f18dacb0253]
12  /usr/lib/x86_64-linux-gnu/libc.so.6(+0x94ac3) [0x7f18daa40ac3]
13  /usr/lib/x86_64-linux-gnu/libc.so.6(+0x126660) [0x7f18daad2660]
=================================
Segmentation fault (core dumped)
```

Although a backtrace is provided, it may not always be helpful as it often lacks source code information. To obtain detailed source code information, using a debugger is necessary.

By setting the `UCX_HANDLE_ERRORS` environment variable to `freeze,bt` and running `./examples/ping_distributed/cpp/ping_distributed`, we can observe that the thread responsible for the segmentation fault is frozen, allowing us to attach a debugger to it for further investigation.

```
$ UCX_HANDLE_ERRORS=freeze,bt ./examples/ping_distributed/cpp/ping_distributed


[holoscan:37   :1:51] Caught signal 11 (Segmentation fault: address not mapped to object␣
↪at address (nil))
==== backtrace (tid:     51) ====
 0  /opt/ucx/1.15.0/lib/libucs.so.0(ucs_handle_error+0x2e4) [0x7f9fc6d75264]
 1  /opt/ucx/1.15.0/lib/libucs.so.0(+0x3045f) [0x7f9fc6d7545f]
 2  /opt/ucx/1.15.0/lib/libucs.so.0(+0x30746) [0x7f9fc6d75746]
 3  /usr/lib/x86_64-linux-gnu/libc.so.6(+0x42520) [0x7f9fc803e520]
 4  /workspace/holoscan-sdk/build-x86_64/lib/libholoscan_op_ping_tensor_tx.so.2(_
↪ZN8holoscan3ops14PingTensorTxOp7computeERNS_12InputContextERNS_13OutputContextERNS_
↪16ExecutionContextE+0x53) [0x7f9fcad9e7f1]
 5  /workspace/holoscan-sdk/build-x86_64/lib/libholoscan_core.so.2(_
↪ZN8holoscan3gxf10GXFWrapper4tickEv+0x155) [0x7f9fc9e415eb]
 6  /workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem11tickCodeletERKNS0_6HandleINS0_
↪7CodeletEEE+0x1a7) [0x7f9fc88f0347]
 7  /workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem4tickElPNS0_6RouterE+0x460) [0x7f9fc88f29c0]
 8  /workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so(_
↪ZN6nvidia3gxf14EntityExecutor10EntityItem7executeElPNS0_6RouterERl+0x31e)␣
↪[0x7f9fc88f31ee]
```

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```
 9  /workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so(_
↪ZN6nvidia3gxf14EntityExecutor13executeEntityEll+0x2e7) [0x7f9fc88f39d7]
10  /workspace/holoscan-sdk/build-x86_64/lib/libgxf_serialization.so(_
↪ZN6nvidia3gxf20MultiThreadScheduler20workerThreadEntranceEPNS0_10ThreadPoolEl+0x419)␣
↪[0x7f9fc8605dd9]
11  /usr/lib/x86_64-linux-gnu/libstdc++.so.6(+0xdc253) [0x7f9fc8321253]
12  /usr/lib/x86_64-linux-gnu/libc.so.6(+0x94ac3) [0x7f9fc8090ac3]
13  /usr/lib/x86_64-linux-gnu/libc.so.6(clone+0x44) [0x7f9fc8121a04]
=================================
[holoscan:2127091:0:2127105] Process frozen, press Enter to attach a debugger...
```

It is observed that the thread responsible for the segmentation fault is 51 (`tid: 51`). To attach a debugger to this thread, simply press Enter.

Upon attaching the debugger, a backtrace will be displayed, but it may not be from the thread that triggered the segmentation fault. To handle this, use the `info threads` command to list all threads, and the `thread <thread_id>` command to switch to the thread that caused the segmentation fault.

```
(gdb) info threads
  Id   Target Id                                    Frame
* 1    Thread 0x7f9fc6ce2000 (LWP 37) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  2    Thread 0x7f9fc51bb000 (LWP 39) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  3    Thread 0x7f9fc11ba000 (LWP 40) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  4    Thread 0x7f9fbd1b9000 (LWP 41) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  5    Thread 0x7f9fabfff000 (LWP 42) "cuda00001400006" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  6    Thread 0x7f9f99fff000 (LWP 43) "async"           0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  7    Thread 0x7f9f95ffe000 (LWP 44) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  8    Thread 0x7f9f77fff000 (LWP 45) "dispatcher"      0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  9    Thread 0x7f9f73ffe000 (LWP 46) "async"           0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  10   Thread 0x7f9f6fffd000 (LWP 47) "worker"          0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  11   Thread 0x7f9f5bfff000 (LWP 48) "ping_distribute" 0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  12   Thread 0x7f9f57ffe000 (LWP 49) "dispatcher"      0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  13   Thread 0x7f9f53ffd000 (LWP 50) "async"           0x00007f9fc80e6612 in __libc_
↪pause () at ../sysdeps/unix/sysv/linux/pause.c:29
  14   Thread 0x7f9f4fffc000 (LWP 51) "worker"          0x00007f9fc80e642f in __GI___
↪wait4 (pid=pid@entry=52, stat_loc=stat_loc@entry=0x7f9f4fff6cfc,␣
↪options=options@entry=0, usage=usage@entry=0x0) at ../sysdeps/unix/sysv/linux/wait4.
↪c:30
```

It's evident that thread ID 14 is responsible for the segmentation fault (`LWP 51`). To investigate further, we can switch to this thread using the command `thread 14` in GDB:

```
(gdb) thread 14
```

After switching, we can employ the `bt` command to examine the backtrace of this thread.

```
(gdb) bt
#0  0x00007f9fc80e642f in __GI___wait4 (pid=pid@entry=52, stat_loc=stat_
↪loc@entry=0x7f9f4fff6cfc, options=options@entry=0, usage=usage@entry=0x0) at ../
↪sysdeps/unix/sysv/linux/wait4.c:30
#1  0x00007f9fc80e63ab in __GI___waitpid (pid=pid@entry=52, stat_loc=stat_
↪loc@entry=0x7f9f4fff6cfc, options=options@entry=0) at ./posix/waitpid.c:38
#2  0x00007f9fc6d72587 in ucs_debugger_attach () at /opt/ucx/src/contrib/../src/ucs/
↪debug/debug.c:816
#3  0x00007f9fc6d7531d in ucs_error_freeze (message=0x7f9fc6d93c53 "address not mapped␣
↪to object") at /opt/ucx/src/contrib/../src/ucs/debug/debug.c:919
#4  ucs_handle_error (message=0x7f9fc6d93c53 "address not mapped to object") at /opt/ucx/
↪src/contrib/../src/ucs/debug/debug.c:1089
#5  ucs_handle_error (message=0x7f9fc6d93c53 "address not mapped to object") at /opt/ucx/
↪src/contrib/../src/ucs/debug/debug.c:1077
#6  0x00007f9fc6d7545f in ucs_debug_handle_error_signal (signo=signo@entry=11,␣
↪cause=0x7f9fc6d93c53 "address not mapped to object", fmt=fmt@entry=0x7f9fc6d93cf5 " at␣
↪address %p") at /opt/ucx/src/contrib/../src/ucs/debug/debug.c:1038
#7  0x00007f9fc6d75746 in ucs_error_signal_handler (signo=11, info=0x7f9f4fff73b0,␣
↪context=<optimized out>) at /opt/ucx/src/contrib/../src/ucs/debug/debug.c:1060
#8  <signal handler called>
#9  holoscan::ops::PingTensorTxOp::compute (this=0x5643fdcbd540, op_output=..., context=.
↪..) at /workspace/holoscan-sdk/src/operators/ping_tensor_tx/ping_tensor_tx.cpp:139
#10 0x00007f9fc9e415eb in holoscan::gxf::GXFWrapper::tick (this=0x5643fdcfef00) at /
↪workspace/holoscan-sdk/src/core/gxf/gxf_wrapper.cpp:78
#11 0x00007f9fc88f0347 in␣
↪nvidia::gxf::EntityExecutor::EntityItem::tickCodelet(nvidia::gxf::Handle
↪<nvidia::gxf::Codelet> const&) () from /workspace/holoscan-sdk/build-x86_64/lib/libgxf_
↪sample.so
#12 0x00007f9fc88f29c0 in nvidia::gxf::EntityExecutor::EntityItem::tick(long,␣
↪nvidia::gxf::Router*) () from /workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so
#13 0x00007f9fc88f31ee in nvidia::gxf::EntityExecutor::EntityItem::execute(long,␣
↪nvidia::gxf::Router*, long&) () from /workspace/holoscan-sdk/build-x86_64/lib/libgxf_
↪sample.so
#14 0x00007f9fc88f39d7 in nvidia::gxf::EntityExecutor::executeEntity(long, long) () from␣
↪/workspace/holoscan-sdk/build-x86_64/lib/libgxf_sample.so
#15 0x00007f9fc8605dd9 in␣
↪nvidia::gxf::MultiThreadScheduler::workerThreadEntrance(nvidia::gxf::ThreadPool*,␣
↪long) () from /workspace/holoscan-sdk/build-x86_64/lib/libgxf_serialization.so
#16 0x00007f9fc8321253 in ?? () from /usr/lib/x86_64-linux-gnu/libstdc++.so.6
#17 0x00007f9fc8090ac3 in start_thread (arg=<optimized out>) at ./nptl/pthread_create.
↪c:442
#18 0x00007f9fc8121a04 in clone () at ../sysdeps/unix/sysv/linux/x86_64/clone.S:100
```

Under the backtrace of thread 14, you will find:

```
#8  <signal handler called>
#9  holoscan::ops::PingTensorTxOp::compute (this=0x5643fdcbd540, op_output=..., context=.
↪..) at /workspace/holoscan-sdk/src/operators/ping_tensor_tx/ping_tensor_tx.cpp:139
```

This indicates that the segmentation fault occurred at line 139 in `/workspace/holoscan-sdk/src/operators/`

ping_tensor_tx/ping_tensor_tx.cpp.

To view the backtrace of all threads, use the `thread apply all bt` command.

```
(gdb) thread apply all bt

...
Thread 14 (Thread 0x7f9f4fffc000 (LWP 51) "worker"):
#0  0x00007f9fc80e642f in __GI___wait4 (pid=pid@entry=52, stat_loc=stat_
↪loc@entry=0x7f9f4fff6cfc, options=options@entry=0, usage=usage@entry=0x0) at ../
↪sysdeps/unix/sysv/linux/wait4.c:30
...

Thread 13 (Thread 0x7f9f53ffd000 (LWP 50) "async"):
#0  0x00007f9fc80e6612 in __libc_pause () at ../sysdeps/unix/sysv/linux/pause.c:29
...
```

18.4 Debugging Holoscan Python Application

The Holoscan SDK provides support for tracing and profiling tools, particularly focusing on the `compute` method of Python operators. Debugging Python operators using Python IDEs can be challenging since this method is invoked from the C++ runtime. This also applies to the `initialize`, `start`, and `stop` methods of Python operators.

Users can leverage IDEs like VSCode/PyCharm (which utilize the PyDev.Debugger) or other similar tools to debug Python operators:

- For VSCode, refer to VSCode Python Debugging.
- For PyCharm, consult PyCharm Python Debugging.

Subsequent sections will detail methods for debugging, profiling, and tracing Python applications using the Holoscan SDK.

18.4.1 pdb example

The following command initiates a Python application within a pdb debugger session:

```
python python/tests/system/test_pytracing.py pdb

# Type the following commands to check if the breakpoints are hit:
#
#   b test_pytracing.py:78
#   c
#   exit
```

```
This is an interactive session.
Please type the following commands to check if the breakpoints are hit.

  (Pdb) b test_pytracing.py:78
  Breakpoint 1 at /workspace/holoscan-sdk/python/tests/system/test_pytracing.py:78
  (Pdb) c
  ...
  > /workspace/holoscan-sdk/python/tests/system/test_pytracing.py(78)start()
```

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```
  -> print("Mx start")
  (Pdb) exit
```

For more details, please refer to the `pdb_main()` method in `test_pytracing.py`.

It is also possible to launch the pdb session without having to manually add a breakpoint() to the source file before main() as was done in test_pytracing.py. In that case, just launch the existing application using `python -m pdb my_app.py`. For example, we can launch the existing ping_multi_port.py example included with the SDK like this

```
python -m pdb ./examples/ping_multi_port/python/ping_multi_port.py
```

We will then be at the pdb prompt, from which we can insert a break point (at the first line of the `compute` method in this case) and then use `c` to continue execution until the breakpoint is reached.

```
(Pdb) b ping_multi_port.py:97
Breakpoint 1 at /workspace/holoscan-sdk/build-x86_64/examples/ping_multi_port/python/
↪ping_multi_port.py:97
(Pdb) c
[info] [fragment.cpp:588] Loading extensions from configs...
[info] [gxf_executor.cpp:262] Creating context
[info] [gxf_executor.cpp:1767] creating input IOSpec named 'in2'
[info] [gxf_executor.cpp:1767] creating input IOSpec named 'in1'
[info] [gxf_executor.cpp:1767] creating input IOSpec named 'receivers:1'
[info] [gxf_executor.cpp:1767] creating input IOSpec named 'receivers:0'
[info] [gxf_executor.cpp:1767] creating input IOSpec named 'receivers'
[info] [gxf_executor.cpp:2174] Activating Graph...
[info] [gxf_executor.cpp:2204] Running Graph...
[info] [gxf_executor.cpp:2206] Waiting for completion...
[info] [greedy_scheduler.cpp:191] Scheduling 3 entities
> /workspace/holoscan-sdk/build-x86_64/examples/ping_multi_port/python/ping_multi_port.
↪py(97)compute()
-> value1 = op_input.receive("in1")
```

Now that we are at the desired breakpoint, we can interactively debug the operator. The following show an example of using `s` to step by one line then `p value1` to print the value of the "value1" variable. The `l` command is used to show the surrounding context. In the output, the arrow indicates the line where we are currently at in the debugger and the "B" indicates the breakpoint that was previously added.

```
(Pdb) s
> /workspace/holoscan-sdk/build-x86_64/examples/ping_multi_port/python/ping_multi_port.
↪py(98)compute()
-> value2 = op_input.receive("in2")
(Pdb) p value1
ValueData(1)
(Pdb) l
 93                 spec.output("out2")
 94                 spec.param("multiplier", 2)
 95
 96             def compute(self, op_input, op_output, context):
 97 B               value1 = op_input.receive("in1")
 98  ->             value2 = op_input.receive("in2")
 99                 print(f"Middle message received (count: {self.count})")
100                 self.count += 1
```

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```

            print(f"Middle message value1: {value1.data}")
            print(f"Middle message value2: {value2.data}")
```

18.4.2 Profiling a Holoscan Python Application

For profiling, users can employ tools like cProfile or line_profiler for profiling Python applications/operators.

Note that when using a multithreaded scheduler, cProfile or the profile module might not accurately identify worker threads, or errors could occur.

In such cases with multithreaded schedulers, consider using multithread-aware profilers like pyinstrument, pprofile, or yappi.

For further information, refer to the test case at test_pytracing.py.

Using pyinstrument

pyinstrument is a call stack profiler for Python, designed to highlight performance bottlenecks in an easily understandable format directly in your terminal as the code executes.

```
python -m pip install pyinstrument
pyinstrument python/tests/system/test_pytracing.py

## Note: With a multithreaded scheduler, the same method may appear multiple times␣
↪across different threads.
# pyinstrument python/tests/system/test_pytracing.py -s multithread
```

```
...
0.107 [root]  None
├─ 0.088 MainThread  <thread>:140079743820224
│  └─ 0.088 <module>  ../../../bin/pyinstrument:1
│     └─ 0.088 main  pyinstrument/__main__.py:28
│           [7 frames hidden]  pyinstrument, <string>, runpy, <built...
│              0.087 _run_code  runpy.py:63
│              └─ 0.087 <module>  test_pytracing.py:1
│                 ├─ 0.061 main  test_pytracing.py:153
│                 │  ├─ 0.057 MyPingApp.compose  test_pytracing.py:141
│                 │  │  ├─ 0.041 PingMxOp.__init__  test_pytracing.py:59
│                 │  │  │  └─ 0.041 PingMxOp.__init__  ../core/__init__.py:262
│                 │  │  │        [35 frames hidden]  .., numpy, re, sre_compile, sre_
↪parse...
│                 │  │  └─ 0.015 [self]  test_pytracing.py
│                 │  └─ 0.002 [self]  test_pytracing.py
│                 ├─ 0.024 <module>  ../__init__.py:1
│                 │     [5 frames hidden]  .., <built-in>
│                 └─ 0.001 <module>  ../conditions/__init__.py:1
│                       [2 frames hidden]  .., <built-in>
└─ 0.019 Dummy-1  <thread>:140078275749440
   └─ 0.019 <module>  ../../../bin/pyinstrument:1
      └─ 0.019 main  pyinstrument/__main__.py:28
```

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```
            [5 frames hidden]  pyinstrument, <string>, runpy
               0.019 _run_code  runpy.py:63
               └─ 0.019 <module>  test_pytracing.py:1
                  └─ 0.019 main  test_pytracing.py:153
                     ├─ 0.014 [self]  test_pytracing.py
                     └─ 0.004 PingRxOp.compute  test_pytracing.py:118
                        └─ 0.004 print  <built-in>
```

Using pprofile

pprofile is a line-granularity, thread-aware deterministic and statistic pure-python profiler.

```
python -m pip install pprofile
pprofile --include test_pytracing.py python/tests/system/test_pytracing.py -s multithread
```

```
Total duration: 0.972872s
File: python/tests/system/test_pytracing.py
File duration: 0.542628s (55.78%)
Line #|      Hits|         Time| Time per hit|      %|Source code
------+----------+-------------+-------------+-------+-----------
...
    33|         0|            0|            0|  0.00%|
    34|         2|  2.86102e-06|  1.43051e-06|  0.00%|    def setup(self, spec:␣
↪OperatorSpec):
    35|         1|  1.62125e-05|  1.62125e-05|  0.00%|        spec.output("out")
    36|         0|            0|            0|  0.00%|
    37|         2|  3.33786e-06|  1.66893e-06|  0.00%|    def initialize(self):
    38|         1|  1.07288e-05|  1.07288e-05|  0.00%|        print("Tx initialize")
    39|         0|            0|            0|  0.00%|
    40|         2|  1.40667e-05|  7.03335e-06|  0.00%|    def start(self):
    41|         1|  1.23978e-05|  1.23978e-05|  0.00%|        print("Tx start")
    42|         0|            0|            0|  0.00%|
    43|         2|  3.09944e-05|  1.54972e-05|  0.00%|    def stop(self):
    44|         1|  2.88486e-05|  2.88486e-05|  0.00%|        print("Tx stop")
    45|         0|            0|            0|  0.00%|
    46|         4|  4.05312e-05|  1.01328e-05|  0.00%|    def compute(self, op_input, op_
↪output, context):
    47|         3|  2.57492e-05|  8.58307e-06|  0.00%|        value = self.index
    48|         3|  2.12193e-05|  7.07308e-06|  0.00%|        self.index += 1
```

Using yappi

yappi is a tracing profiler that is multithreading, asyncio and gevent aware.

```
python -m pip install yappi
# yappi requires setting a context ID callback function to specify the correct context␣
↪ID for
# Holoscan's worker threads.
# For more details, please see `yappi_main()` in `test_pytracing.py`.
python python/tests/system/test_pytracing.py yappi | grep test_pytracing.py
```

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```
## Note: With a multithreaded scheduler, method hit counts are distributed across␣
↪multiple threads.
#python python/tests/system/test_pytracing.py yappi -s multithread | grep test_pytracing.
↪py
```

```
...
  test_pytracing.py main:153 1
  test_pytracing.py MyPingApp.compose:141 1
  test_pytracing.py PingMxOp.__init__:59 1
  test_pytracing.py PingTxOp.__init__:29 1
  test_pytracing.py PingMxOp.setup:65 1
  test_pytracing.py PingRxOp.__init__:99 1
  test_pytracing.py PingRxOp.setup:104 1
  test_pytracing.py PingTxOp.setup:34 1
  test_pytracing.py PingTxOp.initialize:37 1
  test_pytracing.py PingRxOp.stop:115 1
  test_pytracing.py PingRxOp.initialize:109 1
  test_pytracing.py PingMxOp.initialize:72 1
  test_pytracing.py PingMxOp.stop:78 1
  test_pytracing.py PingMxOp.compute:81 3
  test_pytracing.py PingTxOp.compute:46 3
  test_pytracing.py PingRxOp.compute:118 3
  test_pytracing.py PingTxOp.start:40 1
  test_pytracing.py PingMxOp.start:75 1
  test_pytracing.py PingRxOp.start:112 1
  test_pytracing.py PingTxOp.stop:43 1
```

Using profile/cProfile

profile/cProfile is a deterministic profiling module for Python programs.

```
python -m cProfile python/tests/system/test_pytracing.py 2>&1 | grep test_pytracing.py

## Executing a single test case
#python python/tests/system/test_pytracing.py profile
```

```
        1    0.001    0.001    0.107    0.107 test_pytracing.py:1(<module>)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:104(setup)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:109(initialize)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:112(start)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:115(stop)
        3    0.000    0.000    0.000    0.000 test_pytracing.py:118(compute)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:140(MyPingApp)
        1    0.014    0.014    0.073    0.073 test_pytracing.py:141(compose)
        1    0.009    0.009    0.083    0.083 test_pytracing.py:153(main)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:28(PingTxOp)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:29(__init__)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:34(setup)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:37(initialize)
```

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```
        1    0.000    0.000    0.000    0.000 test_pytracing.py:40(start)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:43(stop)
        3    0.000    0.000    0.000    0.000 test_pytracing.py:46(compute)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:58(PingMxOp)
        1    0.000    0.000    0.058    0.058 test_pytracing.py:59(__init__)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:65(setup)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:72(initialize)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:75(start)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:78(stop)
        3    0.001    0.000    0.001    0.000 test_pytracing.py:81(compute)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:98(PingRxOp)
        1    0.000    0.000    0.000    0.000 test_pytracing.py:99(__init__)
```

Using line_profiler

line_profiler is a module for doing line-by-line profiling of functions.

```
python -m pip install line_profiler

# Insert `@profile` before the function `def compute(self, op_input, op_output,␣
↪context):`.
# The original file will be backed up as `test_pytracing.py.bak`.
file="python/tests/system/test_pytracing.py"
pattern="    def compute(self, op_input, op_output, context):"
insertion="    @profile"

if ! grep -q "^$insertion" "$file"; then
    sed -i.bak "/^$pattern/i\\
$insertion" "$file"
fi

kernprof -lv python/tests/system/test_pytracing.py

# Remove the inserted `@profile` decorator.
mv "$file.bak" "$file"
```

```
...
Wrote profile results to test_pytracing.py.lprof
Timer unit: 1e-06 s

Total time: 0.000304244 s
File: python/tests/system/test_pytracing.py
Function: compute at line 46

Line #      Hits         Time  Per Hit   % Time  Line Contents
==============================================================
    46                                               @profile
    47                                               def compute(self, op_input, op_
↪output, context):
    48         3          2.3      0.8      0.8          value = self.index
    49         3          9.3      3.1      3.0          self.index += 1
```

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```
    50
    51          3           0.5       0.2       0.2          output = []
    52         18           5.0       0.3       1.6          for i in range(0, 5):
    53         15           4.2       0.3       1.4              output.append(value)
    54         15           2.4       0.2       0.8              value += 1
    55
    56          3         280.6      93.5      92.2          op_output.emit(output, "out")
...
```

18.4.3 Measuring Code Coverage

The Holoscan SDK provides support for measuring code coverage using Coverage.py.

```
python -m pip install coverage

coverage erase
coverage run examples/ping_vector/python/ping_vector.py
coverage report examples/ping_vector/python/ping_vector.py
coverage html

# Open the generated HTML report in a browser.
xdg-open htmlcov/index.html
```

To record code coverage programmatically, please refer to the `coverage_main()` method in `test_pytracing.py`.

You can execute the example application with code coverage enabled by running the following command:

```
python -m pip install coverage
python python/tests/system/test_pytracing.py coverage
# python python/tests/system/test_pytracing.py coverage -s multithread
```

The following command starts a Python application using the `trace` module:

```
python -m trace --trackcalls python/tests/system/test_pytracing.py | grep test_pytracing
```

```
...
    test_pytracing.main -> test_pytracing.MyPingApp.compose
    test_pytracing.main -> test_pytracing.PingMxOp.compute
    test_pytracing.main -> test_pytracing.PingMxOp.initialize
    test_pytracing.main -> test_pytracing.PingMxOp.start
    test_pytracing.main -> test_pytracing.PingMxOp.stop
    test_pytracing.main -> test_pytracing.PingRxOp.compute
    test_pytracing.main -> test_pytracing.PingRxOp.initialize
    test_pytracing.main -> test_pytracing.PingRxOp.start
    test_pytracing.main -> test_pytracing.PingRxOp.stop
    test_pytracing.main -> test_pytracing.PingTxOp.compute
    test_pytracing.main -> test_pytracing.PingTxOp.initialize
    test_pytracing.main -> test_pytracing.PingTxOp.start
    test_pytracing.main -> test_pytracing.PingTxOp.stop
```

A test case utilizing the `trace` module programmatically can be found in the `trace_main()` method in `test_pytracing.py`.

```
python python/tests/system/test_pytracing.py trace
# python python/tests/system/test_pytracing.py trace -s multithread
```

CHAPTER

NINETEEN

WRITING PYTHON BINDINGS FOR A C++ OPERATOR

For convenience while maintaining high performance, *operators written in C++* can be wrapped in Python. The general approach uses Pybind11 to concisely create bindings that provide a familiar, Pythonic experience to application authors.

Note: While we provide some utilities to simplify part of the process, this section is designed for advanced developers, since the wrapping of the C++ class using pybind11 is mostly manual and can vary between each operator.

The existing Pybind11 documentation is good and it is recommended to read at least the basics on wrapping functions and classes. The material below will assume some basic familiarity with Pybind11, covering the details of creation of the bindings of a C++ `Operator`. As a concrete example, we will cover creation of the bindings for ToolTrackingPostprocessorOp from Holohub as a simple case and then highlight additional scenarios that might be encountered.

Tip: There are several examples of bindings on Holohub in the operators folder. The subset of operators that provide a Python wrapper on top of a C++ implementation will have any C++ headers and sources together in a common folder, while any corresponding Python bindings will be in a "python" subfolder (see the tool_tracking_postprocessor folder layout, for example).

There are also several examples of bindings for the built-in operators of the SDK. Unlike on Holohub, for the SDK, the corresponding C++ headers and sources of an operator are stored under separate directory trees.

Warning: It is recommended to put any cleanup of resources allocated in the C++ operator's `initialize()` and/or `start()` methods into the `stop()` method of the operator and **not** in its destructor. This is necessary as a workaround to a current issue where it is not guaranteed that the destructor always gets called prior to Python application termination. The `stop()` method will always be explicitly called, so we can be assured that any cleanup happens as expected.

19.1 Tutorial: binding the ToolTrackingPostprocessorOp class

19.1.1 Creating a PyToolTrackingPostprocessorOp trampoline class

In a C++ file (tool_tracking_postprocessor.cpp in this case), create a subclass of the C++ Operator class to wrap. The general approach taken is to create a Python-specific class that provides a constructor that takes a `Fragment*`, an explicit list of the operators parameters with default values for any that are optional, and an operator name. This constructor needs to setup the operator as done in `Fragment::make_operator`, so that it is ready for initialization by the GXF executor. We use the convention of prepending "Py" to the C++ class name for this (so, `PyToolTrackingPostprocessorOp` in this case). :

Listing 19.1: tool_tracking_post_processor/python/tool_tracking_post_processor.cpp

```
class PyToolTrackingPostprocessorOp : public ToolTrackingPostprocessorOp {
 public:
  /* Inherit the constructors */
  using ToolTrackingPostprocessorOp::ToolTrackingPostprocessorOp;

  // Define a constructor that fully initializes the object.
  PyToolTrackingPostprocessorOp(
      Fragment* fragment, const py::args& args, std::shared_ptr<Allocator> device_
↪allocator,
      std::shared_ptr<Allocator> host_allocator, float min_prob = 0.5f,
      std::vector<std::vector<float>> overlay_img_colors = VIZ_TOOL_DEFAULT_COLORS,
      std::shared_ptr<holoscan::CudaStreamPool> cuda_stream_pool = nullptr,
      const std::string& name = "tool_tracking_postprocessor")
      : ToolTrackingPostprocessorOp(ArgList{Arg{"device_allocator", device_allocator},
                                            Arg{"host_allocator", host_allocator},
                                            Arg{"min_prob", min_prob},
                                            Arg{"overlay_img_colors", overlay_img_colors}
↪,
                                            }) {
    if (cuda_stream_pool) { this->add_arg(Arg{"cuda_stream_pool", cuda_stream_pool}); }
    add_positional_condition_and_resource_args(this, args);
    name_ = name;
    fragment_ = fragment;
    spec_ = std::make_shared<OperatorSpec>(fragment);
    setup(*spec_.get());
  }
};
```

This constructor will allow providing a Pythonic experience for creating the operator. Specifically, the user can pass Python objects for any of the parameters without having to explicitly create any `holoscan::Arg` objects via `holoscan.core.Arg`. For example, a standard Python float can be passed to `min_prob` and a Python `list[list[float]]` can be passed for `overlay_img_colors` (Pybind11 handles conversion between the C++ and Python types). Pybind11 will also take care of conversion of a Python allocator class like `holoscan.resources.UnboundedAllocator` or `holoscan.resources.BlockMemoryPool` to the underlying C++ `std::shared_ptr<holoscan::Allocator>` type. The arguments `device_allocator` and `host_allocator` correspond to required Parameters of the C++ class and can be provided from Python either positionally or via keyword while the Parameters `min_prob` and `overlay_img_colors` will be optional keyword arguments. `cuda_stream_pool` is also optional, but is only conditionally passed as an argument to the underlying `ToolTrackingPostprocessorOp` constructor when it is not a `nullptr`.

- For all operators, the first argument should be `Fragment* fragment` and is the fragment the operator will be assigned to. In the case of a single fragment application (i.e. not a distributed application), the fragment is just the application itself.
- An (optional) `const std::string& name` argument should be provided to enable the application author to set the operator's name.
- The `const py::args& args` argument corresponds to the `*args` notation in Python. It is a set of 0 or more positional arguments. It is not required to provide this in the function signature, but is recommended in order to enable passing additional conditions such as a `CountCondition` or `PeriodicCondtion` as positional arguments to the operator. The call below to

```
add_positional_condition_and_resource_args(this, args);
```

uses a helper function defined in operator_util.hpp to add any `Condition` or `Resource` arguments found in the list of positional arguments.

- The other arguments all correspond to the various parameters (`holoscan::Parameter`) that are defined for the C++ `ToolTrackingPostProcessorOp` class.
  - All other parameters except `cuda_stream_pool` are passed directly in the argument list to the parent `ToolTrackingPostProcessorOp` class. The parameters present on the C++ operator can be seen in its header here with default values taken from the `setup` method of the source file here. Note that `CudaStreamHandler` is a utility that will add a parameter of type `Parameter<std::shared_ptr<CudaStreamPool>>`.
  - The `cuda_stream_pool` argument is only conditionally added if it was not `nullptr` (Python's `None`). This is done via

    ```
    if (cuda_stream_pool) { this->add_arg(Arg{"cuda_stream_pool", cuda_stream_pool}
    ↪); }
    ```

    instead of passing it as part of the `holoscan::ArgList` provided to the `ToolTrackingPostprocessorOp` constructor call above.

The remaining lines of the constructor

```
    name_ = name;
    fragment_ = fragment;
    spec_ = std::make_shared<OperatorSpec>(fragment);
    setup(*spec_.get());
```

are required to properly initialize it and should be the same across all operators. These correspond to equivalent code within the Fragment::make_operator method.

19.1.2 Defining the Python module

For this operator, there are no other custom classes aside from the operator itself, so we define a module using `PYBIND11_MODULE` as shown below with only a single class definition. This is done in the same tool_tracking_postprocessor.cpp file where we defined the `PyToolTrackingPostprocessorOp` trampoline class.

The following header will always be needed.

```
#include <pybind11/pybind11.h>

namespace py = pybind11;
using pybind11::literals::operator""_a;
```

Here, we typically also add defined the `py` namespace as a shorthand for `pybind11` and indicated that we will use the `_a` literal (it provides a shorthand notation when defining keyword arguments).

Often it will be necessary to include the following header if any parameters to the operator involve C++ standard library containers such as `std::vector` or `std::unordered_map`.

```
#include <pybind11/stl.h>
```

This allows pybind11 to cast between the C++ container types and corresponding Python types (Python `dict` / C++ `std::unordered_map`, for example).

Listing 19.2: tool_tracking_post_processor/python/tool_tracking_post_processor.cpp

```
PYBIND11_MODULE(_tool_tracking_postprocessor, m) {
  py::class_<ToolTrackingPostprocessorOp,
             PyToolTrackingPostprocessorOp,
             Operator,
             std::shared_ptr<ToolTrackingPostprocessorOp>>(
      m,
      "ToolTrackingPostprocessorOp",
      doc::ToolTrackingPostprocessorOp::doc_ToolTrackingPostprocessorOp_python)
      .def(py::init<Fragment*,
                    const py::args& args,
                    std::shared_ptr<Allocator>,
                    std::shared_ptr<Allocator>,
                    float,
                    std::vector<std::vector<float>>,
                    std::shared_ptr<holoscan::CudaStreamPool>,
                    const std::string&>(),
           "fragment"_a,
           "device_allocator"_a,
           "host_allocator"_a,
           "min_prob"_a = 0.5f,
           "overlay_img_colors"_a = VIZ_TOOL_DEFAULT_COLORS,
           "cuda_stream_pool"_a = py::none(),
           "name"_a = "tool_tracking_postprocessor"s,
           doc::ToolTrackingPostprocessorOp::doc_ToolTrackingPostprocessorOp_python);
}  // PYBIND11_MODULE NOLINT
```

Note:

- If you are implementing the python wrapping in Holohub, the `<module_name>` passed to `PYBIND_11_MODULE` **must** match `_<CPP_CMAKE_TARGET>` as *covered below*).
- If you are implementing the python wrapping in a standalone CMake project,the `<module_name>` passed to `PYBIND_11_MODULE` **must** match the name of the module passed to the pybind11-add-module CMake function.

Using a mismatched name in `PYBIND_11_MODULE` will result in failure to import the module from Python.

The order in which the classes are specified in the `py::class_<>` template call is important and should follow the convention shown here. The first in the list is the C++ class name (`ToolTrackingPostprocessorOp`) and second is the `PyToolTrackingPostprocessorOp` class we defined above with the additional, explicit constructor. We also need to list the parent `Operator` class so that all of the methods such as `start`, `stop`, `compute`, `add_arg`, etc. that were already wrapped for the parent class don't need to be redefined here.

The single `.def(py::init<...` call wraps the `PyToolTrackingPostprocessorOp` constructor we wrote above. As such, the argument types provided to `py::init<>` must exactly match the order and types of arguments in that constructor's function signature. The subsequent arguments to `def` are the names and default values (if any) for the named arguments in the same order as the function signature. Note that the `const py::args& args` (Python `*args`) argument is not listed as these are positional arguments that don't have a corresponding name. The use of `py::none()` (Python's `None`) as the default for `cuda_stream_pool` corresponds to the `nullptr` in the C++ function signature. The "_a" literal used in the definition is enabled by the following declaration earlier in the file.

The final argument to `.def` here is a documentation string that will serve as the Python docstring for the function. It is optional and we chose here to define it in a separate header as described in the next section.

19.1.3 Documentation strings

Prepare documentation strings (`const char*`) for your python class and its parameters.

Note: Below we use a `PYDOC` macro defined in the SDK and available in HoloHub as a utility to remove leading spaces. In this case, the documentation code is located in header file tool_tracking_post_processor_pydoc.hpp, under a custom `holoscan::doc::ToolTrackingPostprocessorOp` namespace. None of this is required, you just need to make any documentation strings available for use as an argument to the `py::class_` constructor or method definition calls.

Listing 19.3: tool_tracking_post_processor/python/tool_tracking_post_processor_pydoc.hpp

```
#include "../macros.hpp"

namespace holoscan::doc {

namespace ToolTrackingPostprocessorOp {

// PyToolTrackingPostprocessorOp Constructor
PYDOC(ToolTrackingPostprocessorOp_python, R"doc(
Operator performing post-processing for the endoscopy tool tracking demo.

**==Named Inputs==**

    in : nvidia::gxf::Entity containing multiple nvidia::gxf::Tensor
        Must contain input tensors named "probs", "scaled_coords" and "binary_masks" that
        correspond to the output of the LSTMTensorRTInfereceOp as used in the endoscopy
        tool tracking example applications.

**==Named Outputs==**

    out_coords : nvidia::gxf::Tensor
        Coordinates tensor, stored on the host (CPU).

    out_mask : nvidia::gxf::Tensor
        Binary mask tensor, stored on device (GPU).

Parameters
----------
fragment : Fragment
    The fragment that the operator belongs to.
device_allocator : ``holoscan.resources.Allocator``
    Output allocator used on the device side.
host_allocator : ``holoscan.resources.Allocator``
    Output allocator used on the host side.
min_prob : float, optional
    Minimum probability (in range [0, 1]). Default value is 0.5.
overlay_img_colors : sequence of sequence of float, optional
    Color of the image overlays, a list of RGB values with components between 0 and 1.
    The default value is a qualitative colormap with a sequence of 12 colors.
cuda_stream_pool : ``holoscan.resources.CudaStreamPool``, optional
    `holoscan.resources.CudaStreamPool` instance to allocate CUDA streams.
```

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```
    Default value is ``None``.
name : str, optional
    The name of the operator.
)doc")

}  // namespace ToolTrackingPostprocessorOp
}  // namespace holoscan::doc
```

We tend to use NumPy-style docstrings for parameters, but also encourage adding a custom section at the top that describes the input and output ports and what type of data is expected on them. This can make it easier for developers to use the operator without having to inspect the source code to determine this information.

19.1.4 Configuring with CMake

We use CMake to configure pybind11 and build the bindings for the C++ operator you wish to wrap. There are two approaches detailed below, one for HoloHub (recommended), one for standalone CMake projects.

Tip: To have your bindings built, ensure the CMake code below is executed as part of a CMake project which already defines the C++ operator as a CMake target, either built in your project (with `add_library`) or imported (with `find_package` or `find_library`).

In HoloHub

We provide a CMake utility function named pybind11_add_holohub_module in HoloHub to facilitate configuring and building your python bindings.

In our skeleton code below, a top-level CMakeLists.txt which already defined the `tool_tracking_postprocessor` target for the C++ operator would need to do `add_subdirectory(tool_tracking_postprocessor)` to include the following CMakeLists.txt. The `pybind11_add_holohub_module` lists that C++ operator target, the C++ class to wrap, and the path to the C++ binding source code we implemented above. Note how the module name provided as the first argument to PYPBIND11_MODULE needs to match `_<CPP_CMAKE_TARGET>` (`_tool_tracking_postprocessor_op` in this case).

Listing 19.4: tool_tracking_postprocessor/python/CMakeLists.txt

```
include(pybind11_add_holohub_module)
pybind11_add_holohub_module(
    CPP_CMAKE_TARGET tool_tracking_postprocessor
    CLASS_NAME "ToolTrackingPostprocessorOp"
    SOURCES tool_tracking_postprocessor.cpp
)
```

The key details here are that `CLASS_NAME` should match the name of the C++ class that is being wrapped and is also the name that will be used for the class from Python. `SOURCES` should point to the file where the C++ operator that is being wrapped is defined. The `CPP_CMAKE_TARGET` name will be the name of the holohub package submodule that will contain the operator.

Note that the python subdirectory where this CMakeLists.txt resides is reachable thanks to the `add_subdirectory(python)` in the CMakeLists.txt one folder above, but that's an arbitrary opinionated location and not a required directory structure.

Standalone CMake

Follow the pybind11 documentation to configure your CMake project to use pybind11. Then, use the pybind11_add_module function with the cpp files containing the code above, and link against `holoscan::core` and the library that exposes your C++ operator to wrap.

Listing 19.5: my_op_python/CMakeLists.txt

```
pybind11_add_module(my_python_module my_op_pybind.cpp)
target_link_libraries(my_python_module
  PRIVATE holoscan::core
  PUBLIC my_op
)
```

Example: in the SDK, this is done here.

Warning: The name chosen for `CPP_CMAKE_TARGET` **must** also be used (along with a preceding underscore) as the module name passed as the first argument to the PYBIND11_MODULE macro in the bindings.

Note that there is an initial underscore prepended to the name. This is the naming convention used for the shared library and corresponding `__init__.py` file that will be generated by the `pybind11_add_holohub_module` helper function above.

If the name is specified incorrectly, the build will still complete, but at application run time an `ImportError` such as the following would occur

```
[command] python3 /workspace/holohub/applications/endoscopy_tool_tracking/python/
↪endoscopy_tool_tracking.py --data /workspace/holohub/data/endoscopy
Traceback (most recent call last):
  File "/workspace/holohub/applications/endoscopy_tool_tracking/python/endoscopy_tool_
↪tracking.py", line 38, in <module>
    from holohub.tool_tracking_postprocessor import ToolTrackingPostprocessorOp
  File "/workspace/holohub/build/python/lib/holohub/tool_tracking_postprocessor/__
↪init__.py", line 19, in <module>
    from ._tool_tracking_postprocessor import ToolTrackingPostprocessorOp
ImportError: dynamic module does not define module export function (PyInit__tool_
↪tracking_postprocessor)
```

19.1.5 Importing the class in Python

In HoloHub

When building your project, two files will be generated inside `<build_or_install_dir>/python/lib/holohub/<CPP_CMAKE_TARGET>` (e.g. `build/python/lib/holohub/tool_tracking_postprocessor/`):

1. the shared library for your bindings (`_tool_tracking_postprocessor_op.cpython-<pyversion>-<arch>-linux-gnu.so`)
2. an `__init__.py` file that makes the necessary imports to expose this in python

Assuming you have `export PYTHONPATH=<build_or_install_dir>/python/lib/`, you should then be able to create an application in Holohub that imports your class via:

```
from holohub.tool_tracking_postprocessor_op import ToolTrackingPostProcessorOp
```

Example: `ToolTrackingPostProcessorOp` is imported in the Endoscopy Tool Tracking application on HoloHub here.

Standalone CMake

When building your project, a shared library file holding the python bindings and named `my_python_module.cpython-<pyversion>-<arch>-linux-gnu.so` will be generated inside `<build_or_install_dir>/my_op_python` (configurable with `OUTPUT_NAME` and `LIBRARY_OUTPUT_DIRECTORY` respectively in CMake).

From there, you can import it in python via:

```
import holoscan.core
import holoscan.gxf  # if your c++ operator uses gxf extensions

from <build_or_install_dir>.my_op_python import MyOp
```

Tip: To imitate HoloHub's behavior, you can also place that file alongside the .so file, name it `__init__.py`, and replace `<build_or_install_dir>.` by `..` It can then be imported as a python module, assuming `<build_or_install_dir>` is a module under the `PYTHONPATH` environment variable.

19.2 Additional Examples

In this section we will cover other cases that may occasionally be encountered when writing Python bindings for operators.

19.2.1 Optional arguments

It is also possible to use `std::optional` to handle optional arguments. The `ToolTrackingProcessorOp` example above, for example, has a default argument defined in the spec for `min_prob`.

```
  constexpr float DEFAULT_MIN_PROB = 0.5f;
  // ...

  spec.param(
      min_prob_, "min_prob", "Minimum probability", "Minimum probability.", DEFAULT_MIN_
↪PROB);
```

In the tutorial for `ToolTrackingProcessorOp` above we reproduced this default of 0.5 in both the `PyToolTrackingProcessorOp` constructor function signature as well as the Python bindings defined for it. This carries the risk that the default could change at the C++ operator level without a corresponding change being made for Python.

An alternative way to define the constructor would have been to use `std::optional` as follows

```
  // Define a constructor that fully initializes the object.
  PyToolTrackingPostprocessorOp(
      Fragment* fragment, const py::args& args, std::shared_ptr<Allocator> device_
↪allocator,
```

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```
    std::shared_ptr<Allocator> host_allocator, std::optional<float> min_prob = 0.5f,
    std::optional<std::vector<std::vector<float>>> overlay_img_colors = VIZ_TOOL_
↪DEFAULT_COLORS,
    std::shared_ptr<holoscan::CudaStreamPool> cuda_stream_pool = nullptr,
    const std::string& name = "tool_tracking_postprocessor")
    : ToolTrackingPostprocessorOp(ArgList{Arg{"device_allocator", device_allocator},
                                          Arg{"host_allocator", host_allocator},
                                          }) {
  if (cuda_stream_pool) { this->add_arg(Arg{"cuda_stream_pool", cuda_stream_pool}); }
  if (min_prob.has_value()) { this->add_arg(Arg{"min_prob", min_prob.value() }); }
  if (overlay_img_colors.has_value()) {
      this->add_arg(Arg{"overlay_img_colors", overlay_img_colors.value() });
  }
  add_positional_condition_and_resource_args(this, args);
  name_ = name;
  fragment_ = fragment;
  spec_ = std::make_shared<OperatorSpec>(fragment);
  setup(*spec_.get());
}
```

where now that `min_prob` and `overlay_img_colors` are optional, they are only conditionally added as an argument to ToolTrackingPostprocessorOp when they have a value. If this approach is used, the Python bindings for the constructor should be updated to use `py::none()` as the default as follows:

```
    .def(py::init<Fragment*,
                  const py::args& args,
                  std::shared_ptr<Allocator>,
                  std::shared_ptr<Allocator>,
                  float,
                  std::vector<std::vector<float>>,
                  std::shared_ptr<holoscan::CudaStreamPool>,
                  const std::string&>(),
         "fragment"_a,
         "device_allocator"_a,
         "host_allocator"_a,
         "min_prob"_a = py::none(),
         "overlay_img_colors"_a = py::none(),
         "cuda_stream_pool"_a = py::none(),
         "name"_a = "tool_tracking_postprocessor"s,
         doc::ToolTrackingPostprocessorOp::doc_ToolTrackingPostprocessorOp_python);
```

19.2.2 C++ enum parameters as arguments

Sometimes, operators may use a Parameter with an enum type. It is necessary to wrap the C++ enum to be able to use it as a Python type when providing the argument to the operator.

The built-in `holoscan::ops::AJASourceOp` is an example of a C++ operator that takes a enum Parameter (an `NTV2Channel` enum).

The enum can easily be wrapped for use from Python via `py::enum_` as shown here. It is recommended in this case to follow Python's convention of using capitalized names in the enum.

19.2.3 (Advanced) Custom C++ classes as arguments

Sometimes it is necessary to accept a custom C++ class type as an argument in the operator's constructor. In this case additional interface code and bindings will likely be necessary to support the type.

A relatively simple example of this is the `DataVecMap` type used by `InferenceProcessorOp`. In that case, the type is a structure that holds an internal `std::map<std:string, std::vector<std::string>>`. The bindings are written to accept a Python dict (`py::dict`) and a helper function is used within the constructor to convert that dictionary to the corresponding C++ `DataVecMap`.

A more complicated case is the use of a `InputSpec` type in the `HolovizOp` bindings. This case involves creating Python bindings for classes `InputSpec` and `View` as well as a couple of enum types. To avoid the user having to build a `list[holoscan.operators.HolovizOp.InputSpec]` directly to pass as the `tensors` argument, an additional Python wrapper class was defined in the `__init__.py` to allow passing a simple Python dict for the `tensors` argument and any corresponding InputSpec classes are automatically created in its constructor before calling the underlying Python bindings class.

19.2.4 Customizing the C++ types a Python operator can emit or receive

In some instances, users may wish to be able to have a Python operator receive and/or emit other custom C++ types. As a first example, suppose we are wrapping an operator that emits a custom C++ type. We need any downstream native Python operators to be able to receive that type. By default the SDK is able to handle the needed C++ types for built in operators like `std::vector<holoscan::ops::HolovizOp::InputSpec>`. The SDK provides an `EmitterReceiverRegistry` class that third-party projects can use to register `receiver` and `emitter` methods for any custom C++ type that needs to be handled. To handle a new type, users should implement an `emitter_receiver<T>` struct for the desired type as in the example below. We will first cover the general steps necessary to register such a type and then cover where some steps may be omitted in certain simple cases.

Step 1: define emitter_receiver::emit and emitter_receiver::receive methods

Here is an example for the built-in `std::vector<holoscan::ops::HolovizOp::InputSpec>` used by `HolovizOp` to define the input specifications for its received tensors.

```
#include <holoscan/python/core/emitter_receiver_registry.hpp>

namespace py = pybind11;

namespace holoscan {

/* Implements emit and receive capability for the HolovizOp::InputSpec type.
 */
template <>
struct emitter_receiver<std::vector<holoscan::ops::HolovizOp::InputSpec>> {
  static void emit(py::object& data, const std::string& name, PyOutputContext& op_output,
                   const int64_t acq_timestamp = -1) {
    auto input_spec = data.cast<std::vector<holoscan::ops::HolovizOp::InputSpec>>();
    py::gil_scoped_release release;
    op_output.emit<std::vector<holoscan::ops::HolovizOp::InputSpec>>(input_spec, name.c_
↪str(), acq_timestamp);
    return;
  }

  static py::object receive(std::any result, const std::string& name, PyInputContext& op_
↪input) {
```

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```
    HOLOSCAN_LOG_DEBUG("py_receive: std::vector<HolovizOp::InputSpec> case");
    // can directly return vector<InputSpec>
    auto specs = std::any_cast<std::vector<holoscan::ops::HolovizOp::InputSpec>>(result);
    py::object py_specs = py::cast(specs);
    return py_specs;
  }
};

}
```

This emitter_receiver class defines a receive method that takes a std::any message and casts it to the corresponding Python list[HolovizOp.InputSpect] object. Here the pybind11::cast call works because we have wrapped the HolovizOp::InputSpec class here.

Similarly, the emit method takes a pybind11::object (of type list[HolovizOp.InputSpect]) and casts it to the corresponding C++ type, std::vector<holoscan::ops::HolovizOp::InputSpec>. The conversion between std::vector and a Python list is one of Pbind11's built-in conversions (available as long as "pybind11/stl.h" has been included).

The signature of the emit and receive methods must exactly match the case shown here.

Step 2: Create a register_types method for adding custom types to the EmitterReceiverRegistry.

The bindings in this operators module, should define a method named register_types that takes a reference to an EmitterReceiverRegistry as its only argument. Within this function there should be a call to EmitterReceiverRegistry::add_emitter_receiver for each type that this operator wished to register. The HolovizOp defines this method using a lambda function

```
  // Import the emitter/receiver registry from holoscan.core and pass it to this␣
↪function to
  // register this new C++ type with the SDK.
  m.def("register_types", [](EmitterReceiverRegistry& registry) {
    registry.add_emitter_receiver<std::vector<holoscan::ops::HolovizOp::InputSpec>>(
        "std::vector<HolovizOp::InputSpec>"s);
    // array camera pose object
    registry.add_emitter_receiver<std::shared_ptr<std::array<float, 16>>>(
        "std::shared_ptr<std::array<float, 16>>"s);
    // Pose3D camera pose object
    registry.add_emitter_receiver<std::shared_ptr<nvidia::gxf::Pose3D>>(
        "std::shared_ptr<nvidia::gxf::Pose3D>"s);
    // camera_eye_input, camera_look_at_input, camera_up_input
    registry.add_emitter_receiver<std::array<float, 3>>("std::array<float, 3>"s);
  });
```

Here the following line registers the std::vector<holoscan::ops::HolovizOp::InputSpec> type that we wrote an emitter_receiver for above.

```
registry.add_emitter_receiver<std::vector<holoscan::ops::HolovizOp::InputSpec>>(
        "std::vector<HolovizOp::InputSpec>"s);
```

Internally the registry stores a mapping between the C++ std::type_index of the type specified in the template argument and the emitter_receiver defined for that type. The second argument is a string that the user can choose which is a label for the type. As we will see later, this label can be used from Python to indicate that we want to emit using the emitter_receiver::emit method that was registered for a particular label.

Step 3: In the init.py file for the Python module defining the operator call register_types

To register types with the core SDK, we need to import the `io_type_registry` class (of type `EmitterReceiverRegistry`) from `holoscan.core`. We then pass that class as input to the `register_types` method defined in step 2 to register the 3rd party types with the core SDK.

```python
from holoscan.core import io_type_registry

from ._holoviz import register_types as _register_types

# register methods for receiving or emitting list[HolovizOp.InputSpec] and camera pose␣
↪types
_register_types(io_type_registry)
```

where we chose to import `register_types` with an initial underscore as a common Python convention to indicate it is intended to be "private" to this module.

In some cases steps 1 and 3 as shown above are not necessary.

When creating Python bindings for an Operator on Holohub, the pybind11_add_holohub_module.cmake utility mentioned above will take care of autogenerating the `__init__.py` as shown in step 3, so it will not be necessary to manually create it in that case.

For types for which Pybind11's default casting between C++ and Python is adequate, it is not necessary to explicitly define the `emitter_receiver` class as shown in step 1. This is true because there are a couple of default implementations for `emitter_receiver<T>` and `emitter_receiver<std::shared_ptr<T>>` that already cover common cases. The default emitter_receiver works for the `std::vector<HolovizOp::InputSpec>` type shown above, which is why the code shown for illustration there is not found within the operator's bindings. In that case one could immediately implement `register_types` from step 2 without having to explicitly create an `emitter_receiver` class.

An example where the default `emitter_receiver` would not work is the custom one defined by the SDK for `pybind11::dict`. In this case, to provide convenient emit of multiple tensors via passing a `dict[holoscan::Tensor]` to `op_output.emit` we have special handling of Python dictionaries. The dictionary is inspected and if all keys are strings and all values are tensor-like objects, a single C++ `nvidia::gxf::Entity` containing all of the tensors as an `nvidia::gxf::Tensor` is emitted. If the dictionary is not a tensor map, then it is just emitted as a shared pointer to the Python dict object. The `emitter_receiver` implementations used for the core SDK are defined in emitter_receivers.hpp. These can serve as a reference when creating new ones for additional types.

Runtime behavior of emit and receive

After registering a new type, receive of that type on any input port will automatically be handled. This is because due to the strong typing of C++, any `op_input.receive` call in an operator's `compute` method can find the registered `receive` method that matches the `std::type_index` of the type and use that to convert to a corresponding Python object.

Because Python is not strongly typed, on `emit`, the default behavior remains emitting a shared pointer to the Python object itself. If we instead want to `emit` a C++ type, we can pass a 3rd argument to `op_output.emit` to specify the name that we used when registering the types via the `add_emitter_receiver` call as above.

Example of emitting a C++ type

As a concrete example, the SDK already registers `std::string` by default. If we wanted, for instance, to emit a Python string as a C++ `std::string` for use by a downstream operator that is wrapping a C++ operator expecting string input, we would add a 3rd argument to the `op_output.emit` call as follows

```
# emit a Python filename string on port "filename_out" using registered type "std::string
↪"
my_string = "filename.raw"
op_output.emit(my_string, "filename_out", "std::string")
```

This specifies that the `emit` method that converts to C++ `std::string` should be used instead of the default behavior of emitting the Python string.

Another example would be to emit a Python `List[float]` as a `std::array<float, 3>` parameter as input to the `camera_eye`, `camera_look_at` or `camera_up` input ports of `HolovizOp`.

```
op_output.emit([0.0, 1.0, 0.0], "camera_eye_out", "std::array<float, 3>")
```

Only types registered with the SDK can be specified by name in this third argument to `emit`.

Table of types registered by the core SDK

The list of types that are registered with the SDK's `EmitterReceiverRegistry` are given in the table below.

C++ Type	name in the EmitterReceiverRegistry
holoscan::TensorMap (with single tensor)	"holoscan::Tensor"
std::shared_ptr<holoscan::GILGuardedPyObject>	"PyObject"
std::string	"std::string"
pybind11::dict	"pybind11::dict"
holoscan::gxf::Entity	"holoscan::gxf::Entity"
holoscan::PyEntity	"holoscan::PyEntity"
nullptr_t	"nullptr_t"
CloudPickleSerializedObject	"CloudPickleSerializedObject"
std::array<float, 3>	"std::array<float, 3>"
std::shared_ptr<std::array<float, 16>>	"std::shared_ptr<std::array<float, 16>>"
std::shared_ptr<nvidia::gxf::Pose3D>	"std::shared_ptr<nvidia::gxf::Pose3D>"
std::vector<holoscan::ops::HolovizOp::InputSpec>	"std::vector<HolovizOp::InputSpec>"

Note: There is no requirement that the registered name match any particular convention. We generally used the C++ type as the name to avoid ambiguity, but that is not required.

The sections above explain how a `register_types` function can be added to bindings to expand this list. It is also possible to get a list of all currently registered types, including those that have been registered by any additional imported third-party modules. This can be done via.

Note: For more details on emit/receive behavior for tensor-like types see *this dedicated section*.

```python
from holoscan.core import io_type_registry

print(io_type_registry.registered_types())
```

CHAPTER

TWENTY

BUILT-IN OPERATORS AND EXTENSIONS

The units of work of Holoscan applications are implemented within Operators, as described in the *core concepts* of the SDK. The operators included in the SDK provide domain-agnostic functionalities such as IO, machine learning inference, processing, and visualization, optimized for AI streaming pipelines, relying on a set of *Core Technologies*.

(holoscan-operators=)

20.1 Operators

The operators below are defined under the `holoscan::ops` namespace for C++ and CMake, and under the `holoscan.operators` module in Python.

Class	CMake target/lib	Documentation
AJASourceOp	`aja`	`C++/Python`
BayerDemosaicOp	`bayer_demosaic`	`C++/Python`
FormatConverterOp	`format_converter`	`C++/Python`
HolovizOp	`holoviz`	`C++/Python`
InferenceOp	`inference`	`C++/Python`
InferenceProcessorOp	`inference_processor`	`C++/Python`
PingRxOp	`ping_rx`	`C++/Python`
PingTensorRxOp	`ping_tensor_rx`	`C++/Python`
PingTensorTxOp	`ping_tensor_tx`	`C++/Python`
PingTxOp	`ping_tx`	`C++/Python`
SegmentationPostprocessorOp	`segmentation_postprocessor`	`C++/Python`
VideoStreamRecorderOp	`video_stream_recorder`	`C++/Python`
VideoStreamReplayerOp	`video_stream_replayer`	`C++/Python`
V4L2VideoCaptureOp	`v4l2`	`C++/Python`

Given an instance of an operator class, you can print a human-readable description of its specification to inspect the inputs, outputs, and parameters that can be configured on that operator class:

C++

```
std::cout << operator_object->spec()->description() << std::endl;
```

Python

```
print(operator_object.spec)
```

Note: The Holoscan SDK uses meta-programming with templating and `std::any` to support arbitrary data types. Because of this, some type information (and therefore values) might not be retrievable by the `description` API. If more details are needed, we recommend inspecting the list of `Parameter` members in the operator header to identify their type.

20.2 Extensions

The Holoscan SDK also includes some GXF extensions with GXF codelets, which are typically wrapped as operators, or present for legacy reasons. In addition to the core GXF extensions (std, cuda, serialization, multimedia) listed *here*, the Holoscan SDK includes the following GXF extensions:

- *gxf_holoscan_wrapper*
- *ucx_holoscan*

20.2.1 GXF Holoscan Wrapper

The `gxf_holoscan_wrapper` extension provides the `holoscan::gxf::OperatorWrapper` codelet and the `holoscan::gxf::ResourceWrapper` component. It serves as a utility base class for wrapping a Holoscan operator or resource as a GXF codelet or component, respectively. This extension allows Holoscan operators and resources to be integrated into GXF applications and GraphComposer workflows.

Learn more about it in the *Using Holoscan Operators in GXF Applications* section.

20.2.2 UCX (Holoscan)

The `ucx_holoscan` extension includes `nvidia::holoscan::UcxHoloscanComponentSerializer` which is a `nvidia::gxf::ComponentSerializer` that handles serialization of `holoscan::Message` and `holoscan::Tensor` types for transmission using the Unified Communication X (UCX) library. UCX is the library used by Holoscan SDK to enable communication of data between fragments in distributed applications.

Note: The `UcxHoloscanComponentSerializer` is intended for use in combination with other UCX components defined in the GXF UCX extension. Specifically, it can be used by the `UcxEntitySerializer` where it can operate alongside the `UcxComponentSerializer` that serializes GXF-specific types (`nvidia::gxf::Tensor`, `nvidia::gxf::VideoBuffer`, etc.). This way both GXF and Holoscan types can be serialized by distributed applications.

20.2.3 HoloHub

Visit the HoloHub repository to find a collection of additional Holoscan operators and extensions.

CHAPTER

TWENTYONE

VISUALIZATION

21.1 Overview

Holoviz provides the functionality to composite real-time streams of frames with multiple different other layers like segmentation mask layers, geometry layers, and GUI layers.

For maximum performance, Holoviz makes use of Vulkan, which is already installed as part of the NVIDIA GPU driver.

Holoscan provides the *Holoviz operator* which is sufficient for many, even complex visualization tasks. The *Holoviz operator* is used by multiple Holoscan example applications.

Additionally, for more advanced use cases, the *Holoviz module* can be used to create application-specific visualization operators. The *Holoviz module* provides a C++ API and is also used by the *Holoviz operator*.

The term Holoviz is used for both the *Holoviz operator* and the *Holoviz module* below. Both the operator and the module roughly support the same feature set. Where applicable, information on how to use a feature with the operator and the module is provided. It's explicitly mentioned below when features are not supported by the operator.

21.2 Layers

The core entity of Holoviz are layers. A layer is a two-dimensional image object. Multiple layers are composited to create the final output.

These layer types are supported by Holoviz:

- Image layer
- Geometry layer
- GUI layer

All layers have common attributes which define the look and also the way layers are finally composited.

The priority determines the rendering order of the layers. Before rendering, the layers are sorted by priority. The layers with the lowest priority are rendered first, so that the layer with the highest priority is rendered on top of all other layers. If layers have the same priority, then the render order of these layers is undefined.

The example below draws a transparent geometry layer on top of an image layer (geometry data and image data creation is omitted in the code). Although the geometry layer is specified first, it is drawn last because it has a higher priority (`1`) than the image layer (`0`).

Operator

The operator has a `receivers` port which accepts tensors and video buffers produced by other operators. Each tensor or video buffer will result in a layer.

The operator autodetects the layer type for certain input types (e.g., a video buffer will result in an image layer).

For other input types or more complex use cases, input specifications can be provided either at initialization time as a parameter or dynamically at runtime.

```
std::vector<ops::HolovizOp::InputSpec> input_specs;

auto& geometry_spec =
    input_specs.emplace_back(ops::HolovizOp::InputSpec("point_tensor",␣
↪ops::HolovizOp::InputType::POINTS));
geometry_spec.priority_ = 1;
geometry_spec.opacity_ = 0.5;

auto& image_spec =
    input_specs.emplace_back(ops::HolovizOp::InputSpec("image_tensor",␣
↪ops::HolovizOp::InputType::IMAGE));
image_spec.priority_ = 0;

auto visualizer = make_operator<ops::HolovizOp>("holoviz", Arg("tensors", input_specs));

// the source provides two tensors named "point_tensor" and "image_tensor" at the
↪"outputs" port.
add_flow(source, visualizer, {{"outputs", "receivers"}});
```

Module

The definition of a layer is started by calling one of the layer begin functions `viz::BeginImageLayer()`, `viz::BeginGeometryLayer()` or `viz::BeginImGuiLayer()`. The layer definition ends with `viz::EndLayer()`.

The start of a layer definition is resetting the layer attributes like priority and opacity to their defaults. So for the image layer, there is no need to set the opacity to `1.0` since the default is already `1.0`.

```
namespace viz = holoscan::viz;

viz::Begin();

viz::BeginGeometryLayer();
viz::LayerPriority(1);
viz::LayerOpacity(0.5);
/// details omitted
viz::EndLayer();

viz::BeginImageLayer();
viz::LayerPriority(0);
/// details omitted
viz::EndLayer();

viz::End();
```

21.2.1 Image Layers

Operator

Image data can either be on host or device (GPU); both tensors and video buffers are accepted.

```
std::vector<ops::HolovizOp::InputSpec> input_specs;

auto& image_spec =
    input_specs.emplace_back(ops::HolovizOp::InputSpec("image",␣
↪ops::HolovizOp::InputType::IMAGE));

auto visualizer = make_operator<ops::HolovizOp>("holoviz", Arg("tensors", input_specs));

// the source provides an image named "image" at the "outputs" port.
add_flow(source, visualizer, {{"output", "receivers"}});
```

Module

The function `viz::BeginImageLayer()` starts an image layer. An image layer displays a rectangular 2D image.

The image data is defined by calling `viz::ImageCudaDevice()`, `viz::ImageCudaArray()` or `viz::ImageHost()`. Various input formats are supported, see `viz::ImageFormat`.

For single channel image formats image colors can be looked up by defining a lookup table with `viz::LUT()`.

```
viz::BeginImageLayer();
viz::ImageHost(width, height, format, data);
viz::EndLayer();
```

Supported Image Formats

Operator

Supported formats for `nvidia::gxf::VideoBuffer`.

nvidia::gxf::VideoFormat	Supported	Description
GXF_VIDEO_FORMAT_CUSTOM	-	
GXF_VIDEO_FORMAT_YUV420	✓	BT.601 multi planar 4:2:0 YUV
GXF_VIDEO_FORMAT_YUV420_ER	✓	BT.601 multi planar 4:2:0 YUV ER
GXF_VIDEO_FORMAT_YUV420_709	✓	BT.709 multi planar 4:2:0 YUV
GXF_VIDEO_FORMAT_YUV420_709_ER	✓	BT.709 multi planar 4:2:0 YUV ER
GXF_VIDEO_FORMAT_NV12	✓	BT.601 multi planar 4:2:0 YUV with interleaved UV
GXF_VIDEO_FORMAT_NV12_ER	✓	BT.601 multi planar 4:2:0 YUV ER with interleaved UV
GXF_VIDEO_FORMAT_NV12_709	✓	BT.709 multi planar 4:2:0 YUV with interleaved UV
GXF_VIDEO_FORMAT_NV12_709_ER	✓	BT.709 multi planar 4:2:0 YUV ER with interleaved UV
GXF_VIDEO_FORMAT_RGBA	✓	RGBA-8-8-8-8 single plane
GXF_VIDEO_FORMAT_BGRA	✓	BGRA-8-8-8-8 single plane
GXF_VIDEO_FORMAT_ARGB	✓	ARGB-8-8-8-8 single plane
GXF_VIDEO_FORMAT_ABGR	✓	ABGR-8-8-8-8 single plane
GXF_VIDEO_FORMAT_RGBX	✓	RGBX-8-8-8-8 single plane

continues on next page

Table 21.1 – continued from previous page

nvidia::gxf::VideoFormat	Supported	Description
GXF_VIDEO_FORMAT_BGRX	✓	BGRX-8-8-8-8 single plane
GXF_VIDEO_FORMAT_XRGB	✓	XRGB-8-8-8-8 single plane
GXF_VIDEO_FORMAT_XBGR	✓	XBGR-8-8-8-8 single plane
GXF_VIDEO_FORMAT_RGB	✓	RGB-8-8-8 single plane
GXF_VIDEO_FORMAT_BGR	✓	BGR-8-8-8 single plane
GXF_VIDEO_FORMAT_R8_G8_B8	-	RGB - unsigned 8 bit multiplanar
GXF_VIDEO_FORMAT_B8_G8_R8	-	BGR - unsigned 8 bit multiplanar
GXF_VIDEO_FORMAT_GRAY	✓	8 bit GRAY scale single plane
GXF_VIDEO_FORMAT_GRAY16	✓	16 bit GRAY scale single plane
GXF_VIDEO_FORMAT_GRAY32	-	32 bit GRAY scale single plane
GXF_VIDEO_FORMAT_GRAY32F	✓	float 32 bit GRAY scale single plane
GXF_VIDEO_FORMAT_RGB16	-	RGB-16-16-16 single plane
GXF_VIDEO_FORMAT_BGR16	-	BGR-16-16-16 single plane
GXF_VIDEO_FORMAT_RGB32	-	RGB-32-32-32 single plane
GXF_VIDEO_FORMAT_BGR32	-	BGR-32-32-32 single plane
GXF_VIDEO_FORMAT_R16_G16_B16	-	RGB - signed 16 bit multiplanar
GXF_VIDEO_FORMAT_B16_G16_R16	-	BGR - signed 16 bit multiplanar
GXF_VIDEO_FORMAT_R32_G32_B32	-	RGB - signed 32 bit multiplanar
GXF_VIDEO_FORMAT_B32_G32_R32	-	BGR - signed 32 bit multiplanar
GXF_VIDEO_FORMAT_NV24	-	multi planar 4:4:4 YUV with interleaved UV
GXF_VIDEO_FORMAT_NV24_ER	-	multi planar 4:4:4 YUV ER with interleaved UV
GXF_VIDEO_FORMAT_R8_G8_B8_D8	-	RGBD unsigned 8 bit multiplanar
GXF_VIDEO_FORMAT_R16_G16_B16_D16	-	RGBD unsigned 16 bit multiplanar
GXF_VIDEO_FORMAT_R32_G32_B32_D32	-	RGBD unsigned 32 bit multiplanar
GXF_VIDEO_FORMAT_RGBD8	-	RGBD 8 bit unsigned single plane
GXF_VIDEO_FORMAT_RGBD16	-	RGBD 16 bit unsigned single plane
GXF_VIDEO_FORMAT_RGBD32	-	RGBD 32 bit unsigned single plane
GXF_VIDEO_FORMAT_D32F	✓	Depth 32 bit float single plane
GXF_VIDEO_FORMAT_D64F	-	Depth 64 bit float single plane
GXF_VIDEO_FORMAT_RAW16_RGGB	-	RGGB-16-16-16-16 single plane
GXF_VIDEO_FORMAT_RAW16_BGGR	-	BGGR-16-16-16-16 single plane
GXF_VIDEO_FORMAT_RAW16_GRBG	-	GRBG-16-16-16-16 single plane
GXF_VIDEO_FORMAT_RAW16_GBRG	-	GBRG-16-16-16-16 single plane

Image format detection for `nvidia::gxf::Tensor`. Tensors don't have image format information attached. The Holoviz operator detects the image format from the tensor configuration.

nvidia::gxf::PrimitiveType	Channels	Color format	Index for color lookup
kUnsigned8	1	8 bit GRAY scale single plane	✓
kInt8	1	signed 8 bit GRAY scale single plane	✓
kUnsigned16	1	16 bit GRAY scale single plane	✓
kInt16	1	signed 16 bit GRAY scale single plane	✓
kUnsigned32	1	-	✓
kInt32	1	-	✓
kFloat32	1	float 32 bit GRAY scale single plane	✓
kUnsigned8	3	RGB-8-8-8 single plane	-
kInt8	3	signed RGB-8-8-8 single plane	-
kUnsigned8	4	RGBA-8-8-8-8 single plane	-
kInt8	4	signed RGBA-8-8-8-8 single plane	-
kUnsigned16	4	RGBA-16-16-16-16 single plane	-
kInt16	4	signed RGBA-16-16-16-16 single plane	-
kFloat32	4	RGBA float 32 single plane	-

Module

See `viz::ImageFormat` for supported image formats. Additionally `viz::ImageComponentMapping()` can be used to map the color components of an image to the color components of the output.

21.2.2 Geometry Layers

A geometry layer is used to draw 2d or 3d geometric primitives. 2d primitives are points, lines, line strips, rectangles, ovals or text and are defined with 2d coordinates (x, y). 3d primitives are points, lines, line strips or triangles and are defined with 3d coordinates (x, y, z).

Coordinates start with (0, 0) in the top left and end with (1, 1) in the bottom right for 2d primitives.

Operator

See holoviz_geometry.cpp and holoviz_geometry.py for 2d geometric primitives and and holoviz_geometry.py for 3d geometric primitives.

Module

The function `viz::BeginGeometryLayer()` starts a geometry layer.

See `viz::PrimitiveTopology` for supported geometry primitive topologies.

There are functions to set attributes for geometric primitives like color (`viz::Color()`), line width (`viz::LineWidth()`), and point size (`viz::PointSize()`).

The code below draws a red rectangle and a green text.

```
namespace viz = holoscan::viz;

viz::BeginGeometryLayer();

// draw a red rectangle
viz::Color(1.f, 0.f, 0.f, 0.f);
```

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```
const float data[]{0.1f, 0.1f, 0.9f, 0.9f};
viz::Primitive(viz::PrimitiveTopology::RECTANGLE_LIST, 1, sizeof(data) / sizeof(data[0]),
↪ data);

// draw green text
viz::Color(0.f, 1.f, 0.f, 0.f);
viz::Text(0.5f, 0.5f, 0.2f, "Text");

viz::EndLayer();
```

21.2.3 ImGui Layers

Note: ImGui layers are not supported when using the Holoviz operator.

The Holoviz module supports user interface layers created with Dear ImGui.

Calls to the Dear ImGui API are allowed between `viz::BeginImGuiLayer()` and `viz::EndImGuiLayer()`, and are used to draw to the ImGui layer. The ImGui layer behaves like other layers and is rendered with the layer opacity and priority.

The code below creates a Dear ImGui window with a checkbox used to conditionally show a image layer.

```
namespace viz = holoscan::viz;

bool show_image_layer = false;
while (!viz::WindowShouldClose()) {
    viz::Begin();

    viz::BeginImGuiLayer();

    ImGui::Begin("Options");
    ImGui::Checkbox("Image layer", &show_image_layer);
    ImGui::End();

    viz::EndLayer();

    if (show_image_layer) {
        viz::BeginImageLayer();
        viz::ImageHost(...);
        viz::EndLayer();
    }

    viz::End();
}
```

ImGUI is a static library and has no stable API. Therefore, the application and Holoviz have to use the same ImGUI version. When the link target `holoscan::viz::imgui` is exported, make sure to link your application against that target.

21.2.4 Depth Map Layers

A depth map is a single channel 2d array where each element represents a depth value. The data is rendered as a 3D object using points, lines, or triangles. The color for the elements can also be specified.

Supported formats for the depth map:

- 8-bit unsigned normalized format that has a single 8-bit depth component
- 32-bit signed float format that has a single 32-bit depth component

Supported format for the depth color map:

- 32-bit unsigned normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3

Depth maps are rendered in 3D and support camera movement.

Operator

```
std::vector<ops::HolovizOp::InputSpec> input_specs;

auto& depth_map_spec =
    input_specs.emplace_back(ops::HolovizOp::InputSpec("depth_map",␣
↪ops::HolovizOp::InputType::DEPTH_MAP));
depth_map_spec.depth_map_render_mode_ = ops::HolovizOp::DepthMapRenderMode::TRIANGLES;

auto visualizer = make_operator<ops::HolovizOp>("holoviz",
    Arg("tensors", input_specs));

// the source provides an depth map named "depth_map" at the "output" port.
add_flow(source, visualizer, {{"output", "receivers"}});
```

Module

See holoviz depth map demo.

21.3 Views

By default, a layer will fill the whole window. When using a view, the layer can be placed freely within the window.

Layers can also be placed in 3D space by specifying a 3D transformation matrix.

Note: For geometry layers, there is a default matrix which allows coordinates in the range of [0 … 1] instead of the Vulkan [-1 … 1] range. When specifying a matrix for a geometry layer, this default matrix is overwritten.

When multiple views are specified, the layer is drawn multiple times using the specified layer view.

It's possible to specify a negative term for height, which flips the image. When using a negative height, you should also adjust the y value to point to the lower left corner of the viewport instead of the upper left corner.

Operator

See holoviz_views.py.

Module

Use `viz::LayerAddView()` to add a view to a layer.

21.4 Camera

When rendering 3d geometry using a geometry layer with 3d primitives or using a depth map layer the camera properties can either be set by the application or interactively changed by the user.

To interactively change the camera, use the mouse:

- Orbit (LMB)
- Pan (LMB + CTRL | MMB)
- Dolly (LMB + SHIFT | RMB | Mouse wheel)
- Look Around (LMB + ALT | LMB + CTRL + SHIFT)
- Zoom (Mouse wheel + SHIFT)

Operator

See holoviz_camera.cpp.

Module

Use `viz::SetCamera()` to change the camera.

21.5 Using a Display in Exclusive Mode

Typically, Holoviz opens a normal window on the Linux desktop. In that case, the desktop compositor is combining the Holoviz image with all other elements on the desktop. To avoid this extra compositing step, Holoviz can render to a display directly.

21.5.1 Configure a Display for Exclusive Use

Single display

SSH into the machine and stop the X server:

```
sudo systemctl stop display-manager
```

To resume the `display manager`, run:

```
sudo systemctl start display-manager
```

Multiple displays

The display to be used in exclusive mode needs to be disabled in the NVIDIA Settings application (`nvidia-settings`): open the `X Server Display Configuration` tab, select the display and under `Configuration` select `Disabled`. Press `Apply`.

21.5.2 Enable Exclusive Display in Holoviz

Operator

Arguments to pass to the Holoviz operator:

```
auto visualizer = make_operator<ops::HolovizOp>("holoviz",
    Arg("use_exclusive_display", true), // required
    Arg("display_name", "DP-2"), // optional
    Arg("width", 2560), // optional
    Arg("height", 1440), // optional
    Arg("framerate", 240) // optional
    );
```

Module

Provide the name of the display and desired display mode properties to `viz::Init()`.

If the name is `nullptr`, then the first display is selected.

The name of the display can either be the EDID name as displayed in the NVIDIA Settings, or the output name provided by `xrandr` or `hwinfo --monitor`.

Tip:

X11

In this example output of `xrandr`, `DP-2` would be an adequate display name to use:

```
Screen 0: minimum 8 x 8, current 4480 x 1440, maximum 32767 x 32767
DP-0 disconnected (normal left inverted right x axis y axis)
DP-1 disconnected (normal left inverted right x axis y axis)
DP-2 connected primary 2560x1440+1920+0 (normal left inverted right x axis y axis) 600mm␣
↪x 340mm
   2560x1440     59.98 + 239.97*  199.99   144.00   120.00    99.95
   1024x768      60.00
   800x600       60.32
   640x480       59.94
USB-C-0 disconnected (normal left inverted right x axis y axis)
```

Wayland and X11

In this example output of `hwinfo`, `MSI MPG343CQR would be an adequate display name to use:

```
$ hwinfo --monitor | grep Model
  Model: "MSI MPG343CQR"
```

21.6 CUDA Streams

By default, Holoviz is using CUDA stream `0` for all CUDA operations. Using the default stream can affect concurrency of CUDA operations, see stream synchronization behavior for more information.

Operator

The operator is using a `holoscan::CudaStreamPool` instance if provided by the `cuda_stream_pool` argument. The stream pool is used to create a CUDA stream used by all Holoviz operations.

```
const std::shared_ptr<holoscan::CudaStreamPool> cuda_stream_pool =
    make_resource<holoscan::CudaStreamPool>("cuda_stream", 0, 0, 0, 1, 5);
auto visualizer =
    make_operator<holoscan::ops::HolovizOp>("visualizer",
        Arg("cuda_stream_pool") = cuda_stream_pool);
```

Module

When providing CUDA resources to Holoviz through (e.g., `viz::ImageCudaDevice()`), Holoviz is using CUDA operations to use that memory. The CUDA stream used by these operations can be set by calling `viz::SetCudaStream()`. The stream can be changed at any time.

21.7 Reading the Frame Buffer

The rendered frame buffer can be read back. This is useful when doing offscreen rendering or running Holoviz in a headless environment.

Note: Reading the depth buffer is not supported when using the Holoviz operator.

Operator

To read back the color frame buffer, set the `enable_render_buffer_output` parameter to `true` and provide an allocator to the operator.

The frame buffer is emitted on the `render_buffer_output` port.

```
std::shared_ptr<holoscan::ops::HolovizOp> visualizer =
    make_operator<ops::HolovizOp>("visualizer",
        Arg("enable_render_buffer_output", true),
        Arg("allocator") = make_resource<holoscan::UnboundedAllocator>("allocator"),
        Arg("cuda_stream_pool") = cuda_stream_pool);

add_flow(visualizer, destination, {{"render_buffer_output", "input"}});
```

Module

The rendered color or depth buffer can be read back using `viz::ReadFramebuffer()`.

21.8 sRGB

The sRGB color space is supported for both images and the framebuffer. By default Holoviz is using a linear encoded framebuffer.

Operator

To switch the framebuffer color format set the `framebuffer_srgb` parameter to `true`.

To use sRGB encoded images set the `image_format` field of the `InputSpec` structure to a sRGB image format.

Module

Use the `viz::SetSurfaceFormat()` to set the framebuffer surface format to a sRGB color format.

To use sRGB encoded images set the `fmt` parameter of `viz::ImageCudaDevice()`, `viz::ImageCudaArray()` or `viz::ImageHost()` to a sRGB image format.

21.9 HDR

Holoviz supports selecting the framebuffer surface image format and color space. To enable HDR select a HDR color space.

Operator

Set the `framebuffer_color_space` parameter to a supported HDR color space.

Module

Use the `viz::GetSurfaceFormats()` to query the available surface formats.

Use the `viz::SetSurfaceFormat()` to set the framebuffer surface format to a surface format with a HDR color space.

21.9.1 Distributions supporting HDR

At the time of writing (08/2024) there is currently no official support for HDR on Linux. However there is experimental HDR support for Gnome version 44 and KDE Plasma 6.

KDE Plasma 6

Experimental HDR support is described in this blog post. Three steps are required to use HDR with Holoviz:

1. Enable HDR in the display configuration
2. Install the Vulkan HDR layer
3. Set the `ENABLE_HDR_WSI` environment variable to 1.

Run `vulkaninfo` to verify that HDR color spaces are reported

```
> vulkaninfo
...
GPU id : 0 (NVIDIA RTX 6000 Ada Generation):
        Surface type = VK_KHR_wayland_surface
        Formats: count = 11
                SurfaceFormat[0]:
                        format = FORMAT_A2B10G10R10_UNORM_PACK32
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[1]:
                        format = FORMAT_A2R10G10B10_UNORM_PACK32
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[2]:
                        format = FORMAT_R8G8B8A8_SRGB
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[3]:
                        format = FORMAT_R8G8B8A8_UNORM
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[4]:
                        format = FORMAT_B8G8R8A8_SRGB
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[5]:
                        format = FORMAT_B8G8R8A8_UNORM
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[6]:
                        format = FORMAT_R16G16B16A16_SFLOAT
                        colorSpace = COLOR_SPACE_SRGB_NONLINEAR_KHR
                SurfaceFormat[7]:
```

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```
                format = FORMAT_A2B10G10R10_UNORM_PACK32
                colorSpace = COLOR_SPACE_HDR10_ST2084_EXT
        SurfaceFormat[8]:
                format = FORMAT_A2R10G10B10_UNORM_PACK32
                colorSpace = COLOR_SPACE_HDR10_ST2084_EXT
        SurfaceFormat[9]:
                format = FORMAT_R16G16B16A16_SFLOAT
                colorSpace = COLOR_SPACE_EXTENDED_SRGB_LINEAR_EXT
        SurfaceFormat[10]:
                format = FORMAT_R16G16B16A16_SFLOAT
                colorSpace = COLOR_SPACE_BT709_LINEAR_EXT
...
```

Gnome version 44

Gnome version 44 is part of Ubuntu 24.04.

Experimental HDR support had been added with this MR. To enable HDR, make sure Wayland is used (no HDR with X11), press `Alt+F2`, then type `lg` in the prompt to start the `looking glass` console. Enter `global.compositor.backend.get_monitor_manager().experimental_hdr = 'on'` to enable HDR, `global.compositor.backend.get_monitor_manager().experimental_hdr = 'off'` to disable HDR.

Gnome is not yet passing the HDR color space to Vulkan. The color space and other information can be queried using `drm_info`, check modes where `HDR_OUTPUT_METADATA` is not `0`.

For the case below (`Microstep MSI MPG343CQR` display) the HDR color space is `BT2020_RGB` with `SMPTE ST 2084 (PQ)` EOTF. Max luminance is 446 nits.

```
> drm_info | grep -B 1 -A 11 HDR
...
│   │       ├───"Colorspace": enum {Default, BT2020_RGB, BT2020_YCC} = BT2020_RGB
│   │       ├───"HDR_OUTPUT_METADATA": blob = 114
│   │       │   ├───Type: Static Metadata Type 1
│   │       │   ├───EOTF: SMPTE ST 2084 (PQ)
│   │       │   ├───Display primaries:
│   │       │   │   ├───Red: (0.6768, 0.3096)
│   │       │   │   ├───Green: (0.2764, 0.6445)
│   │       │   │   └───Blue: (0.1514, 0.0693)
│   │       │   ├───White point: (0.3135, 0.3291)
│   │       │   ├───Max display mastering luminance: 446 cd/m²
│   │       │   ├───Min display mastering luminance: 0.0001 cd/m²
│   │       │   ├───Max content light level: 446 cd/m²
│   │       │   └───Max frame average light level: 446 cd/m²
-
...
```

21.10 Callbacks

Callbacks can be used to receive updates on key presses, mouse position and buttons, and window size.

Operator

C++

```
visualizer = make_operator<ops::HolovizOp>(
            "holoviz",
            Arg("key_callback",
                ops::HolovizOp::KeyCallbackFunction([](ops::HolovizOp::Key key,
                                                                        ␣
↪ops::HolovizOp::KeyAndButtonAction action,
                                                        ops::HolovizOp::KeyModifiers␣
↪modifiers) -> void {
                HOLOSCAN_LOG_INFO(
                  "key {} action {} modifiers {}", int(key), int(action), *(uint32_t*)(&
↪modifiers));
            }))
        )
```

Python

```
def callback(
    key: HolovizOp.Key, action: HolovizOp.KeyAndButtonAction, modifiers: HolovizOp.
↪KeyModifiers
):
    print(key, action, modifiers)

visualizer = HolovizOp(
            self,
            name="holoviz",
            key_callback=callback)
```

Module

```
void key_callback(void *user_pointer, Key key, KeyAndButtonAction action, KeyModifiers␣
↪modifiers) {
    ...
}
...
viz::SetKeyCallback(user_pointer, &key_callback);
...
```

21.11 Holoviz operator

21.11.1 Class Documentation

C++

Python.

21.11.2 Holoviz Operator Examples

There are multiple examples, both in Python and C++, showing how to use various features of the Holoviz operator.

21.12 Holoviz module

21.12.1 Concepts

The Holoviz module uses the concept of the immediate mode design pattern for its API, inspired by the Dear ImGui library. The difference to the retained mode, for which most APIs are designed, is that there are no objects created and stored by the application. This makes it fast and easy to make visualization changes in a Holoscan application.

21.12.2 Instances

The Holoviz module uses a thread-local instance object to store its internal state. The instance object is created when calling the Holoviz module is first called from a thread. All Holoviz module functions called from that thread use this instance.

When calling into the Holoviz module from other threads other than the thread from which the Holoviz module functions were first called, make sure to call `viz::GetCurrent()` and `viz::SetCurrent()` in the respective threads.

There are usage cases where multiple instances are needed; for example, to open multiple windows. Instances can be created by calling `viz::Create()`. Call `viz::SetCurrent()` to make the instance current before calling the Holoviz module function to be executed for the window the instance belongs to.

21.12.3 Getting Started

The code below creates a window and displays an image.

First, the Holoviz module needs to be initialized. This is done by calling `viz::Init()`.

The elements to display are defined in the render loop; termination of the loop is checked with `viz::WindowShouldClose()`.

The definition of the displayed content starts with `viz::Begin()`, and ends with `viz::End()`. `viz::End()` starts the rendering and displays the rendered result.

Finally, the Holoviz module is shutdown with `viz::Shutdown()`.

```
#include "holoviz/holoviz.hpp"

namespace viz = holoscan::viz;

```

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```
viz::Init("Holoviz Example");

while (!viz::WindowShouldClose()) {
    viz::Begin();
    viz::BeginImageLayer();
    viz::ImageHost(width, height, viz::ImageFormat::R8G8B8A8_UNORM, image_data);
    viz::EndLayer();
    viz::End();
}

viz::Shutdown();
```

Result:

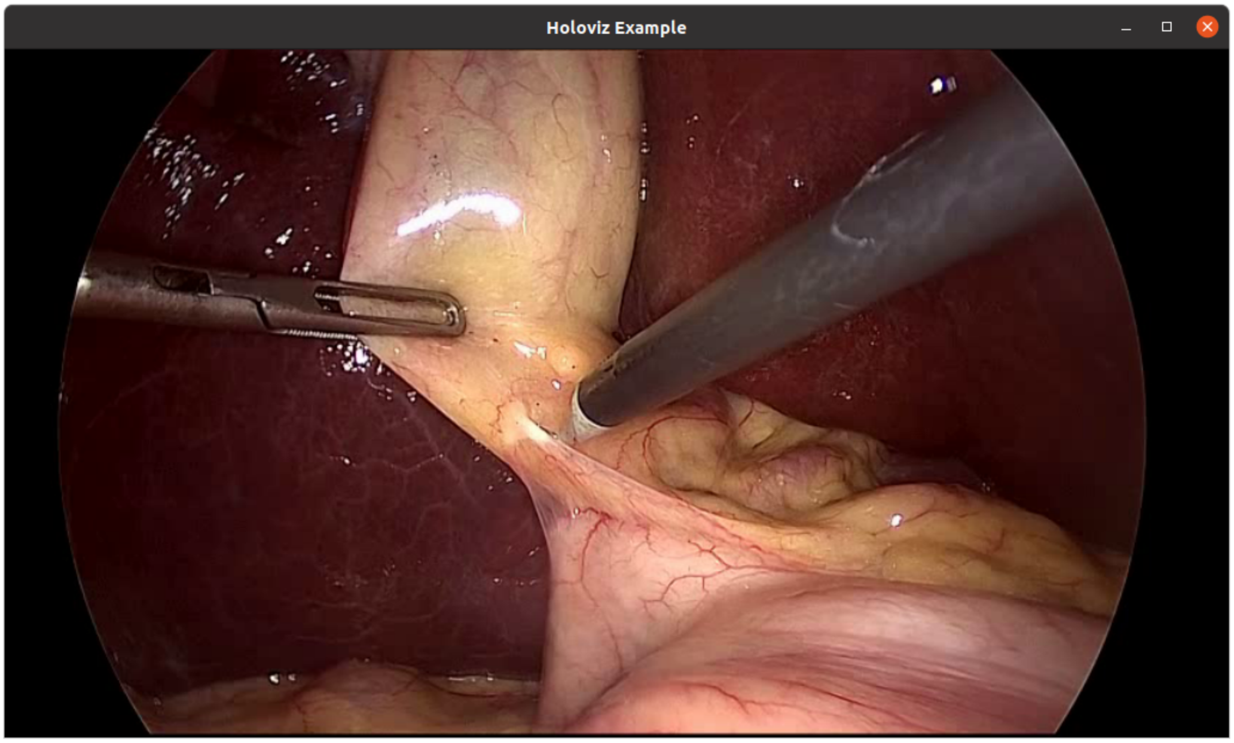

Fig. 21.1: Holoviz example app

21.12.4 API

namespace_holoscan__viz

21.12.5 Holoviz Module Examples

There are multiple examples showing how to use various features of the Holoviz module.

CHAPTER

TWENTYTWO

INFERENCE

22.1 Overview

A Holoscan application that needs to run inference will use an inference operator. The built-in *Inference operator* (`InferenceOp`) can be used, and several related use cases are documented in the Inference operator section below. The use cases are created using the *parameter set* that must be defined in the configuration file of the Holoscan application. If the built-in `InferenceOp` doesn't cover a specific use case, users can create their own custom inference operator as documented in the *Creating an Inference Operator* section.

The core inference functionality in the Holoscan SDK is provided by the Inference Module, which is a framework that facilitates designing and executing inference and processing applications through its APIs. It is used by the built-in `InferenceOp` which supports the same parameters as the Inference Module. All parameters required by the Holoscan Inference Module are passed through a parameter set in the configuration file of an application.

22.2 Parameters and Related Features

Required parameters and related features available with the Holoscan Inference Module are listed below.

- Data Buffer Parameters: Parameters are provided in the inference settings to enable data buffer locations at several stages of the inference. As shown in the figure below, three parameters `input_on_cuda`, `output_on_cuda` and `transmit_on_cuda` can be set by the user.
  - `input_on_cuda` refers to the location of the data going into the inference.
    - If value is `true`, it means the input data is on the device.
    - If value is `false`, it means the input data is on the host.
    - Default value: `true`
  - `output_on_cuda` refers to the data location of the inferred data.
    - If value is `true`, it means the inferred data is on the device.
    - If value is `false`, it means the inferred data is on the host.
    - Default value: `true`
  - `transmit_on_cuda` refers to the data transmission.
    - If value is `true`, it means the data transmission from the inference extension will be on **Device**.
    - If value is `false`, it means the data transmission from the inference extension will be on **Host**.
    - Default value: `true`
- Inference Parameters

- backend parameter is set to either trt for TensorRT, onnxrt for ONNX runtime, or torch for libtorch. If there are multiple models in the inference application, all models will use the same backend. If it is desired to use different backends for different models, specify the backend_map parameter instead.
  - TensorRT:
    - CUDA-based inference supported both on x86_64 and aarch64.
    - End-to-end CUDA-based data buffer parameters supported. input_on_cuda, output_on_cuda and transmit_on_cuda will all be true for end-to-end CUDA-based data movement.
    - input_on_cuda, output_on_cuda and transmit_on_cuda can be either true or false.
    - TensorRT backend expects input models to be in tensorrt engine file format or onnx format.
      - if models are in tensorrt engine file format, parameter is_engine_path must be set to true.
      - if models are in onnx format, it will be automatically converted into tensorrt engine file by the Holoscan inference module.
  - Torch:
    - CUDA and CPU based inference supported both on x86_64 and aarch64.
    - End-to-end CUDA-based data buffer parameters supported. input_on_cuda, output_on_cuda and transmit_on_cuda will all be true for end-to-end CUDA-based data movement.
    - input_on_cuda, output_on_cuda and transmit_on_cuda can be either true or false.
    - Libtorch and TorchVision are included in the Holoscan NGC container, initially built as part of the PyTorch NGC container. To use the Holoscan SDK torch backend outside of these containers, we recommend you download libtorch and torchvision binaries from Holoscan's third-party repository.
    - Torch backend expects input models to be in torchscript format.
      - It is recommended to use the same version of torch for torchscript model generation, as used in the HOLOSCAN SDK on the respective architectures.
      - Additionally, it is recommended to generate the torchscript model on the same architecture on which it will be executed. For example, torchscript model must be generated on x86_64 to be executed in an application running on x86_64 only.
  - ONNX runtime:
    - CUDA and CPU based inference supported both on x86_64 and aarch64.
    - End-to-end CUDA-based data buffer parameters supported. input_on_cuda, output_on_cuda and transmit_on_cuda will all be true for end-to-end CUDA-based data movement.
    - input_on_cuda, output_on_cuda and transmit_on_cuda can be either true or false.
- infer_on_cpu parameter is set to true if CPU based inference is desired.

  The tables below demonstrate the supported features related to the data buffer and the inference with trt, torch and onnxrt based backend.

	input_on_cuda	output_on_cuda	transmit_on_cuda	infer_on_cpu
Supported values for trt	true or false	true or false	true or false	false
Supported values for torch	true or false	true or false	true or false	true or false
Supported values for onnxrt	true or false	true or false	true or false	true or false

- model_path_map: User can design single or multi AI inference pipeline by populating model_path_map in the config file.
  * With a single entry, it is single inference; with more than one entry, multi AI inference is enabled.
  * Each entry in model_path_map has a unique keyword as key (used as an identifier by the Holoscan Inference Module), and the path to the model as value.
  * All model entries must have the models either in **onnx** or **tensorrt engine file** or **torchscript** format.
- pre_processor_map: input tensor to the respective model is specified in pre_processor_map in the config file.
  * The Holoscan Inference Module supports same input for multiple models or unique input per model.
  * Each entry in pre_processor_map has a unique keyword representing the model (same as used in model_path_map), and a vector of tensor names as the value.
  * The Holoscan Inference Module supports multiple input tensors per model.
- inference_map: output tensors per model after inference is specified in inference_map in the config file.
  * Each entry in inference_map has a unique keyword representing the model (same as used in model_path_map and pre_processor_map), and a vector of the output tensor names as the value.
  * The Holoscan Inference Module supports multiple output tensors per model.
- parallel_inference: Parallel or Sequential execution of inferences.
  * If multiple models are input, you can execute models in parallel.
  * Parameter parallel_inference can be either true or false. Default value is true.
  * Inferences are launched in parallel without any check of the available GPU resources. You must ensure that there is enough memory and compute available to run all the inferences in parallel.
- enable_fp16: Generation of the TensorRT engine files with FP16 option
  * If backend is set to onnx or trt if the input models are in **onnx** format, then you can generate the engine file with fp16 option to accelerate inferencing.
  * It takes few minutes to generate the engine files for the first time.
  * It can be either true or false. Default value is false.
- enable_cuda_graphs: Enable usage of CUDA Graphs for backends which support it.
  * Enabled by default for the TensorRT backend.
  * Using CUDA Graphs reduces CPU launch costs and enables optimizations which might not be possible with the piecewise work submission mechanism of streams.
  * Models including loops or conditions are not supported with CUDA Graphs. For these models usage of CUDA Graphs needs to be disabled.

    * It can be either `true` or `false`. Default value is `true`.

- `dla_core`: The DLA core index to execute the engine on, starts at `0`.
    * It can be either `-1` or the DLA core index. Default value is `-1`.
- `dla_gpu_fallback`: Enable DLA GPU fallback
    * If DLA is enabled, use the GPU if a layer cannot be executed on DLA. If the fallback is disabled, engine creation will fail if a layer cannot executed on DLA.
    * It can be either `true` or `false`. Default value is `true`.
- `is_engine_path`: if the input models are specified in **trt engine format** in `model_path_map`, this flag must be set to `true`. Default value is `false`.
- `in_tensor_names`: Input tensor names to be used by `pre_processor_map`. This parameter is optional. If absent in the parameter map, values are derived from `pre_processor_map`.
- `out_tensor_names`: Output tensor names to be used by `inference_map`. This parameter is optional. If absent in the parameter map, values are derived from `inference_map`.
- `device_map`: Multi-GPU inferencing is enabled if `device_map` is populated in the parameter set.
    * Each entry in `device_map` has a unique keyword representing the model (same as used in `model_path_map` and `pre_processor_map`), and GPU identifier as the value. This GPU ID is used to execute the inference for the specified model.
    * GPUs specified in the `device_map` must have P2P (peer to peer) access and they must be connected to the same PCIE configuration. If P2P access is not possible among GPUs, the host (CPU memory) will be used to transfer the data.
    * Multi-GPU inferencing is supported for all backends.
- `dla_core_map`: DLA cores are used for inferencing if `dla_core_map` is populated in the parameter set.
    * Each entry in `dla_core_map` has a unique keyword representing the model (same as used in `model_path_map` and `pre_processor_map`), and a DLA core index as the value. This DLA core index is used to execute the inference for the specified model.
- `temporal_map`: Temporal inferencing is enabled if `temporal_map` is populated in the parameter set.
    * Each entry in `temporal_map` has a unique keyword representing the model (same as used in `model_path_map` and `pre_processor_map`), and frame delay as the value. Frame delay represents the frame count that are skipped by the operator in doing the inference for that particular model. A model with the value of 1, is inferred per frame. A model with a value of 10 is inferred for every 10th frame coming into the operator, which is the 1st frame, 11th frame, 21st frame and so on. Additionally, the operator will transmit the last inferred result for all the frames that are not inferred. For example, a model with a value of 10 will be inferred at 11th frame and from 12th to 20th frame, the result from 11th frame is transmitted.
    * If the `temporal_map` is absent in the parameter set, all models are inferred for all the frames.
    * All models are not mandatory in the `temporal_map`. The missing models are inferred per frame.
    * Temporal map based inferencing is supported for all backends.
- `activation_map`: Dynamic inferencing can be enabled with this parameter. It is populated in the parameter set and is updated at runtime.
    * Each entry in `activation_map` has a unique keyword representing the model (same as used in `model_path_map` and `pre_processor_map`), and activation state as the value. Activation state represents whether the model will be used for inferencing or not on a given frame. Any model(s) with a value of 1 will be active and will be used for inference, and any model(s) with a value of 0 will not run.

The activation map must be initialized in the parameter set for all the models that need to be activated or deactivated dynamically.

* When the activation state is 0 for a particular model in the `activation_map`, the inference operator will not launch the inference for the model and will emits the last inferred result for the model.
* If the `activation_map` is absent in the parameter set, all of the models are inferred for all frames.
* All models are not mandatory in the `activation_map`. The missing models are active on every frame.
* Dynamic inferenceing based on `activation_map` along with the `model_activation_specs` input port is supported for all backends.

– `backend_map`: Multiple backends can be used in the same application with this parameter.

* Each entry in `backend_map` has a unique keyword representing the model (same as used in `model_path_map`), and the `backend` as the value.
* A sample backend_map is shown below. In the example, model_1 uses the `tensorRT` backend, and model 2 and model 3 uses the `torch` backend for inference.

```
backend_map:
    "model_1_unique_identifier": "trt"
    "model_2_unique_identifier": "torch"
    "model_3_unique_identifier": "torch"
```

– `trt_opt_profile`: This parameter is optional and is activated with TensorRT backend. This parameter is applicable on models with dynamic input shapes.

* Parameter is specified as a vector of 3 integers. First is the minimum batch size for the input, second is the optimum batch size and third value is the maximum batch size.
* Users can specify a batch profile for dynamic input. This profile is then used in engine creation. User must clear the cache to apply the updated optimization profile.
* Default value: {1,1,1}

• Other features: The table below illustrates other features and supported values in the current release.

Feature	Supported values
Data type	`float32`, `int32`, `int8`
Inference Backend	`trt`, `torch`, `onnxrt`
Inputs per model	Multiple
Outputs per model	Multiple
GPU(s) supported	Multi-GPU on same PCIE network
Tensor data dimension	Max 8 supported for `onnx` and `trt` backend, 3 (CHW) or 4 (NCHW) for `torch`.
Model Type	`All onnx or all torchscript or all trt engine` type or a `combination of torch and trt engine`

• Multi Receiver and Single Transmitter support

– The Holoscan Inference Module provides an API to extract the data from multiple receivers.

– The Holoscan Inference Module provides an API to transmit multiple tensors via a single transmitter.

- The Holoscan Inference Module provides an API to allow selecting the set of active models for inference at runtime (see example under the directory `examples/activation_map`).

22.2.1 Parameter Specification

All required inference parameters of the inference application must be specified. Below is a sample parameter set for an application that uses three models for inferencing. You must populate all required fields with appropriate values.

```
inference:
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
    parallel_inference: true
    infer_on_cpu: false
    enable_fp16: false
    input_on_cuda: true
    output_on_cuda: true
    transmit_on_cuda: true
    is_engine_path: false
```

22.3 Inference Operator

In Holoscan SDK, the built-in Inference operator (`InferenceOp`) is designed using the Holoscan Inference Module APIs. The Inference operator ingests the inference parameter set (from the configuration file) and the data receivers (from previous connected operators in the application), executes the inference and transmits the inferred results to the next connected operators in the application.

`InferenceOp` is a generic operator that serves multiple use cases via the parameter set. Parameter sets for some key use cases are listed below:

Note: Some parameters have default values set for them in the `InferenceOp`. For any parameters not mentioned in the example parameter sets below, their default is used by the `InferenceOp`. These parameters are used to enable several use cases.

- Single model inference using `TensorRT` backend.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
```

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```
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
```

The value of backend can be modified for other supported backends, and other parameters related to each backend. You must ensure the correct model type and model path are provided into the parameter set, along with supported values of all parameters for the respective backend.

In this example, path_to_model_1 must be an onnx file, which will be converted to a tensorRT engine file at first execution. During subsequent executions, the Holoscan inference module will automatically find the tensorRT engine file (if path_to_model_1 has not changed). Additionally, if you have a pre-built tensorRT engine file, path_to_model_1 must be path to the engine file and the parameter is_engine_path must be set to true in the parameter set.

- Single model inference using TensorRT backend with multiple outputs.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier",
                                      "output_tensor_2_model_1_unique_identifier",
                                      "output_tensor_3_model_1_unique_identifier"]
```

As shown in example above, the Holoscan Inference module automatically maps the model outputs to the named tensors in the parameter set. You must be sure to use the named tensors in the same sequence in which the model generates the output. Similar logic holds for multiple inputs.

- Single model inference using fp16 precision.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier",
                                      "output_tensor_2_model_1_unique_identifier",
                                      "output_tensor_3_model_1_unique_identifier"]
    enable_fp16: true
```

If a tensorRT engine file is not available for fp16 precision, it will be automatically generated by the Holoscan Inference module on the first execution. The file is cached for future executions.

- Single model inference on CPU.

```
    backend: "onnxrt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
```

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```
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
    infer_on_cpu: true
```

Note that the backend can only be onnxrt or torch for CPU-based inference.

- Single model inference with input/output data on Host.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
    input_on_cuda: false
    output_on_cuda: false
```

Data in the core inference engine is passed through the host and is received on the host. Inference can happen on the GPU. Parameters input_on_cuda and output_on_cuda define the location of the data before and after inference respectively.

- Single model inference with data transmission via Host.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
    transmit_on_host: true
```

Data from inference operator to the next connected operator in the application is transmitted via the host.

- Multi model inference with a single backend.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
```

By default, multiple model inferences are launched in parallel. The backend specified via parameter backend is used for all models in the application.

- Multi model inference with sequential inference.

```
    backend: "trt"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
    parallel_inference: false
```

`parallel_inference` is set to `true` by default. To launch model inferences in sequence, `parallel_inference` must be set to `false`.

- Multi model inference with multiple backends.

```
    backend_map:
        "model_1_unique_identifier": "trt"
        "model_2_unique_identifier": "torch"
        "model_3_unique_identifier": "torch"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
```

In the above sample parameter set, the first model will do inference using the `tensorRT` backend, and model 2 and 3 will do inference using the `torch` backend.

Note: The combination of backends in `backend_map` must support all other parameters that will be used during the inference. For example, `onnxrt` and `tensorRT` combination with CPU-based inference is not supported.

- Multi model inference with a single backend on multi-GPU.

```
    backend: "trt"
    device_map:
        "model_1_unique_identifier": "1"
        "model_2_unique_identifier": "0"
        "model_3_unique_identifier": "1"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
```

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```
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
```

In the sample above, model 1 and model 3 will do inference on the GPU with ID 1 and model 2 will do inference on the GPU with ID 0. GPUs must have P2P (peer to peer) access among them. If it is not enabled, the Holoscan inference module enables it by default. If P2P access is not possible between GPUs, then the data transfer will happen via the Host.

- Multi model inference with multiple backends on multiple GPUs.

```
    backend_map:
        "model_1_unique_identifier": "trt"
        "model_2_unique_identifier": "torch"
        "model_3_unique_identifier": "torch"
    device_map:
        "model_1_unique_identifier": "1"
        "model_2_unique_identifier": "0"
        "model_3_unique_identifier": "1"
    model_path_map:
        "model_1_unique_identifier": "path_to_model_1"
        "model_2_unique_identifier": "path_to_model_2"
        "model_3_unique_identifier": "path_to_model_3"
    pre_processor_map:
        "model_1_unique_identifier": ["input_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["input_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["input_tensor_1_model_3_unique_identifier"]
    inference_map:
        "model_1_unique_identifier": ["output_tensor_1_model_1_unique_identifier"]
        "model_2_unique_identifier": ["output_tensor_1_model_2_unique_identifier"]
        "model_3_unique_identifier": ["output_tensor_1_model_3_unique_identifier"]
```

In the sample above, three models are used during the inference. Model 1 uses the trt backend and runs on the GPU with ID 1, model 2 uses the torch backend and runs on the GPU with ID 0, and model 3 uses the torch backend and runs on the GPU with ID 1.

22.4 Creating an Inference Operator

The Inference operator is the core inference unit in an inference application. The built-in Inference operator (`InferenceOp`) can be used for inference, or you can create your own custom inference operator as explained in this section. In Holoscan SDK, the inference operator can be designed using the Holoscan Inference Module APIs.

Arguments in the code sections below are referred to as `...`.

- Parameter Validity Check: Input inference parameters via the configuration (from step 1) are verified for correctness.

```
auto status = HoloInfer::inference_validity_check(...);
```

- Inference specification creation: For a single AI, only one entry is passed into the required entries in the parameter set. There is no change in the API calls below. Single AI or multi AI is enabled based on the number of entries in the parameter specifications from the configuration (in step 1).

```
// Declaration of inference specifications
std::shared_ptr<HoloInfer::InferenceSpecs> inference_specs_;

// Creation of inference specification structure
inference_specs_ = std::make_shared<HoloInfer::InferenceSpecs>(...);
```

- Inference context creation.

```
// Pointer to inference context.
std::unique_ptr<HoloInfer::InferContext> holoscan_infer_context_;
// Create holoscan inference context
holoscan_infer_context_ = std::make_unique<HoloInfer::InferContext>();
```

- Parameter setup with inference context: All required parameters of the Holoscan Inference Module are transferred in this step, and relevant memory allocations are initiated in the inference specification.

```
// Set and transfer inference specification to inference context
auto status = holoscan_infer_context_->set_inference_params(inference_specs_);
```

- Data extraction and allocation: The following API is used from the Holoinfer utility to extract and allocate data for the specified tensor.

```
// Extract relevant data from input, and update inference specifications
gxf_result_t stat = HoloInfer::get_data_per_model(...);
```

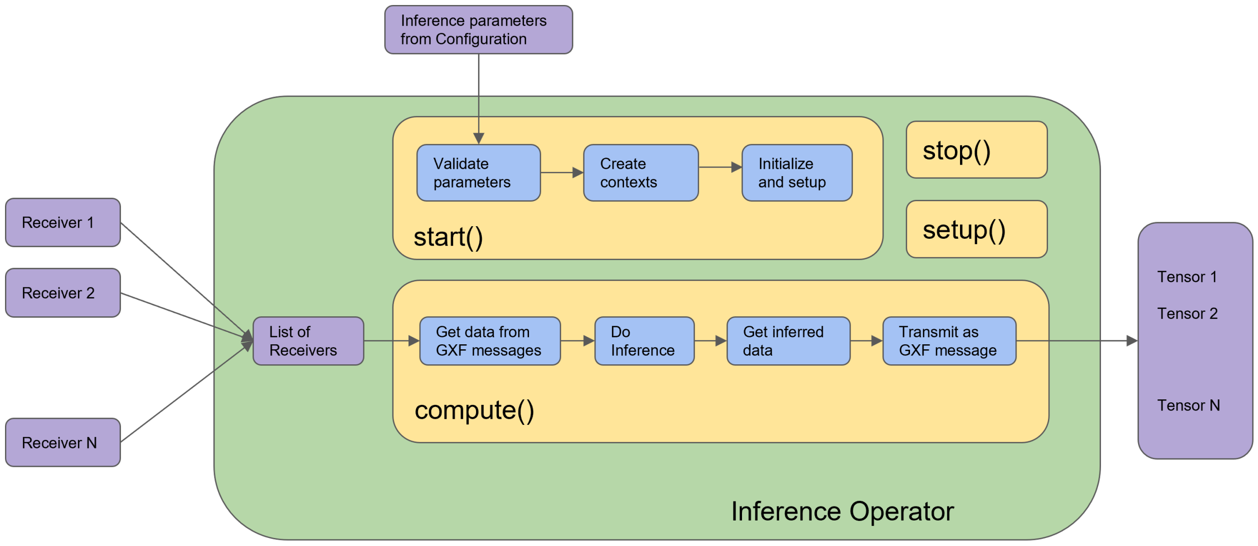
- Inference execution

```
// Execute inference and populate output buffer in inference specifications
auto status = holoscan_infer_context_->execute_inference(inference_specs_->data_per_
↪model_,
                                                          inference_specs_->output_
↪per_model_);
```

- Transmit inferred data:

```
// Transmit output buffers
auto status = HoloInfer::transmit_data_per_model(...);
```

The figure below demonstrates the Inference operator in the Holoscan SDK. All blocks with `blue` color are the API calls from the Holoscan Inference Module.



CHAPTER TWENTYTHREE

SCHEDULERS

The Scheduler component is a critical part of the system responsible for governing the execution of operators in a graph by enforcing conditions associated with each operator. Its primary responsibility includes orchestrating the execution of all operators defined in the graph while keeping track of their execution states.

The Holoscan SDK offers multiple schedulers that can cater to various use cases. These schedulers are:

1. *Greedy Scheduler*: This basic single-threaded scheduler tests conditions in a greedy manner. It is suitable for simple use cases and provides predictable execution. However, it may not be ideal for large-scale applications as it may incur significant overhead in condition execution.
2. *MultiThread Scheduler*: The multithread scheduler is designed to handle complex execution patterns in large-scale applications. This scheduler consists of a dispatcher thread that monitors the status of each operator and dispatches it to a thread pool of worker threads responsible for executing them. Once execution is complete, worker threads enqueue the operator back on the dispatch queue. The multithread scheduler offers superior performance and scalability over the greedy scheduler.
3. *Event-Based Scheduler*: The event-based scheduler is also a multi-thread scheduler, but as the name indicates it is event-based rather than polling based. Instead of having a thread that constantly polls for the execution readiness of each operator, it instead waits for an event to be received which indicates that an operator is ready to execute. The event-based scheduler will have a lower latency than using the multi-thread scheduler with a long polling interval (`check_recession_period_ms`), but without the high CPU usage seen for a multi-thread scheduler with a very short polling interval.

It is essential to select the appropriate scheduler for the use case at hand to ensure optimal performance and efficient resource utilization. Since most parameters of the schedulers overlap, it is easy to switch between them to test which may be most performant for a given application.

Note: Detailed APIs can be found here: `C++`/`Python`).

23.1 Greedy Scheduler

The greedy scheduler has a few parameters that the user can configure.

- The *clock* used by the scheduler can be set to either a `realtime` or `manual` clock.
  - The realtime clock is what should be used for applications as it pauses execution as needed to respect user-specified conditions (e.g., operators with periodic conditions will wait the requested period before executing again).
  - The manual clock is of benefit mainly for testing purposes as it causes operators to run in a time-compressed fashion (e.g., periodic conditions are not respected and operators run in immediate succession).

- The user can specify a `max_duration_ms` that will cause execution of the application to terminate after a specified maximum duration. The default value of `-1` (or any other negative value) will result in no maximum duration being applied.
- This scheduler also has a Boolean parameter, `stop_on_deadlock` that controls whether the application will terminate if a deadlock occurs. A deadlock occurs when all operators are in a `WAIT` state, but there is no periodic condition pending to break out of this state. This parameter is `true` by default.
- When setting the `stop_on_deadlock_timeout` parameter, the scheduler will wait this amount of time (in ms) before determining that it is in deadlock and should stop. It will reset if a job comes in during the wait. A negative value means no stop on deadlock. This parameter only applies when `stop_on_deadlock=true`.

23.2 Multithread Scheduler

The multithread scheduler has several parameters that the user can configure. These are a superset of the parameters available for the `GreedyScheduler` (described in the section above). Only the parameters unique to the multithread scheduler are described here. The multi-thread scheduler uses a dedicated thread to poll the status of operators and schedule any that are ready to execute. This will lead to high CPU usage by this polling thread when `check_recession_period_ms` is close to 0.

- The number of worker threads used by the scheduler can be set via `worker_thread_number`, which defaults to `1`. This should be set based on a consideration of both the workflow and the available hardware. For example, the topology of the computation graph will determine how many operators it may be possible to run in parallel. Some operators may potentially launch multiple threads internally, so some amount of performance profiling may be required to determine optimal parameters for a given workflow.
- The value of `check_recession_period_ms` controls how long the scheduler will sleep before checking a given condition again. In other words, this is the polling interval for operators that are in a `WAIT` state. The default value for this parameter is `5` ms.
- The value of `strict_job_thread_pinning` controls then behavior when user-defined thread pools with thread pinning are used. If this value is `false` (the default), then whenever an operator pinned to a thread is not in a READY state, some other unpinned operator could make use of that thread. If `true` only the pinned operator can make use of the thread.

23.3 Event-Based Scheduler

The event-based scheduler is also a multi-thread scheduler, but it is event-based rather than polling based. As such, there is no `check_recession_period_ms` parameter, and this scheduler will not have the high CPU usage that can occur when polling at a short interval. Instead, the scheduler only wakes up when an event is received indicating that an operator is ready to execute. The parameters of this scheduler are a superset of the parameters available for the `GreedyScheduler` (described above). Only the parameters unique to the event-based scheduler are described here.

- The number of worker threads used by the scheduler can be set via `worker_thread_number`, which defaults to `1`. This should be set based on a consideration of both the workflow and the available hardware. For example, the topology of the computation graph will determine how many operators it may be possible to run in parallel. Some operators may potentially launch multiple threads internally, so some amount of performance profiling may be required to determine optimal parameters for a given workflow.

For this scheduler, there is no `strict_job_thread_pinning` option (see description for the Multithread Scheduler above). The thread pinning is always strict.

CHAPTER

TWENTYFOUR

CONDITIONS

The following table shows various states of the scheduling status of an operator:

Scheduling Status	Description
NEVER	Operator will never execute again
READY	Operator is ready for execution
WAIT	Operator may execute in the future
WAIT_TIME	Operator will be ready for execution after specified duration
WAIT_EVENT	Operator is waiting on an asynchronous event with unknown time interval

Note:

- A failure in execution of any single operator stops the execution of all the operators.
- Operators are naturally unscheduled from execution when their scheduling status reaches `NEVER` state.

By default, operators are always `READY`, meaning they are scheduled to continuously execute their `compute()` method. To change that behavior, some condition classes can be assigned to an operator. There are various conditions currently supported in the Holoscan SDK:

- MessageAvailableCondition
- ExpiringMessageAvailableCondition
- MultiMessageAvailableCondition
- MultiMessageAvailableTimeoutCondition
- DownstreamMessageAffordableCondition
- MemoryAvailableCondition
- CountCondition
- BooleanCondition
- PeriodicCondition
- AsynchronousCondition

These conditions fall under various types as detailed below. Often, conditions are explicitly added to an operator by the application author, but it should also be noted that unless the default is overridden, a `MessageAvailableCondition` is automatically added for each of an operator's input ports and a `DownstreamMessageAffordableCondition` is automatically added for each of it's output ports.

Note: Detailed APIs can be found here: C++/`Python`.

24.1 Condition combination logic

By Default conditions are AND-combined

An Operator can be associated with multiple conditions that define its execution behavior. By default, conditions are AND combined to describe the operator's current state. For an operator to be executed by the scheduler, all conditions must be in the `READY` state. Conversely, the operator is unscheduled whenever any of the scheduling terms reaches the `NEVER` state. The priority of various states during AND combine follows the order `NEVER`, `WAIT_EVENT`, `WAIT`, `WAIT_TIME`, and `READY`.

OR combination of conditions

An `OrConditionCombiner` class is also provided which can be used to allow OR combination of the set of conditions associated with it. For concrete code on how to configure an operator to use OR combination see the section on OR combination of conditions(*C++*, *Python*) or port conditions(*C++*, *Python*). The general logic when combining conditions is described in the following section and example.

Note that when OR combining conditions if any of the conditions has state NEVER the combination will also return NEVER.

24.1.1 General Condition Combination Logic Used by GXF

- **Initial Setup**
  - Start with a default combined condition of `READY`
- **Process Any Combiners (e.g. OrConditionCombiner) First**
  - For each `ConditionCombiner` associated with the `Operator`:
    - Get all conditions managed by this combiner
    - Check the first condition and use its result as the initial combiner result
    - For each additional condition in the combiner:
      - Check the status of the condition
      - Combine with previous result using the combiner's logic (OR for `OrConditionCombiner`)
    - AND-combine this combiner's final result with results from other combiners
- **Process Standalone Conditions**
  - For each standalone condition (not in any combiner):
    - Check the status of the condition
    - AND-combine this condition with the current combined result
- **Return Final Result**
  - The final combined condition determines if and when the entity should execute

A concrete diagram illustrating the logic bulleted above is shown in the diagram below:

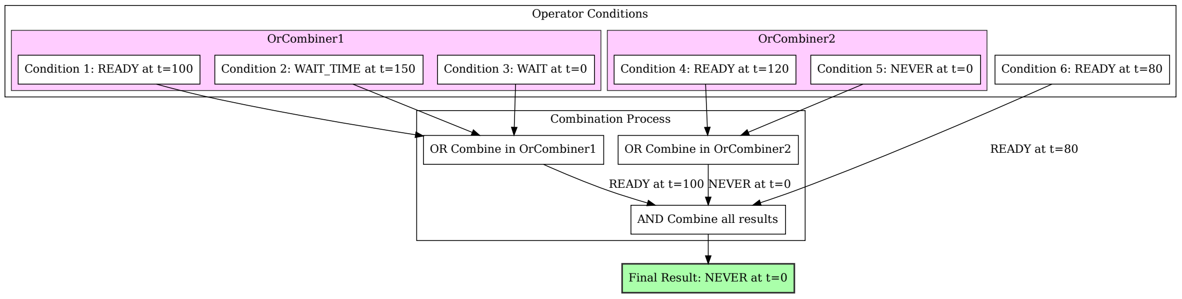

Operator Conditions
OrCombiner1
Condition 1: READY at t=100
Condition 2: WAIT_TIME at t=150
Condition 3: WAIT at t=0
OrCombiner2
Condition 4: READY at t=120
Condition 5: NEVER at t=0
Condition 6: READY at t=80
Combination Process
OR Combine in OrCombiner1
OR Combine in OrCombiner2
READY at t=80
READY at t=100
NEVER at t=0
AND Combine all results
Final Result: NEVER at t=0

Fig. 24.1: condition-combination-example

24.1.2 Detailed Condition Status Combination Logic Used by AND combination

24.1.3 Detailed Condition Status Combination Logic Used by OR combination

24.2 Condition Types

The following table gives a rough categorization of the available condition types to help better understand their purpose and how they are assigned. More detailed descriptions of the individual conditions are given in the following sections.

Condition Name	Classification	Associated With
MessageAvailableCondition	message-driven	single input port
ExpiringMessageAvailableCondition	message-driven	single input port
MultiMessageAffordableCondition	message-driven	multiple input ports
MultiMessageAffordableTimeoutCondition	message-driven	single or multiple input ports
DownstreamMessageAffordableCondition	message-driven	single output port
PeriodicCondition	clock-driven	operator as a whole
CountCondition	other	operator as a whole
BooleanCondition	execution-driven	operator as a whole
AsynchronousCondition	execution-driven	operator as a whole
MemoryAvailableCondition	other	single holoscan::Allocator
CudaStreamCondition	message-driven (CUDA sync)	single input port
CudaEventCondition	message-driven (CUDA sync)	single input port
CudaBufferAvailableCondition	message-driven (CUDA sync)	single input port

Here, the various message-driven conditions are associated with an input port (receiver) or output port (transmitter). Message-driven conditions that are associated with a single input port are typically assigned via the `IOSpec::condition` method (C++/`Python`) method as called from an operator's `setup` (C++/`Python`) method. Those associated with multiple input ports would instead be assigned via the `OperatorSpec::multi_port_condition` method (C++/`Python`) method as called from an operator's `setup` (C++/`Python`) method.

All other condition types are typically passed as either a positional or keyword argument during operator construction in the application's `compose` method (i.e. passed to `make_operator()` in C++ or the operator class's constructor in Python). Once these conditions are assigned, they automatically enforce the associated criteria for that transmitter/receiver as part of the conditions controlling whether the operator will call `compute`. Due to the AND combination of conditions discussed above, all ports must meet their associated conditions in order for an operator to call `compute`.

As of Holoscan v2.8, it is also possible to add a message-based condition that takes a "receiver" or "transmitter" argument as a positional argument to `Fragment::make_operator` (C++) or the operator's constructor (Python). Any

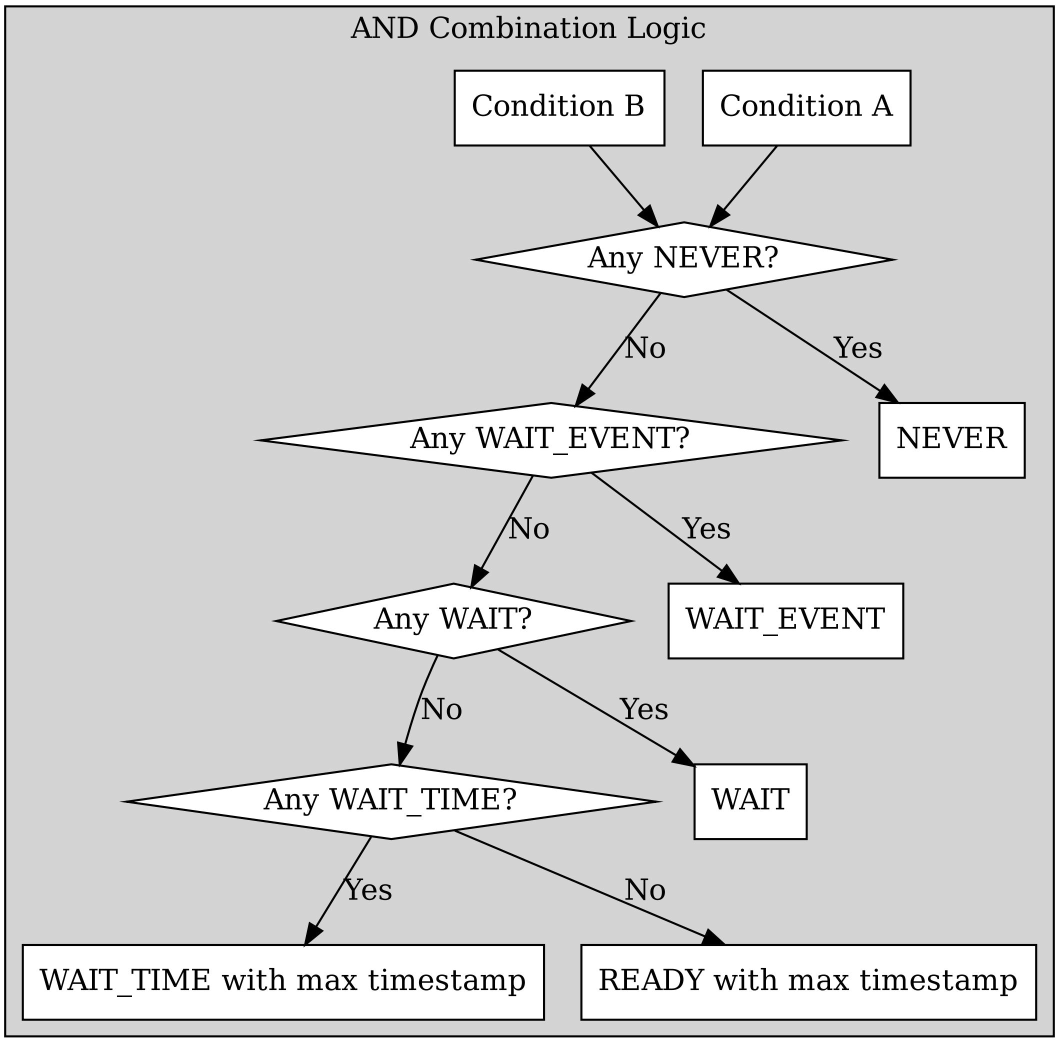


Fig. 24.2: AND combination logic

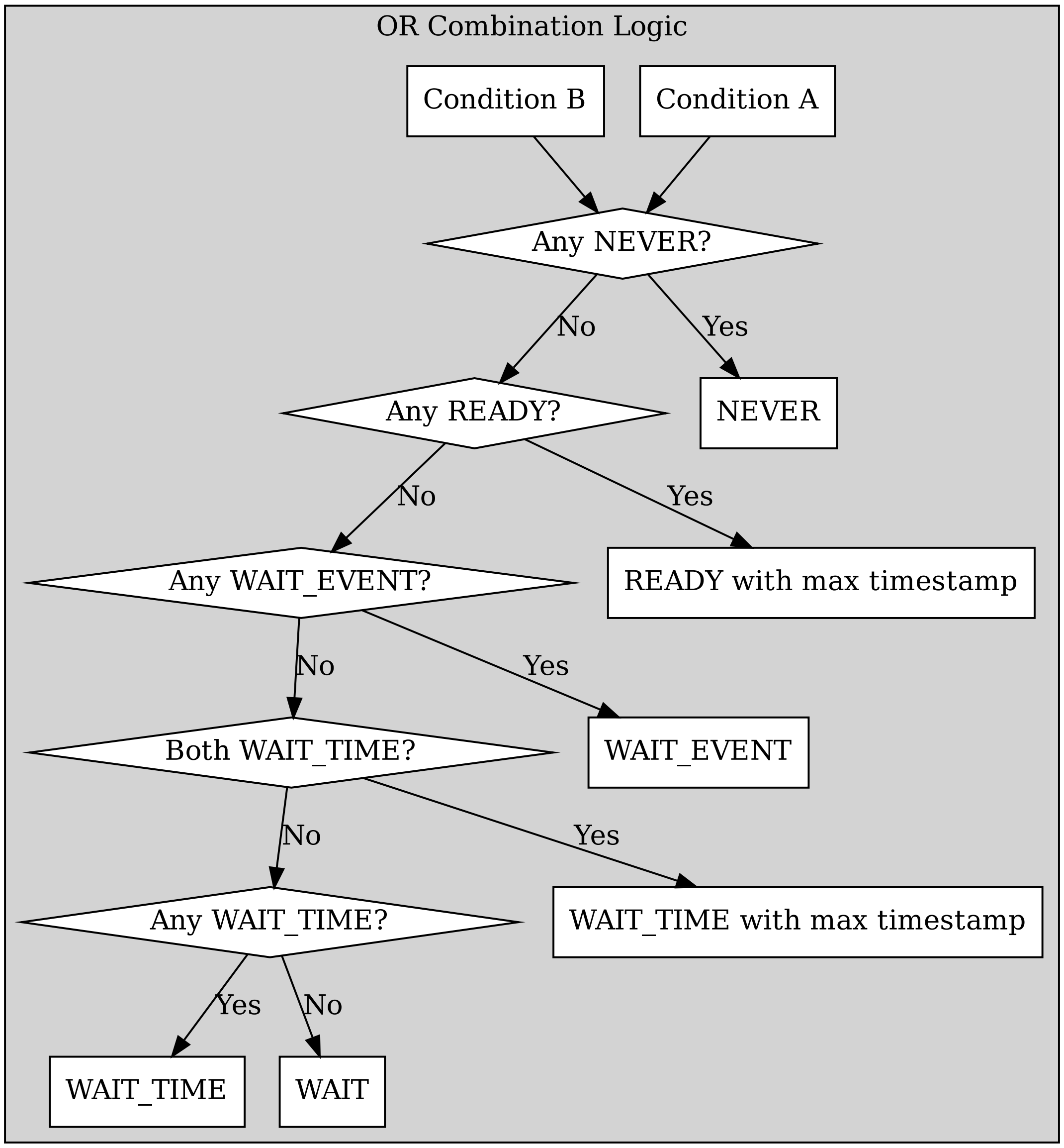


Fig. 24.3: OR Combination Logic

"receiver" or "transmitter" parameter of the condition should be specified via a string-valued argument that takes the name of the port to which the condition would apply. The SDK will then take care of automatically swapping in the actual underlying `Receiver` or `Transmitter` object used by the named port when the application is run. As a concrete example, if the `setup` method of an operator had set a `ConditionType::kNone` (C++) condition on an input port, but we want to add a `MessageAvailableCondition` without modifying that setup method. This could be done via:

```
// assuming that an operator has an input port named "in1" we could explicitly create a␣
↪condition for this port via
auto in1_condition = make_condition<MessageAvailableCondition>("in1_condition",
                                                              Arg("min_size_", static_
↪cast<uint64_t>(1)),
                                                              Arg("receiver", "in1"));
// then `in1_condition` can be passed as an argument to the `Fragment::make_operator`␣
↪call for the operator
```

or equivalently, in Python

```
# assuming that an operator has an input port named "in1" we could explicitly create a␣
↪condition for this port via
in1_condition = MessageAvailableCondition(fragment, name="in1_condition", min_size=1,␣
↪receiver="in");

# then in1_condition can be passed as a positional argument to the operator's constructor
```

The `PeriodicCondition` is clock-driven. It automatically takes effect based on timing from it's associated clock. The `CountCondition` is another condition type that automatically takes effect, stopping execution of an operator after a specified count is reached.

The conditions that are marked as execution-driven, by contrast, require an application or operator thread to explicitly trigger a change in the condition. For example, the built-in `HolovizOp` operator's `compute` method implements logic to update an associated `BooleanCondition` to disable the operator when a user closes the display window. Similarly, the `AsynchronousCondition` requires some thread to emit events to trigger an update of its state.

24.3 MessageAvailableCondition

An operator associated with `MessageAvailableCondition` (`C++`/`Python`) is executed when the associated queue of the input port has at least a certain number of elements. This condition is associated with a specific input port of an operator through the `condition()` method on the return value (IOSpec) of the OperatorSpec's `input()` method.

The minimum number of messages that permits the execution of the operator is specified by `min_size` parameter (default: `1`). An optional parameter for this condition is `front_stage_max_size`, the maximum front stage message count. If this parameter is set, the condition will only allow execution if the number of messages in the queue does not exceed this count. It can be used for operators which do not consume all messages from the queue.

24.4 ExpiringMessageAvailableCondition

An operator associated with `ExpiringMessageAvailableCondition` (`C++`/`Python`) is executed when the first message received in the associated queue is expiring or when there are enough messages in the queue. This condition is associated with a specific input or output port of an operator through the `condition()` method on the return value (IOSpec) of the OperatorSpec's `input()` or `output()` method.

The parameters `max_batch_size` and `max_delay_ns` dictate the maximum number of messages to be batched together and the maximum delay from first message to wait before executing the entity respectively. Please note that `ExpiringMessageAvailableCondition` requires that the input messages sent to any port using this condition must contain a timestamp. This means that the upstream operator has to emit using a timestamp.

To obtain a similar capability without the need for a timestamp, the `MultiMessageAvailableTimeoutCondition` described below can be used with only a single input port assigned. The difference in the timing computation is that `MultiMessageAvailableTimeOutCondition` measures time between the last time `compute` was called on the operator while `ExpiringMessageAvailableCondition` is instead based on the elapsed time since a message arrived in the operator's input queue.

24.5 DownstreamMessageAffordableCondition

The `DownstreamMessageAffordableCondition` (`C++`/`Python`) condition specifies that an operator shall be executed if the input port of the downstream operator for a given output port can accept new messages. This condition is associated with a specific output port of an operator through the `condition()` method on the return value (IOSpec) of the OperatorSpec's `output()` method. The minimum number of messages that permits the execution of the operator is specified by `min_size` parameter (default: `1`).

24.6 MultiMessageAvailableCondition

An operator associated with `MultiMessageAvailableCondition` (`C++`/`Python`) is executed when the associated queues of multiple user-specified input ports have the required number of elements.

This condition is associated with multiple input ports of an operator through the `multi_port_condition()` method on OperatorSpec. The `port_names` argument to `multi_port_condition` controls which input ports are associated with this condition.

This condition has two operating modes. The first mode is `MultiMessageAvailableCondition::SamplingMode::SumOfAll` (C++) or `holoscan.conditions.MultiMessageAvailableCondition.SamplingMode.SUM_OF_ALL` (Python). In this mode, the `min_sum` parameter is used to specify the total number of messages that must be received across all the ports included in `port_names` for the operator to execute. The second available mode is `MultiMessageAvailableCondition::SamplingMode::PerReceiver` (C++) or `holoscan.conditions.MultiMessageAvailableCondition.SamplingMode.PER_RECEIVER` (Python). This mode instead takes a vector/list of `min_sizes` equal in length to the `port_names`. This controls the number of messages that must arrive at each individual port in order for the operator to execute. This latter, "per-receiver" mode is equivalent to setting a `MessageAvailableCondition` in each input port individually.

For more details see the C++ example or Python example.

24.7 MultiMessageAvailableTimeoutCondition

This operator is the same as `MultiMessageAvailableCondition` described above, but has one additional parameter "execution_frequency" that can be used to specify a timeout interval after which the operator will be allowed to execute even if the condition on the number of messages received has not yet been met.

For more details see the C++ example or Python example.

Note: This condition can also be assigned via `IOSpec::condition` instead of `OperatorSpec::multi_port_condition` to support the use case where there is only one port to consider. This provides a way for a single input port to support a message available condition that has a timeout interval.

24.8 CountCondition

An operator associated with `CountCondition` (`C++`/`Python`) is executed for a specific number of times specified using its `count` parameter. The scheduling status of the operator associated with this condition can either be in `READY` or `NEVER` state. The scheduling status reaches the `NEVER` state when the operator has been executed `count` number of times. The `count` parameter can be set to a negative value to indicate that the operator should be executed an infinite number of times (default: `1`).

24.9 BooleanCondition

An operator associated with `BooleanCondition` (`C++`/`Python`) is executed when the associated boolean variable is set to `true`. The boolean variable is set to `true`/`false` by calling the `enable_tick()`/`disable_tick()` methods on the `BooleanCondition` object. The `check_tick_enabled()` method can be used to check if the boolean variable is set to `true`/`false`. The scheduling status of the operator associated with this condition can either be in `READY` or `NEVER` state. If the boolean variable is set to `true`, the scheduling status of the operator associated with this condition is set to `READY`. If the boolean variable is set to `false`, the scheduling status of the operator associated with this condition is set to `NEVER`. The `enable_tick()`/`disable_tick()` methods can be called from any operator in the workflow.

C++

```
void compute(InputContext&, OutputContext& op_output, ExecutionContext&) override {
  // ...
  if (<condition expression>) {           // e.g. if (index_ >= 10)
    auto my_bool_condition = condition<BooleanCondition>("my_bool_condition");
    if (my_bool_condition) {              // if condition exists (not true or false)
      my_bool_condition->disable_tick();  // this will stop the operator
    }
  }
  // ...
}
```

PYTHON

```python
def compute(self, op_input, op_output, context):
  # ...
  if <condition expression>:             # e.g, self.index >= 10
      my_bool_condition = self.conditions.get("my_bool_condition")
      if my_bool_condition:              # if condition exists (not true or false)
        my_bool_condition.disable_tick()  # this will stop the operator
  # ...
```

24.10 PeriodicCondition

An operator associated with `PeriodicCondition` (`C++`/`Python`) is executed after periodic time intervals specified using its `recess_period` parameter. The scheduling status of the operator associated with this condition can either be in `READY` or `WAIT_TIME` state. For the first time or after periodic time intervals, the scheduling status of the operator associated with this condition is set to `READY` and the operator is executed. After the operator is executed, the scheduling status is set to `WAIT_TIME`, and the operator is not executed until the `recess_period` time interval. The `PeriodicConditionPolicy` specifies how the scheduler handles the recess period: `CatchUpMissedTicks (default)`,`MinTimeBetweenTicks`, or `NoCatchUpMissedTicks`.

The `PeriodicSchedulingPolicy` enum defines three different policies for handling periodic tasks:

`CatchUpMissedTicks`:

- Tries to catch up on any missed ticks by executing them as quickly as possible
- If multiple ticks were missed, it will try to execute them in rapid succession
- For example, if a tick at 100ms was missed and the time at next tick was 250ms, it will still set the next target time as 200ms resulting in possible immediate rescheduling of the operator since we are already at time 250 ms (i.e. next tick is shown at 255 ms in the example below). After this tick at 255 ms, the target time is then 300 ms.

```
// eg. assume recess period of 100ms:
 tick 0 at 0ms -> next_target_ = 100ms
 tick 1 at 250ms -> next_target_ = 200ms (next_target_ < timestamp)
 tick 2 at 255ms -> next_target_ = 300ms (double tick before 300ms)
```

`MinTimeBetweenTicks`:

- Ensures that at least the specified period has elapsed between ticks
- Won't try to catch up, but guarantees minimum spacing between ticks
- For example, with 100ms period, if current time is 350ms, next tick will be at 450ms (current time + period)

```
// eg. assume recess period of 100ms:
// tick 0 at 0ms -> next_target_ = 100ms
// tick 1 at 101ms -> next_target_ = 201ms
// tick 2 at 350ms -> next_target_ = 450ms
```

`NoCatchUpMissedTicks`:

- Simply continues with the regular schedule without trying to catch up
- If ticks are missed, they stay missed and scheduling continues from current time
- For example, if at 250ms and period is 100ms, next tick will be at 300ms (rounds up to next period boundary)

```
// eg. assume recess period of 100ms:
// tick 0 at 0ms -> next_target_ = 100ms
// tick 1 at 250ms -> next_target_ = 300ms (single tick before 300ms)
// tick 2 at 305ms -> next_target_ = 400ms
```

24.11 MemoryAvailableCondition

For operators that have an associated `Allocator` (C++/Python), that allocator can be assigned to a `MemoryAvailableCondition` (C++/Python). This condition will prevent the operator from executing unless the allocatore has a specified number of bytes free to be allocated.

For the `BlockMemoryPool`, the user can optionally specify the condition in terms of the minimum number of memory blocks instead of in terms of raw bytes.

This condition can be used with `BlockMemoryPool` or `StreamOrderedAllocator` classes to prevent operators using one of those allocator types from executing if there is not sufficient memory available.

Note: This condition type will have no effect if it is used with an `UnboundedAllocator` as there is no associated memory limit for that allocator type. It also currently does **not** have any affect when applied with an `RMMAllocator` because that allocator supports dual (host and device) memory pools and does not meet the API assumptions of this condition.

Example code for how the condition would be configured from an application's `compose` method is shown below.

C++

```
void compose() override {
  // ...

  // declare an allocator
  auto block_allocator = make_resource<BlockMemoryPool>(
      "block_mem_pool",
      Arg("storage_type", MemoryStorageType::kDevice),
      Arg("block_size", 1024*768*4),
      Arg("num_blocks", 4));

  // create a Memory available condition associate with that allocator
  // can use `min_blocks` for BlockMemoryPool, but for other, non-block
  // allocators, the user should specify `min_bytes` instead.
  auto mem_available_condition = make_condition<MemoryAvailableCondition>(
      "mem_avail_tx"
      Arg("allocator", block_allocator),
      Arg("min_blocks, static_cast<uint64_t>(1));

  // pass the condition as a positional argument to an operator that uses that
  // same allocator. This will prevent the operator from executing unless the
  // amount of memory specified by the condition is available.
  auto tx = make_operator<PingTensorTxOp>(
      "tx",
```

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```
        mem_available_condition,
        Arg("allocator", block_allocator),
        Arg("rows", 768),
        Arg("columns", 1024),
        Arg("channels", 4));

    // ...
```

PYTHON

```
    def compose(self):
        # ...

        # declare an allocator
        block_allocator = BlockMemoryPool(
            self,
            storage_type=MemoryStorageType.DEVICE,
            block_size=1024*768*4,
            num_blocks=4,
            name="block_mem_pool",
        )

        # create a Memory available condition associate with that allocator
        # can use `min_blocks` for BlockMemoryPool, but for other, non-block
        # allocators, the user should specify `min_bytes` instead.
        mem_available_condition = MemoryAvailableCondition(
            self,
            allocator=block_allocator,
            min_blocks=1,
            name="mem_avail_tx",
        )

        # pass the condition as a positional argument to an operator that uses that
        # same allocator. This will prevent the operator from executing unless the
        # amount of memory specified by the condition is available.
        tx = PingTensorTxOp(
            self
            mem_available_condition,
            allocator=block_allocator,
            rows=768,
            columns=1024,
            channels=4,
            name="tx",
        )

        # ...
```

24.12 AsynchronousCondition

`AsynchronousCondition` (C++/Python) is primarily associated with operators which are working with asynchronous events happening outside of their regular execution performed by the scheduler. Since these events are non-periodic in nature, `AsynchronousCondition` prevents the scheduler from polling the operator for its status regularly and reduces CPU utilization. The scheduling status of the operator associated with this condition can either be in `READY`, `WAIT`, `WAIT_EVENT`, or `NEVER` states based on the asynchronous event it's waiting on.

The state of an asynchronous event is described using `AsynchronousEventState` and is updated using the `event_state()` API.

AsynchronousEventState	Description
READY	Init state, first execution of `compute()` method is pending
WAIT	Request to async service yet to be sent, nothing to do but wait
EVENT_WAITING	Request sent to an async service, pending event done notification
EVENT_DONE	Event done notification received, operator ready to be ticked
EVENT_NEVER	Operator does not want to be executed again, end of execution

Operators associated with this scheduling term most likely have an asynchronous thread which can update the state of the condition outside of its regular execution cycle performed by the scheduler. When the asynchronous event state is in `WAIT` state, the scheduler regularly polls for the scheduling state of the operator. When the asynchronous event state is in `EVENT_WAITING` state, schedulers will not check the scheduling status of the operator again until they receive an event notification. Setting the state of the asynchronous event to `EVENT_DONE` automatically sends the event notification to the scheduler. Operators can use the `EVENT_NEVER` state to indicate the end of its execution cycle. As for all of the condition types, the condition type can be used with any of the schedulers.

Please refer to the Asynchronous Operator Execution Control Example and Ping Async Example for more details on how to use this condition.

24.13 CudaStreamCondition

This condition can be used to require work on an input stream to complete before an operator is ready to schedule. When a message is sent to the port to which a `CudaStreamCondition` has been assigned, this condition sets an internal host callback function on the CUDA stream found on this input port. The callback function will set the operator's status to READY once other work on the stream has completed. This will then allow the scheduler to execute the operator.

A limitation of `CudaStreamCondition` is that it only looks for a stream on the first message in the input port's queue. It does not currently support handling ports with multiple different input stream components within the same message (entity) or across multiple messages in the queue. The behavior of `CudaStreamCondition` is sufficient for Holoscan's default queue size of one and for use with `receive_cuda_stream` which places just a single CUDA stream component in an upstream operator's outgoing messages. Cases where it is not appropriate are:

- The input port's *queue size was explicitly set* with capacity greater than one and it is not known that all messages in the queue correspond to the same CUDA stream.
- The input port is a multi-receiver port (i.e. `IOSpec::kAnySize`) that any number of upstream operators could connect to.

In cases where no stream is found in the input message, this condition will allow execution of the operator.

24.14 CudaEventCondition

This condition is not intended for regular use in Holoscan applications as Holoscan does not provide any API related to GXF's `nvidia::gxf:CudaEvent` type. This condition is provided purely to allow writing an operator that could interoperate with a different operator that wraps a GXF codelet that includes a `CudaEvent` component in its emitted output messages. It checks for a `CudaEvent` with the specified `event_name` in the first message of the input queue. It will then only allow execution of an operator once a `cudaEventQuery` on the corresponding event indicates that it is ready.

24.15 CudaBufferAvailableCondition

This condition is not intended for regular use in Holoscan applications as Holoscan does not provide any API related to GXF's `nvidia::gxf:CudaBuffer` type. This condition is provided purely to allow writing an operator that could interoperate with a different operator that wraps a GXF codelet that includes a `CudaBuffer` component in its emitted output messages. It checks for a `CudaBuffer` component in the first message of the input queue and will only allow execution of the operator once that buffer has status `CudaBuffer::State::DATA_AVAILABLE`.

CHAPTER TWENTYFIVE

RESOURCES

Resource classes represent resources such as a allocators, clocks, transmitters, or receivers that may be used as a parameter for operators or schedulers. The resource classes that are likely to be directly used by application authors are documented here.

Note: There are a number of other resources classes used internally which are not documented here, but appear in the API Documentation (C++/`Python`).

25.1 Allocator

25.1.1 UnboundedAllocator

An allocator that uses dynamic host or device memory allocation without an upper bound. This allocator does not take any user-specified parameters. This memory pool is easy to use and is recommended for initial prototyping. Once an application is working, switching to a `BlockMemoryPool` instead may help provide additional performance.

25.1.2 BlockMemoryPool

This is a memory pool which provides a user-specified number of equally sized blocks of memory. Using this memory pool provides a way to allocate memory blocks once and reuse the blocks on each subsequent call to an Operator's `compute` method. This saves overhead relative to allocating memory again each time `compute` is called. For the built-in operators which accept a memory pool parameer, there is a section in it's API docstrings titled "Device Memory Requirements" which provides guidance on the `num_blocks` and `block_size` needed for use with this memory pool.

- The `storage_type` parameter can be set to determine the memory storage type used by the operator. This can be 0 for page-locked host memory (allocated with `cudaMallocHost`), 1 for device memory (allocated with `cudaMalloc`) or 2 for system memory (allocated with C++ `new`).
- The `block_size` parameter determines the size of a single block in the memory pool in bytes. Any allocation requests made of this allocator must fit into this block size.
- The `num_blocks` parameter controls the total number of blocks that are allocated in the memory pool.
- The `dev_id` parameter is an optional parameter that can be used to specify the CUDA ID of the device on which the memory pool will be created.

25.1.3 RMMAllocator

This allocator provides a pair of memory pools (one is a CUDA device memory pool and the other corresponds to pinned host memory). The underlying implementation is based on the RAPIDS memory manager (RMM) and uses a pair of `rmm::mr::pool_memory_resource` resource types (The device memory pool is a `rmm::mr::cuda_memory_resource` and the host pool is a `rmm::mr::pinned_memory_resource`) . Unlike `BlockMemoryPool`, this allocator can be used with operators like `VideoStreamReplayerOp` that require an allocator capable of allocating both host and device memory. Rather than fixed block sizes, it uses just an initial memory size to allocate and a maximum size that the pool can expand to.

- The `device_memory_initial_size` parameter specifies the initial size of the device (GPU) memory pool. This is an optional parameter that defaults to 8 MB on aarch64 and 16 MB on x86_64. See note below on the format used to specify the value.
- The `device_memory_max_size` parameter specifies the maximum size of the device (GPU) memory pool in MiB. This is an optional parameter that defaults to twice the value of `device_memory_initial_size`. See note below on the format used to specify the value.
- The `host_memory_initial_size` parameter specifies the initial size of the device (GPU) memory pool in MiB. This is an optional parameter that defaults to 8 MB on aarch64 and 16 MB on x86_64. See note below on the format used to specify the value.
- The `host_memory_max_size` parameter specifies the maximum size of the device (GPU) memory pool in MiB. This is an optional parameter that defaults to twice the value of `host_memory_initial_size`. See note below on the format used to specify the value.
- The `dev_id` parameter is an optional parameter that can be used to specify the GPU device ID (as an integer) on which the memory pool will be created.

Note: The values for the memory parameters, such as `device_memory_initial_size` must be specified in the form of a string containing a non-negative integer value followed by a suffix representing the units. Supported units are B, KB, MB, GB and TB where the values are powers of 1024 bytes (e.g. MB = 1024 * 1024 bytes). Examples of valid units are “512MB”, “256 KB”, “1 GB”. If a floating point number is specified that decimal portion will be truncated (i.e. the value is rounded down to the nearest integer).

25.1.4 CudaStreamPool

This allocator creates a pool of CUDA streams.

- The `stream_flags` parameter specifies the flags sent to cudaStreamCreateWithPriority when creating the streams in the pool.
- The `stream_priority` parameter specifies the priority sent to cudaStreamCreateWithPriority when creating the streams in the pool. Lower values have a higher priority.
- The `reserved_size` parameter specifies the initial number of CUDA streams created in the pool upon initialization.
- The `max_size` parameter is an optional parameter that can be used to specify a maximum number of CUDA streams that can be present in the pool. The default value of 0 means that the size of the pool is unlimited.
- The `dev_id` parameter is an optional parameter that can be used to specify the CUDA ID of the device on which the stream pool will be created.

25.2 Clock

Clock classes can be provided via a `clock` parameter to the `Scheduler` classes to manage the flow of time.

All clock classes provide a common set of methods that can be used at runtime in user applications.

- The `time()` method returns the current time in seconds (floating point).
- The `timestamp()` method returns the current time as an integer number of nanoseconds.
- The `sleep_for()` method sleeps for a specified duration in ns. An overloaded version of this method allows specifying the duration using a `std::chrono::duration<Rep, Period>` from the C++ API or a datetime.timedelta from the Python API.
- The `sleep_until()` method sleeps until a specified target time in ns.

25.2.1 Realtime Clock

The `RealtimeClock` respects the true duration of conditions such as `PeriodicCondition`. It is the default clock type and the one that would likely be used in user applications.

In addition to the general clock methods documented above:

- This class has a `set_time_scale()` method which can be used to dynamically change the time scale used by the clock.
- The parameter `initial_time_offset` can be used to set an initial offset in the time at initialization.
- The parameter `initial_time_scale` can be used to modify the scale of time. For instance, a scale of 2.0 would cause time to run twice as fast.
- The parameter `use_time_since_epoch` makes times relative to the POSIX epoch (`initial_time_offset` becomes an offset from epoch).

25.2.2 Manual Clock

The `ManualClock` compresses time intervals (e.g., `PeriodicCondition` proceeds immediately rather than waiting for the specified period). It is provided mainly for use during testing/development.

The parameter `initial_timestamp` controls the initial timestamp on the clock in ns.

25.3 Transmitter (advanced)

Typically users don't need to explicitly assign transmitter or receiver classes to the IOSpec ports of Holoscan SDK operators. For connections between operators a `DoubleBufferTransmitter` will automatically be used, while for connections between fragments in a distributed application, a `UcxTransmitter` will be used. When data frame flow tracking is enabled any `DoubleBufferTransmitter` will be replaced by an `AnnotatedDoubleBufferTransmitter` which also records the timestamps needed for that feature.

25.3.1 DoubleBufferTransmitter

This is the transmitter class used by output ports of operators within a fragment.

25.3.2 UcxTransmitter

This is the transmitter class used by output ports of operators that connect fragments in a distributed applications. It takes care of sending UCX active messages and serializing their contents.

25.4 Receiver (advanced)

Typically users don't need to explicitly assign transmitter or receiver classes to the IOSpec ports of Holoscan SDK operators. For connections between operators, a `DoubleBufferReceiver` will be used, while for connections between fragments in a distributed application, the `UcxReceiver` will be used. When data frame flow tracking is enabled, any `DoubleBufferReceiver` will be replaced by an `AnnotatedDoubleBufferReceiver` which also records the timestamps needed for that feature.

25.4.1 DoubleBufferReceiver

This is the receiver class used by input ports of operators within a fragment.

25.4.2 UcxReceiver

This is the receiver class used by input ports of operators that connect fragments in a distributed applications. It takes care of receiving UCX active messages and deserializing their contents.

25.5 Condition Combiners

The default behavior for Holoscan's schedulers is AND combination of any conditions on an operator when determining if it should execute. It is possible to assign conditions to a different `ConditionCombiner` class which will combine the conditions using the rules of this combiner and omit those conditions from consideration by the default AND combiner.

25.5.1 OrConditionCombiner

The `OrConditionCombiner` applies an OR condition to the conditions passed to its "terms" argument. For example, assume an operator had a `CountCondition` as well as a `MessageAvailableCondition` for port "in1" and a `MessageAvailableCondition` for port "in2". If an `OrConditionCombiner` was added to the operator with the two message-available conditions passed to its "terms" argument, then the scheduling logic for the operator would be:

- (CountCondition satisfied) AND ((message available on port "in1") OR (message available on port "in2"))

In other words, any condition like the `CountCondition` in this example that is not otherwise assigned to a custom `ConditionCombiner` will use the default AND combiner.

Holoscan provides a `IOSpec::or_combine_port_conditions` method which can be called from `Operator::setup` to enable OR combination of conditions that apply to specific input (or output) ports.

25.6 System Resources

The components in this "system resources" section are related to system resources such as CPU Threads that can be used by operators.

25.6.1 ThreadPool

This resource represents a thread pool that can be used to pin operators to run using specific CPU threads. This functionality is not supported by the `GreedyScheduler` because it is single-threaded, but it is supported by both the `EventBasedScheduler` and `MultiThreadScheduler`. Unlike other resource types, a ThreadPool should **not** be created via `make_resource` (`C++`/`Python`), but should instead use the dedicated `make_thread_pool` (`C++`/`Python`) method. This dedicated method is necessary as the thread pool requires some additional initialization logic that is not required by the other resource types. See the section on *configuring thread pools* in the user guide for usage.

- The parameter `initial_size` indicates the number of threads to initialize the thread pool with.

CHAPTER

TWENTYSIX

ANALYTICS

26.1 Data Exporter API

The new Data Exporter C++ API (`DataExporter` and `CsvDataExporter`) is now available. This API can be used to export output from Holoscan applications to comma separated value (CSV) files for Holoscan Federated Analytics applications. `DataExporter` is a base class to support exporting Holoscan application output in different formats. `CsvDataExporter` is a class derived from `DataExporter` to support exporting Holoscan application output to CSV files.

The data root directory can be specified using the environment variable `HOLOSCAN_ANALYTICS_DATA_DIRECTORY`. If not specified, it defaults to the current directory. The data file name can be specified using the environment variable `HOLOSCAN_ANALYTICS_DATA_FILE_NAME`. If not specified, it defaults to the name `data.csv`. All the generated data will be stored inside a directory with the same name as the application name that is passed to the `DataExporter` constructor. On each run, a new directory inside the `<root_dir>\<app_dir>\` will be created and a new data file will be created inside it. Each new data directory will be named with the current timestamp. This timestamp convention prevents a given run of the application from overwriting any data stored previously by an earlier run of that same application.

26.1.1 Sample usage of the API

```cpp
// Include Header
#include <holoscan/core/analytics/csv_data_exporter.hpp>

// Define CsvDataExporter member variable
CsvDataExporter exporter

// Initialize CsvDataExporter
exporter("app_name", std::vector<std::string>({"column1", "column2", "column3"}))

// Export data (typically called within an Operator::compute method)
exporter.export_data(std::vector<std::string>({"value1", "value2", "value3"}))
```

26.2 Using Data Exporter API with DataProcessor

The Holoscan applications like `Endoscopy Out of Body Detection` uses Inference Processor operator (`InferenceProcessorOp`) to output the binary classification results. The `DataProcessor` class used by the inference processor operator (`InferenceProcessorOp`) is now updated to support writing output to CSV files which can then be used as input to analytics applications. Also any other application using `InferenceProcessorOp` can now export the binary classification output to the CSV files.

Below is an example application config using the new export operation:

```
inference_processor_op:
  process_operations:
    "out_of_body_inferred": ["export_results_to_csv,
                             out_of_body_detection,
                             In-body,
                             Out-of-body,
                             Confidence Score"]
  in_tensor_names: ["out_of_body_inferred"]
```

This will create a folder named `out_of_body_detection` in the specified root directory, creates another folder inside it with current timestamp on each run, and creates a `.csv` file with specified name and three columns - `In-body`, `Out-of-body`, and `Confidence Score`. The lines in the `data.csv` file will look like:

```
    In-body,Out-of-body,Confidence Score
    1,0,0.972435
    1,0,0.90207
    1,0,0.897973
    0,1,0.939281
    0,1,0.948691
    0,1,0.94994
```

CHAPTER

TWENTYSEVEN

HOLOSCAN APPLICATION PACKAGE SPECIFICATION (HAP)

27.1 Introduction

The Holoscan Application Package specification extends the MONAI Deploy Application Package specification to provide the streaming capabilities, multi-fragment, and other features of the Holoscan SDK.

27.2 Overview

This document includes the specification of the Holoscan Application Package (HAP). A HAP is a containerized application or service which is self-descriptive, as defined by this document.

27.2.1 Goal

This document aims to define the structure and purpose of a HAP, including which parts are optional and which are required so that developers can easily create conformant HAPs.

27.2.2 Assumptions, Constraints, Dependencies

The following assumptions relate to HAP execution, inspection and general usage:

- Containerized applications will be based on Linux x64 (AMD64) and/or ARM64 (aarch64).
- Containerized applications' host environment will be based on Linux x64 (AMD64) and/or ARM64 (aarch64) with container support.
- Developers expect the local execution of their applications to behave identically to the execution of the containerized version.
- Developers expect the local execution of their containerized applications to behave identically to the execution in deployment.
- Developers and operations engineers want the application packages to be self-describing.
- Applications may be created using tool other than that provided in the Holoscan SDK or the MONAI Deploy App SDK.
- Holoscan Application Package may be created using a tool other than that provided in the Holoscan SDK or the MONAI Deploy App SDK.
- Pre-existing, containerized applications must be "converted" into Holoscan Application Packages.

- A Holoscan Application Package may contain a classical application (non-fragment based), a single-fragment application, or a multi-fragment application. (Please see the definition of fragment in *Definitions, Acronyms, Abbreviations*)
- The scalability of a multi-fragment application based on Holoscan SDK is outside the scope of this document.
- Application packages are expected to be deployed in one of the supported environments. For additional information, see *Holoscan Operating Environments*.

27.3 Definitions, Acronyms, Abbreviations

Term	Definition
ARM64	Or, AARCH64. See Wikipedia for details.
Container	See What's a container?
Fragment	A fragment is a building block of the Application. It is a directed graph of operators. For details, please refer to the MONAI Deploy App SDK or Holoscan App SDK.
Gigibytes (GiB)	A gibibyte (GiB) is a unit of measurement used in computer data storage that equals to 1,073,741,824 bytes.
HAP	Holoscan Application Package. A containerized application or service which is self-descriptive.
Hosting Service	A service that hosts and orchestrates HAP containers.
MAP	MONAI Application Package. A containerized application or service which is self-descriptive.
Mebibytes (MiB)	A mebibyte (MiB) is a unit of measurement used in computer data storage that equals to 1,048,576 bytes.
MONAI	Medical Open Network for Artificial Intelligence.
SDK	Software Development Kit.
Semantic Version	See Semantic Versioning 2.0.
x64	Or, x86-64 or AMD64. See Wikipedia for details.

27.4 Requirements

The following requirements MUST be met by the HAP specification to be considered complete and approved. All requirements marked as `MUST` or `SHALL` MUST be implemented in order to be supported by a HAP-ready hosting service.

27.4.1 Single Artifact

- A HAP SHALL comprise a single container, meeting the minimum requirements set forth by this document.
- A HAP SHALL be a containerized application to maximize the portability of its application.

27.4.2 Self-Describing

- A HAP MUST be self-describing and provide a mechanism for extracting its description.
  - A HAP SHALL provide a method to print the metadata files to the console.
  - A HAP SHALL provide a method to copy the metadata files to a user-specified directory.
- The method of description SHALL be in a machine-readable and writable format.
- The method of description SHALL be in a human-readable format.
- The method of description SHOULD be a human writable format.
- The method of description SHALL be declarative and immutable.
- The method of description SHALL provide the following information about the HAP:
  - Execution requirements such as dependencies and restrictions.
  - Resource requirements include CPU cores, system memory, shared memory, GPU, and GPU memory.

27.4.3 Runtime Characteristics of the HAP

- A HAP SHALL start the packaged Application when it is executed by the users when arguments are specified.
- A HAP SHALL describe the packaged Application as a long-running service or an application so an external agent can manage its lifecycle.

27.4.4 IO Specification

- A HAP SHALL provide information about its expected inputs such that an external agent can determine if the HAP can receive a workload.
- A HAP SHALL provide sufficient information about its outputs so that an external agent knows how to handle the results.

27.4.5 Local Execution

A HAP MUST be in a format that supports local execution in a development environment.

[Note] See *Holoscan Operating Environments* for additional information about supported environments.

27.4.6 Compatible with Kubernetes

- A HAP SHALL support deployment using Kubernetes.

27.4.7 OCI Compliance

The containerized portion of a HAP SHALL comply with Open Container Initiative format standards.

Image Annotations

All annotations for the containerized portion of a HAP MUST adhere to the specifications laid out by The OpenContainers Annotations Spec

- `org.opencontainers.image.title`: A HAP container image SHALL provide a human-readable title (string).
- `org.opencontainers.image.version`: A HAP container image SHALL provide a version of the packaged application using the semantic versioning format. This value is the same as the value defined in `/etc/holoscan/app.json#version` in the *Table of Application Manifest Fields*.
- All other OpenContainers predefined keys SHOULD be provided when available.

27.4.8 Hosting Environment

The HAP Hosting Environment executes the HAP and provides the application with a customized set of environment variables and command line options as part of the invocation.

- The Hosting Service MUST, by default, execute the application as defined by `/etc/holoscan/app.json#command` and then exit when the application or the service completes.
- The Hosting Service MUST provide any environment variables specified by `/etc/holoscan/app.json#environment`.
- The Hosting Service SHOULD monitor the Application process and record its CPU, system memory, and GPU utilization metrics.
- The Hosting Service SHOULD monitor the Application process and enforce any timeout value specified in `/etc/holoscan/app.json#timeout`.

Table of Environment Variables

A HAP SHALL contain the following environment variables and their default values, if not specified by the user, in the Application Manifest `/etc/holoscan/app.json#environment`.

Variable	Default	Format	Description
HOLOSCAN_INPUT_PATH	/var/holoscan/input/	Folder Path	Path to the input folder for the Application.
HOLOSCAN_OUTPUT_PATH	/var/holoscan/output/	Folder Path	Path to the output folder for the Application.
HOLOSCAN_WORKDIR	/var/holoscan/	Folder Path	Path to the Application's working directory.
HOLOSCAN_MODEL_PATH	/opt/holoscan/models/	Folder Path	Path to the Application's models directory.
HOLOSCAN_CONFIG_PATH	/var/holoscan/app.yaml	File Path	Path to the Application's configuration file.
HOLOSCAN_APP_MANIFEST_PATH	/etc/holoscan/app.config	File Path	Path to the Application's configuration file.
HOLOSCAN_PKG_MANIFEST_PATH	/etc/holoscan/pkg.config	File Path	Path to the Application's configuration file.
HOLOSCAN_DOCS	/opt/holoscan/docs	Folder Path	Path to the folder containing application documentation and licenses.
HOLOSCAN_LOGS	/var/holoscan/logs	Folder Path	Path to the Application's logs.

27.5 Architecture & Design

27.5.1 Description

The Holoscan Application Package (HAP) is a functional package designed to act on datasets of a prescribed format. A HAP is a container image that adheres to the specification provided in this document.

27.5.2 Application

The primary component of a HAP is the application. The application is provided by an application developer and incorporated into the HAP using the Holoscan Application Packager.

All application code and binaries SHALL be in the `/opt/holoscan/app/` folder, except for any dependencies installed by the Holoscan Application Packager during the creation of the HAP.

All AI models (PyTorch, TensorFlow, TensorRT, etc.) SHOULD be in separate sub-folders of the `/opt/holoscan/models/` folder. In specific use cases where the app package developer is prevented from enclosing the model files in the package/container due to intellectual property concerns, the models can be supplied from the host system when the app package is run, e.g., via the volume mount mappings and the use of container env variables.

27.5.3 Manifests

A HAP SHALL contain two manifests: the Application Manifest and the Package Manifest. The Package Manifest shall be stored in `/etc/holoscan/pkg.json`, and the Application Manifest shall be stored in `/etc/holoscan/app.json`. Once a HAP is created, its manifests are expected to be immutable.

Application Manifest

Table of Application Manifest Fields

Name	Required	Default	Type	Format
`apiVersion`	No	0.0.0	string	semantic version
`command`	**Yes**	N/A	string	shell command
`environment`	**No**	N/A	object	object w/ name-va
`input`	**Yes**	N/A	object	object
`input.formats`	**Yes**	N/A	array	array of objects
`input.path`	No	input/	string	relative file-system
`readiness`	No	N/A	object	object
`readiness.type`	**Yes**	N/A	string	string
`readiness.command`	**Yes** (when type is `command`)	N/A	array	shell command
`readiness.port`	**Yes** (when type is `tcp`, `grpc`, or `http-get`)	N/A	integer	number
`readiness.path`	**Yes** (when type is `http-get`)	N/A	string	string
`readiness.initialDelaySeconds`	No	1	integer	number
`readiness.periodSeconds`	No	10	integer	number
`readiness.timeoutSeconds`	No	1	integer	number
`readiness.failureThreshold`	No	3	integer	number
`liveness`	No	N/A	object	object
`liveness.type`	**Yes**	N/A	string	string
`liveness.command`	**Yes** (when type is `command`)	N/A	array	shell command
`liveness.port`	**Yes** (when type is `tcp`, `grpc`, or `http-get`)	N/A	integer	number
`liveness.path`	**Yes** (when type is `http-get`)	N/A	string	string
`liveness.initialDelaySeconds`	No	1	integer	number
`liveness.periodSeconds`	No	10	integer	number
`liveness.timeoutSeconds`	No	1	integer	number
`liveness.failureThreshold`	No	3	integer	number
`output`	**Yes**	N/A	object	object
`output.format`	**Yes**	N/A	object	object
`output.path`	No	output/	string	relative file-system
`sdk`	No	N/A	string	string
`sdkVersion`	No	0.0.0	string	semantic version
`timeout`	No	0	integer	number
`version`	No	0.0.0	string	semantic version
`workingDirectory`	No	/var/holoscan/	string	absolute file-syste

The Application Manifest file provides information about the HAP's Application.

- The Application Manifest MUST define the type of the containerized application (`/etc/holoscan/app.json#type`).
  - Type SHALL have the value of either `service` or `application`.

- The Application Manifest MUST define the command used to run the Application (`/etc/holoscan/app.json#command`).
- The Application Manifest SHOULD define the version of the manifest file schema (`/etc/holoscan/app.json#apiVersion`).
  - The Manifest schema version SHALL be provided as a semantic version string.
  - When not provided, the default value `0.0.0` SHALL be assumed.
- The Application Manifest SHOULD define the SDK used to create the Application (`/etc/holoscan/app.json#sdk`).
- The Application Manifest SHOULD define the version of the SDK used to create the Application (`/etc/holoscan/app.json#sdkVersion`).
  - SDK version SHALL be provided as a semantic version string.
  - When not provided, the default value `0.0.0` SHALL be assumed.
- The Application Manifest SHOULD define the version of the application itself (`/etc/holoscan/app.json#version`).
  - The Application version SHALL be provided as a semantic version string.
  - When not provided, the default value `0.0.0` SHALL be assumed.
- The Application Manifest SHOULD define the application's working directory (`/etc/holoscan/app.json#workingDirectory`).
  - The Application will execute with its current directory set to this value.
  - The value provided must be an absolute path (the first character is `/`).
  - The default path `/var/holoscan/` SHALL be assumed when not provided.
- The Application Manifest SHOULD define the data input path, relative to the working directory, used by the Application (`/etc/holoscan/app.json#input.path`).
  - The input path SHOULD be a relative to the working directory or an absolute file-system path to a directory.
    * When the value is a relative file-system path (the first character is not `/`), it is relative to the application's working directory.
    * When the value is an absolute file-system path (the first character is `/`), the file-system path is used as-is.
  - When not provided, the default value `input/` SHALL be assumed.
- The Application Manifest SHOULD define input data formats supported by the Application (`/etc/holoscan/app.json#input.formats`).
  - Possible values include, but are not limited to, `none`, `network`, `file`.
- The Application Manifest SHOULD define the output path relative to the working directory used by the Application (`/etc/holoscan/app.json#output.path`).
  - The output path SHOULD be relative to the working directory or an absolute file-system path to a directory.
    * When the value is a relative file-system path (the first character is not `/`), it is relative to the application's working directory.
    * When the value is an absolute file-system path (the first character is `/`), the file-system path is used as-is.
  - When not provided, the default value `output/` SHALL be assumed.

- The Application Manifest SHOULD define the output data format produced by the Application (`/etc/holoscan/app.json#output.format`).
  - Possible values include, but are not limited to, `none`, `screen`, `file`, `network`.
- The Application Manifest SHOULD configure a check to determine whether or not the application is "ready."
  - The Application Manifest SHALL define the probe type to be performed (`/etc/holoscan/app.json#readiness.type`).
    - Possible values include `tcp`, `grpc`, `http-get`, and `command`.
  - The Application Manifest SHALL define the probe commands to execute when the type is `command` (`/etc/holoscan/app.json#readiness.command`).
    - The data structure is expected to be an array of strings.
  - The Application Manifest SHALL define the port to perform the readiness probe when the type is `grpc`, `tcp`, or `http-get`. (`/etc/holoscan/app.json#readiness.port`)
    - The value provided must be a valid port number ranging from 1 through 65535. (Please note that port numbers below 1024 are root-only privileged ports.)
  - The Application Manifest SHALL define the path to perform the readiness probe when the type is `http-get` (`/etc/holoscan/app.json#readiness.path`).
    - The value provided must be an absolute path (the first character is `/`).
  - The Application Manifest SHALL define the number of seconds after the container has started before the readiness probe is initiated. (`/etc/holoscan/app.json#readiness.initialDelaySeconds`).
    - The default value `0` SHALL be assumed when not provided.
  - The Application Manifest SHALL define how often to perform the readiness probe (`/etc/holoscan/app.json#readiness.periodSeconds`).
    - When not provided, the default value `10` SHALL be assumed.
  - The Application Manifest SHALL define the number of seconds after which the probe times out (`/etc/holoscan/app.json#readiness.timeoutSeconds`)
    - When not provided, the default value `1` SHALL be assumed.
  - The Application Manifest SHALL define the number of times to perform the probe before considering the service is not ready (`/etc/holoscan/app.json#readiness.failureThreshold`)
    - The default value `3` SHALL be assumed when not provided.
- The Application Manifest SHOULD configure a check to determine whether or not the application is "live" or not.
  - The Application Manifest SHALL define the type of probe to be performed (`/etc/holoscan/app.json#liveness.type`).
    - Possible values include `tcp`, `grpc`, `http-get`, and `command`.
  - The Application Manifest SHALL define the probe commands to execute when the type is `command` (`/etc/holoscan/app.json#liveness.command`).
    - The data structure is expected to be an array of strings.
  - The Application Manifest SHALL define the port to perform the liveness probe when the type is `grpc`, `tcp`, or `http-get`. (`/etc/holoscan/app.json#liveness.port`)
    - The value provided must be a valid port number ranging from 1 through 65535. (Please note that port numbers below 1024 are root-only privileged ports.)

- The Application Manifest SHALL define the path to perform the liveness probe when the type is `http-get` (`/etc/holoscan/app.json#liveness.path`).
  - The value provided must be an absolute path (the first character is `/`).
- The Application Manifest SHALL define the number of seconds after the container has started before the liveness probe is initiated. (`/etc/holoscan/app.json#liveness.initialDelaySeconds`).
  - The default value `0` SHALL be assumed when not provided.
- The Application Manifest SHALL define how often to perform the liveness probe (`/etc/holoscan/app.json#liveness.periodSeconds`).
  - When not provided, the default value `10` SHALL be assumed.
- The Application Manifest SHALL define the number of seconds after which the probe times out (`/etc/holoscan/app.json#liveness.timeoutSeconds`)
  - The default value `1` SHALL be assumed when not provided.
- The Application Manifest SHALL define the number of times to perform the probe before considering the service is not alive (`/etc/holoscan/app.json#liveness.failureThreshold`)
  - When not provided, the default value `3` SHALL be assumed.

- The Application Manifest SHOULD define any timeout applied to the Application (`/etc/holoscan/app.json#timeout`).
  - When the value is `0`, timeout SHALL be disabled.
  - When not provided, the default value `0` SHALL be assumed.
- The Application Manifest MUST enable the specification of environment variables for the Application (`/etc/holoscan/app.json#environment`)
  - The data structure is expected to be in `"name": "value"` members of the object.
  - The field's name will be the name of the environment variable verbatim and must conform to all requirements for environment variables and JSON field names.
  - The field's value will be the value of the environment variable and must conform to all requirements for environment variables.

Package Manifest

Table of Package Manifest Fields

Name	Required	Default	Type	Format	Description
`apiVersion`	No	`0.0.0`	string	semantic version	Version of the manifest file schema.
`applicationRoot`	**Yes**	`/opt/holoscan/app/`	string	absolute file-system path	Absolute file-system path to the folder which contains the Application
`modelRoot`	No	`/opt/holoscan/models/`	string	absolute file-system path	Absolute file-system path to the folder which contains the model(s).
`models`	No	N/A	array	array of objects	Array of objects which describe models in the package.
`models[*].name`	**Yes**	N/A	string	string	Name of the model.
`models[*].path`	No	N/A	string	Relative file-system path	File-system path to the folder which contains the model that is relative to the value defined in `modelRoot`.
`resources`	No	N/A	object	object	Object describing resource requirements for the Application.
`resources.cpu`	No	`1`	decimal (2)	number	Number of CPU cores required by the Application or the Fragment.
`resources.cpuLimit`	No	N/A	decimal (2)	number	The CPU core limit for the Application or the Fragment. (1)
`resources.gpu`	No	`0`	decimal (2)	number	Number of GPU devices required by the Application or the Fragment.
`resources.gpuLimit`	No	N/A	decimal (2)	number	The GPU device limit for the Application or the Fragment. (1)
`resources.memory`	No	`1Gi`	string	memory size	The memory required by the Application or the Fragment.
`resources.memoryLimit`	No	N/A	string	memory size	The memory limit for the Application or the Fragment. (1)
`resources.gpuMemory`	No	N/A	string	memory size	The GPU memory required by the Application or the Fragment.
`resources.gpuMemoryLimit`	No	N/A	string	memory size	The GPU memory limit for the Application or the Fragment. (1)
`resources.sharedMemory`	No	`64Mi`	string	memory size	The shared memory required by the Application or the Fragment.
`resources.fragments`	No	N/A	object	objects	Nested objects which describe resources for a Multi-Fragment Application.
`resources.fragments.<fragment-name>`	**Yes**	N/A	string	string	Name of the fragment.
`resources.fragments.<fragment-name>.cpu`	No	`1`	decimal (2)	number	Number of CPU cores required by the Fragment.
`resources.fragments.<fragment-name>.cpuLimit`	No	N/A	decimal (2)	number	The CPU core limit for the Fragment. (1)
`resources.fragments.<fragment-name>.gpu`	No	`0`	decimal (2)	number	Number of GPU devices required by the Fragment.
`resources.fragments.`	No	N/A	dec-	number	The GPU device limit for the Fragment. (1)

[Notes] (1) Use of resource limits depend on the orchestration service or the hosting environment's configuration and implementation. (2) Consider rounding up to a whole number as decimal values may not be supported by all orchestration/hosting services.

The Package Manifest file provides information about the HAP's package layout. It is not intended as a mechanism for controlling how the HAP is used or how the HAP's Application is executed.

- The Package Manifest MUST be UTF-8 encoded and use the JavaScript Object Notation (JSON) format.
- The Package Manifest SHOULD support either CRLF or LF style line endings.
- The Package Manifest SHOULD specify the folder which contains the application (`/etc/holoscan/pkg.json#applicationRoot`).
  - When not provided, the default path `/opt/holoscan/app/` will be assumed.
- The Package Manifest SHOULD provide the version of the package file manifest schema (`/etc/holoscan/pkg.json#apiVersion`).
  - The Manifest schema version SHALL be provided as a semantic version string.
- The Package Manifest SHOULD provide the package version of itself (`/etc/holoscan/pkg.json#version`).
  - The Package version SHALL be provided as a semantic version string.
- The Package Manifest SHOULD provide the directory path to the user-provided models. (`/etc/holoscan/pkg.json#modelRoot`).
  - The value provided must be an absolute path (the first character is `/`).
  - When not provided, the default path `/opt/holoscan/models/` SHALL be assumed.
- The Package Manifest SHOULD list the models used by the application (`/etc/holoscan/pkg.json#models`).
  - Models SHALL be defined by name (`/etc/holoscan/pkg.json#models[*].name`).
    * Model names SHALL NOT contain any Unicode whitespace or control characters.
    * Model names SHALL NOT exceed 128 bytes in length.
  - Models SHOULD provide a file-system path if they're included in the HAP itself (`/etc/holoscan/pkg.json#models[*].path`).
    * When the value is a relative file-system path (the first character is not `/`), it is relative to the model root directory defined in `/etc/holoscan/pkg.json#modelRoot`.
    * When the value is an absolute file-system path (the first character is `/`), the file-system path is used as-is.
    * When no value is provided, the name is assumed as the name of the directory relative to the model root directory defined in `/etc/holoscan/pkg.json#modelRoot`.
- The Package Manifest SHOULD specify the resources required to execute the Application and the fragments for a Multi-Fragment Application.

  This information is used to provision resources when running the containerized application using a compatible application deployment service.
- A classic Application or a single Fragment Application SHALL define its resources in the `/etc/holoscan/pkg.json#resource` object.
  - The `/etc/holoscan/pkg.json#resource` object is for the whole application. It CAN also be used as a catchall for all fragments in a multi-fragment application where applicable.
  - CPU requirements SHALL be denoted using the decimal count of CPU cores (`/etc/holoscan/pkg.json#resources.cpu`).

- Optional CPU limits SHALL be denoted using the decimal count of CPU cores (`/etc/holoscan/pkg.json#resources.cpuLimit`)
- GPU requirements SHALL be denoted using the decimal count of GPUs (`/etc/holoscan/pkg.json#resources.gpu`).
- Optional GPU limits SHALL be denoted using the decimal count of GPUs (`/etc/holoscan/pkg.json#resources.gpuLimit`)
- Memory requirements SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.memory`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- Optional memory limits SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.memoryLimit`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- GPU memory requirements SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.gpuMemory`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- Optional GPU memory limits SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.gpuMemoryLimit`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- Shared memory requirements SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.sharedMemory`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- Optional shared memory limits SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.sharedMemoryLimit`).
  - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
    - Example: `1.5Gi`, `2048Mi`
- Integer values MUST be positive and not contain any position separators.
  - Example legal values: `1`, `42`, `2048`
  - Example illegal values: `-1`, `1.5`, `2,048`
- Decimal values MUST be positive, rounded to the nearest tenth, use the dot (`.`) character to separate whole and fractional values, and not contain any positional separators.
  - Example legal values: `1`, `1.0`, `0.5`, `2.5`, `1024`
  - Example illegal values: `1,024`, `-1.0`, `3.14`
- When not provided, the default values of `cpu=1`, `gpu=0`, `memory="1Gi"`, and `sharedMemory="64Mi"` will be assumed.

- A Multi-Fragment Application SHOULD define its resources in the `/etc/holoscan/pkg.json#resource.fragments.<fragment-name>` object.
  - When a matching `fragment-name` cannot be found, the `/etc/holoscan/pkg.json#resource` definition is used.
  - Fragment names (`fragment-name`) SHALL NOT contain any Unicode whitespace or control characters.
  - Fragment names (`fragment-name`) SHALL NOT exceed 128 bytes in length.
  - CPU requirements for fragments SHALL be denoted using the decimal count of CPU cores (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.cpu`).
  - Optional CPU limits for fragments SHALL be denoted using the decimal count of CPU cores (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.cpuLimit`).
  - GPU requirements for fragments SHALL be denoted using the decimal count of GPUs (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.gpu`).
  - Optional GPU limits for fragments SHALL be denoted using the decimal count of GPUs (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.gpuLimit`).
  - Memory requirements for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.memory`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - Optional memory limits for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.memoryLimit`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - GPU memory requirements for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.gpuMemory`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - Optional GPU memory limits for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.gpuMemoryLimit`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - Shared memory requirements for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.sharedMemory`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - Optional shared memory limits for fragments SHALL be denoted using decimal values followed by units (`/etc/holoscan/pkg.json#resources.fragments.<fragment-name>.sharedMemoryLimit`).
    - Supported units SHALL be mebibytes (`MiB`) and gibibytes (`GiB`).
      - Example: `1.5Gi`, `2048Mi`
  - Integer values MUST be positive and not contain any position separators.
    - Example legal values: `1`, `42`, `2048`

    * Example illegal values: `-1`, `1.5`, `2,048`

- Decimal values MUST be positive, rounded to the nearest tenth, use the dot (`.`) character to separate whole and fractional values, and not contain any positional separators.
    * Example legal values: `1`, `1.0`, `0.5`, `2.5`, `1024`
    * Example illegal values: `1,024`, `-1.0`, `3.14`
- When not provided, the default values of `cpu=1`, `gpu=0`, `memory="1Gi"`, and `sharedMemory="64Mi"` will be assumed.

27.6 Supplemental Application Files

- A HAP SHOULD package supplemental application files provided by the user.
    - Supplemental files SHOULD be in sub-folders of the `/opt/holoscan/docs/` folder.
    - Supplemental files include, but are not limited to, the following:
        * README.md
        * License.txt
        * Changelog.txt
        * EULA
        * Documentation
        * Third-party licenses

27.6.1 Container Behavior and Interaction

A HAP is a single container supporting the following defined behaviors when started.

Default Behavior

When a HAP is started from the CLI or other means without any parameters, the HAP shall execute the contained application. The HAP internally may use `Entrypoint`, `CMD`, or a combination of both.

Manifest Export

A HAP SHOULD provide at least one method to access the *embedded application*, *models*, *licenses*, *README*, or *manifest files*, namely, `app.json` and `package.json`.

- The Method SHOULD provide a container command, *`show`*, to print one or more manifest files to the console.
- The Method SHOULD provide a container command, *`export`*, to copy one or more manifest files to a mounted volume path, as described below
    - `/var/run/holoscan/export/app/`: when detected, the Method copies the contents of `/opt/holoscan/app/` to the folder.
    - `/var/run/holoscan/export/config/`: when detected, the Method copies `/var/holoscan/app.yaml`, `/etc/holoscan/app.json` and `/etc/holoscan/pkg.json` to the folder.
    - `/var/run/holoscan/export/models/`: when detected, the Method copies the contents of `/opt/holoscan/models/` to the folder.

- `/var/run/holoscan/export/docs/`: when detected, the Method copies the contents of `/opt/holoscan/docs/` to the folder.
- `/var/run/holoscan/export/`: when detected without any of the above being detected, the Method SHALL copy all of the above.

Since a HAP is an OCI compliant container, a user can also run a HAP and log in to an interactive shell, using a method supported by the container engine and its command line interface; e.g., Docker supports this by setting the entrypoint option. The files in the HAP can then be opened or copied to the mapped volumes with shell commands or scripts. A specific implementation of a HAP may choose to streamline such a process with scripts and applicable user documentation.

27.6.2 Table of Important Paths

Path	Purpose
`/etc/holoscan/`	HAP manifests and immutable configuration files.
`/etc/holoscan/app.json`	Application Manifest file.
`/etc/holoscan/pkg.json`	Package Manifest file.
`/opt/holoscan/app/`	Application code, scripts, and other files.
`/opt/holoscan/models/`	AI models. Each model should be in a separate sub-folder.
`/opt/holoscan/docs/`	Documentation, licenses, EULA, changelog, etc…
`/var/holoscan/`	Default working directory.
`/var/holoscan/input/`	Default input directory.
`/var/holoscan/output/`	Default output directory.
`/var/run/holoscan/export/`	Special case folder, causes the Script to export contents related to the app. (see: *Manifest Export*)
`/var/run/holoscan/export/app/`	Special case folder, causes the Script to export the contents of `/opt/holoscan/app/` to the folder.
`/var/run/holoscan/export/config/`	Special case folder, causes the Script to export `/etc/holoscan/app.json` and `/etc/holoscan/pkg.json` to the folder.
`/var/run/holoscan/export/models/`	Special case folder, causes the Script to export the contents of `/opt/holoscan/models/` to the folder.

27.7 Operating Environments

Holoscan SDK supports the following operating environments.

Operating Environment Name	Characteristics
AGX Devkit	Clara AGX devkit with RTX 6000 dGPU only
IGX Orin Devkit	Clara Holoscan devkit with A6000 dGPU only
IGX Orin Devkit - integrated GPU only	IGX Orin Devkit, iGPU only
IGX Orin Devkit with discrete GPU	IGX Orin Devkit, with RTX A6000 dGPU
Jetson AGX Orin Devkit	Jetson Orin Devkit, iGPU only
Jetson Orin Nano Devkit	Jetson Orin Nano Devkit, iGPU only
X86_64	dGPU only on Ubuntu 18.04 and 20.04

CHAPTER

TWENTYEIGHT

HOLOSCAN CLI

holoscan - a command-line interface for packaging and running your Holoscan applications into *HAP-compliant* containers.

28.1 Synopsis

holoscan *[--help|-h] [--log-level|-l {DEBUG,INFO,WARN,ERROR,CRITICAL}]* {*package*,*run*,*version*,nics}

28.2 Positional Arguments

28.2.1 Holoscan CLI - Package Command

holoscan package - generate *HAP-compliant* container for your application.

Synopsis

holoscan package *[--help|-h] [--log-level|-l {DEBUG,INFO,WARN,ERROR,CRITICAL}] --config|-c CONFIG [--docs|-d DOCS] [--add DIR_PATH] [--models|-m MODELS] --platform PLATFORM [--platform-config PLATFORM_CONFIG] [--timeout TIMEOUT] [--version VERSION] [--base-image BASE_IMAGE] [--build-image BUILD_IMAGE] [--includes [{debug,holoviz,torch,onnx}]] [--build-cache BUILD_CACHE] [--cmake-args CMAKE_ARGS] [--no-cache|-n] [--sdk SDK] [--source URL|FILE] [--sdk-version SDK_VERSION] [--holoscan-sdk-file HOLOSCAN_SDK_FILE] [--monai-deploy-sdk-file MONAI_DEPLOY_SDK_FILE] [--output|-o OUTPUT] --tag|-t TAG [--username USERNAME] [--uid UID] [--gid GID] application [--source URL|FILE]*

Examples

The code below package a python application for x86_64 systems:

```
# Using a Python directory as input
# Required: a `__main__.py` file in the application directory to execute
# Optional: a `requirements.txt` file in the application directory to install dependencies
holoscan package --platform x64-workstation --tag my-awesome-app --config /path/to/my/
↪awesome/application/config.yaml /path/to/my/awesome/application/

# Using a Python file as input
holoscan package --platform x64-workstation --tag my-awesome-app --config /path/to/my/
↪awesome/application/config.yaml /path/to/my/awesome/application/my-app.py
```

The code below package a C++ application for the IGX Orin DevKit (aarch64) with a discrete GPU:

```
# Using a C++ source directory as input
# Required: a `CMakeLists.txt` file in the application directory
holoscan package --platform igx-orin-devkit --platform-config dgpu --tag my-awesome-app -
↪-config /path/to/my/awesome/application/config.yaml /path/to/my/awesome/application/

# Using a C++ pre-compiled executable as input
holoscan package --platform igx-orin-devkit --platform-config dgpu --tag my-awesome-app -
↪-config /path/to/my/awesome/application/config.yaml /path/to/my/awesome/bin/
↪application-executable
```

Note: The commands above load the generated image onto Docker to make the image accessible with `docker images`.

If you need to package for a different platform or want to transfer the generated image to another system, use the `--output /path/to/output` flag so the generated package can be saved to the specified location.

Positional Arguments

`application`

Path to the application to be packaged. The following inputs are supported:

- **C++ source code**: you may pass a directory path with your C++ source code with a `CMakeLists.txt` file in it, and the **Packager** will attempt to build your application using CMake and include the compiled application in the final package.
- **C++ pre-compiled executable**: A pre-built executable binary file may be directly provided to the **Packager**.
- **Python application**: you may pass either:
  - a directory which includes a `__main__.py` file to execute (required) and an optional `requirements.txt` file that defined dependencies for your Python application, or
  - the path to a single python file to execute

Warning: Python (PyPI) modules are installed into the user's (via *[--username USERNAME]* argument) directory with the user ID specified via *[--uid UID]*. Therefore, when running a packaged Holoscan application on Kubernetes or other service providers, running Docker with non root user, and running Holoscan CLI `run` command where the logged-on user's ID is different, ensure to specify the `USER ID` that is used when building the application package.

For example, include the `securityContext` when running a Holoscan packaged application with `UID=1000` using Argo:

```
spec:
  securityContext:
    runAsUser: 1000
    runAsNonRoot: true
```

Flags

`--config|-c CONFIG`

Path to the application's *configuration file*. The configuration file must be in `YAML` format with a `.yaml` file extension.

`[--docs|-d DOCS]`

An optional directory path of documentation, README, licenses that shall be included in the package.

`[--add DIR_PATH]`

`--add` enables additional files to be added to the application package. Use this option to include additional Python modules, files, or static objects (.so) on which the application depends.

- `DIR_PATH` must be a directory path. The packager recursively copies all the files and directories inside `DIR_PATH` to `/opt/holoscan/app/lib`.
- `--add` may be specified multiple times.

For example:

```
holoscan package --add /path/to/python/module-1 --add /path/to/static-objects
```

With the example above, assuming the directories contain the following:

```
/path/to/
├── python
│   ├── module-1
│   │   ├── __init__.py
│   │   └── main.py
└── static-objects
    ├── my-lib.so
    └── my-other-lib.so
```

The resulting package will contain the following:

```
/opt/holoscan/
├── app
│   └── my-app
└──lib/
    ├── module-1
    │   ├── __init__.py
    │   └── main.py
    ├── my-lib.so
    └── my-other-lib.so
```

[--models|-m MODELS]

An optional directory path to a model file, a directory with a single model, or a directory with multiple models.

Single model example:

```
my-model/
├── surgical_video.gxf_entities
└── surgical_video.gxf_index

my-model/
└── model
    ├── surgical_video.gxf_entities
    └── surgical_video.gxf_index
```

Multi-model example:

```
my-models/
├── model-1
│   ├── my-first-model.gxf_entities
│   └── my-first-model.gxf_index
└── model-2
    └── my-other-model.ts
```

--platform PLATFORM

A comma-separated list of platform types to generate. Each platform value specified generates a standalone container image. If you are running the **Packager** on the same architecture, the generated image is automatically loaded onto Docker and is available with `docker images`. Otherwise, use `--output` flag to save the generated image onto the disk.

`PLATFORM` must be one of: `clara-agx-devkit`, `igx-orin-devkit`, `jetson-agx-orin-devkit`, `x64-workstation`.

- `igx-orin-devkit`: IGX Orin DevKit
- `jetson-agx-orin-devkit`: Orin AGX DevKit
- `x64-workstation`: systems with a x86-64 processor(s)

[--platform-config PLATFORM_CONFIG]

Specifies the platform configuration to generate. `PLATFORM_CONFIG` must be one of: `igpu`, `igpu-assist`, `dgpu`.

- `igpu`: Supports integrated GPU
- `igpu-assist`: Supports compute-only tasks on iGPU in presence of a dGPU
- `dgpu`: Supports dedicated GPU

Note: `--platform-config` is required when `--platform` is not `x64-workstation` (which uses `dgpu`).

`[--timeout TIMEOUT]`

An optional timeout value of the application for the supported orchestrators to manage the application's lifecycle. Defaults to `0`.

`[--version VERSION]`

An optional version number of the application. When specified, it overrides the value specified in the *configuration file*.

`[--base-image BASE_IMAGE]`

Optionally specifies the base container image for building packaged application. It must be a valid Docker image tag either accessible online or via `docker images. By default, the **Packager** picks a base image to use from NGC.

`[--build-image BUILD_IMAGE]`

Optionally specifies the build container image for building C++ applications. It must be a valid Docker image tag either accessible online or via `docker images. By default, the **Packager** picks a build image to use from NGC.

`[--includes [{debug,holoviz,torch,onnx}]]`

To reduce the size of the packaged application container, the CLI Packager, by default, includes minimum runtime dependencies to run applications designed for Holoscan. You can specify additional runtime dependencies to be included in the packaged application using this option. The following options are available:

- `debug`: includes debugging tools, such as `gdb`
- `holoviz`: includes dependencies for Holoviz rendering on x11 and Wayland
- `torch`: includes `libtorch` and `torchvision` runtime dependencies
- `onnx`: includes `onnxruntime` runtime, `libnvinfer-plugin8`, `libnconnxparser8` dependencies.

Note: Refer to Developer Resources for dependency versions.

Usage:

```
holoscan package --includes holoviz torch onnx
```

`[--build-cache BUILD_CACHE]`

Specifies a directory path for storing Docker cache. Defaults to `~/.holoscan_build_cache`. If the `$HOME` directory is inaccessible, the CLI uses the `/tmp` directory.

[--cmake-args CMAKE_ARGS]

A comma-separated list of *cmake* arguments to be used when building C++ applications.

For example:

```
holoscan package --cmake-args "-DCMAKE_BUILD_TYPE=DEBUG -DCMAKE_ARG=VALUE"
```

[--no-cache|-n]

Do not use cache when building image.

[--sdk SDK]

SDK for building the application: Holoscan or MONAI-Deploy. `SDK` must be one of: holoscan, monai-deploy.

[--source URL|FILE]

Override the artifact manifest source with a securely hosted file or from the local file system.

E.g. https://my.domain.com/my-file.json

[--sdk-version SDK_VERSION]

Set the version of the SDK that is used to build and package the Application. If not specified, the packager attempts to detect the installed version.

[--holoscan-sdk-file HOLOSCAN_SDK_FILE]

Path to the Holoscan SDK Debian or PyPI package. If not specified, the packager downloads the SDK file from the internet depending on the SDK version detected/specified. The `HOLOSCAN_SDK_FILE` filename must have `.deb` or `.whl` file extension for Debian package or PyPI wheel package, respectively.

[--monai-deploy-sdk-file MONAI_DEPLOY_SDK_FILE]

Path to the MONAI Deploy App SDK Debian or PyPI package. If not specified, the packager downloads the SDK file from the internet based on the SDK version. The `MONAI_DEPLOY_SDK_FILE` package filename must have `.whl` or `.gz` file extension.

[--output|-o OUTPUT]

Output directory where result images will be written.

Note: If this flag isn't present, the packager will load the generated image onto Docker to make the image accessible with `docker images`. The `--output` flag is therefore required when building a packaging for a different target architecture than the host system that runs the packaer.

--tag|-t TAG

Name and optionally a tag (format: `name:tag`).

For example:

```
my-company/my-application:latest
my-company/my-application:1.0.0
my-application:1.0.1
my-application
```

[--username USERNAME]

Optional *username* to be created in the container execution context. Defaults to `holoscan`.

[--uid UID]

Optional *user ID* to be associated with the user created with `--username` with default of `1000`.

Warning: A very large UID value may result in a very large image due to an open issue with Docker. It is recommended to use the default value of `1000` when packaging an application and use your current UID/GID when running the application.

[--gid GID]

Optional *group ID* to be associated with the user created with `--username` with default of `1000`

28.2.2 Holoscan CLI - Run Command

`holoscan run` - simplifies running a packaged Holoscan application by reducing the number of arguments required compared to `docker run`. In addition, it follows the guidelines of *HAP specification* when launching your packaged Holoscan application.

Warning: When running a packaged Holoscan application on Kubernetes or other service providers, running Docker with non root user, and running Holoscan CLI `run` command where the logged-on user's ID is different, ensure to specify the `USER ID` that is used when building the application package.

For example, include the `securityContext` when running a Holoscan packaged application with `UID=1000` using Argo:

```yaml
spec:
  securityContext:
    runAsUser: 1000
    runAsNonRoot: true
```

Synopsis

`holoscan run` *[--help|-h] [--log-level|-l {DEBUG,INFO,WARN,ERROR,CRITICAL}] [--address ADDRESS] [--driver] [--input|-i INPUT] [--output|-o OUTPUT] [--fragments|-f FRAGMENTS] [--worker] [--worker-address WORKER_ADDRESS] [--config CONFIG] [--health-check HEALTH_CHECK] [--network|-n NETWORK] [--nic NETWORK_INTERFACE] [--use-all-nics] [--render|-r] [--quiet|-q] [--shm-size][--terminal] [--device] [--gpu] [--uid UID] [--gid GID]image:[tag]*

Examples

To run a packaged Holoscan application:

```
holoscan run -i /path/to/my/input -o /path/to/application/generated/output my-
↪application:1.0.1
```

Positional Arguments

`image:[tag]`

Name and tag of the Docker container image to execute.

Flags

`[--address ADDRESS]`

Address (`[<IP or hostname>][:<port>]`) of the *App Driver*. If not specified, the *App Driver* uses the default host address (`0.0.0.0`) with the default port number (`8765`).

For example:

```
--address my_app_network
--address my_app_network:8765
```

Note: Ensure that the IP address is not blocked and the port is configured with the firewall accordingly.

`[--driver]`

Run the **App Driver** on the current machine. Can be used together with the *[--worker]* option to run both the **App Driver** and the **App Worker** on the same machine.

`[--input|-i INPUT]`

Specifies a directory path with input data for the application to process. When specified, a directory mount is set up to the value defined in the environment variable `HOLOSCAN_INPUT_PATH`.

Note: Ensure that the directory on the host is accessible by the current user or the user specified with *–uid*.

Note: Use the host system path when running applications inside Docker (DooD).

`[--output|-o OUTPUT]`

Specifies a directory path to store application-generated artifacts. When specified, a directory mount is set up to the value defined in the environment variable `HOLOSCAN_OUTPUT_PATH`.

Note: Ensure that the directory on the host is accessible by the current user or the user specified with *–uid*.

`[--fragments|-f FRAGMENTS]`

Comma-separated names of the fragments to be executed by the **App Worker**. If not specified, only one fragment (selected by the **App Driver**) will be executed. `all` can be used to run all the fragments.

`[--worker]`

Run the **App Worker**.

`[--worker-address WORKER_ADDRESS]`

The address (`[<IP or hostname>][:<port>]`) of the **App Worker**. If not specified, the **App Worker** uses the default host address (`0.0.0.0`) with a randomly chosen port number between `10000` and `32767` that is not currently in use. This argument automatically sets the `HOLOSCAN_UCX_SOURCE_ADDRESS` environment variable if the worker address is a local IP address. Refer to *Environment Variables for Distributed Applications* for details.

For example:

```
--worker-address my_app_network
--worker-address my_app_network:10000
```

Note: Ensure that the IP address is not blocked and the port is configured with the firewall accordingly.

`[--config CONFIG]`

Path to the application configuration file. If specified, it overrides the embedded configuration file found in the environment variable `HOLOSCAN_CONFIG_PATH`.

`[--health-check HEALTH_CHECK]`

Enables the health check service for *distributed applications* by setting the `HOLOSCAN_ENABLE_HEALTH_CHECK` environment variable to `true`. This allows grpc-health-probe to monitor the application's liveness and readiness.

`[--network|-n NETWORK]`

The Docker network that the application connects to for communicating with other containers. The **Runner** use the `host` network by default if not specified. Otherwise, the specified value is used to create a network with the `bridge` driver.

For advanced uses, first create a network using `docker network create` and pass the name of the network to the `--network` option. Refer to Docker Networking documentation for additional details.

`[--nic NETWORK_INTERFACE]`

Name of the network interface to use with a distributed multi-fragment application. This option sets `UCX_NET_DEVICES` environment variable with the value specified and is required when running a distributed multi-fragment application across multiple nodes. See *UCX Network Interface Selection* for details.

`[--use-all-nics]`

When set, this option allows UCX to control the selection of network interface cards for data transfer. Otherwise, the network interface card specified with '–nic' is used. This option sets the environment variable `UCX_CM_USE_ALL_DEVICES` to `y` (default: False).

When this option is not set, the CLI runner always sets `UCX_CM_USE_ALL_DEVICES` to `n`.

`[--render|-r]`

Enable graphic rendering from your application. Defaults to `False`.

`[--quiet|-q]`

Suppress the STDOUT and print only STDERR from the application. Defaults to `False`.

[--shm-size]

Sets the size of /dev/shm. The format is <number(int,float)>[MB|m|GB|g|Mi|MiB|Gi|GiB]. Use config to read the shared memory value defined in the app.json manifest. By default, the container is launched using --ipc=host with host system's /dev/shm mounted.

[--terminal]

Enters terminal with all configured volume mappings and environment variables.

[--device]

Map host devices into the application container.

By default, the CLI searches the /dev/ path for devices unless the specified string starts with /.

For example:

```
# mount all AJA capture cards
--device ajantv*
# mount AJA capture card 0 and 1
--device ajantv0 ajantv1
# mount V4L2 video device 1 and AJAX capture card 2
--device video1 --device /dev/ajantv2
```

Warning: When using the --device option, append -- after the last item to avoid misinterpretation by the CLI. For example:

```
holoscan run --render --device ajantv0 video1 -- my-application-image:1.0
```

[--gpu]

Override the value of the NVIDIA_VISIBLE_DEVICES environment variable with the default value set to the value defined in the *package manifest file* or all if undefined.

Refer to the GPU Enumeration page for all available options.

Note: The default value is nvidia.com/igpu=0 when running a HAP built for iGPU on a system with both iGPU and dGPU,

Note: A single integer value translates to the device index, not the number of GPUs.

`[--uid UID]`

Run the application with the specified user ID (UID). Defaults to the current user's UID.

`[--gid GID]`

Run the application with the specified group ID (GID). Defaults to the current user's GID.

Note: The Holoscan Application supports various environment variables for configuration. Refer to *Environment Variables for Distributed Applications* for details.

28.2.3 Holoscan CLI - Version Command

`holoscan version` - print version information for the Holoscan SDK

Synopsis

`holoscan version` *[--help|-h] [--log-level|-l {DEBUG,INFO,WARN,ERROR,CRITICAL}]*

`package`

Package a Holoscan application

`run`

Run a packaged Holoscan application

`version`

Print version information for the Holoscan SDK

`nics`

Print all available network interface cards and its assigned IP address

28.3 CLI-Wide Flags

28.3.1 `[--help|-h]`

Display detailed help.

28.3.2 `[--log-level|-l {DEBUG,INFO,WARN,ERROR,CRITICAL}]`

Override the default logging verbosity. Defaults to `INFO`.

CHAPTER

TWENTYNINE

APPLICATION RUNNER CONFIGURATION

The Holoscan runner requires a YAML configuration file to define some properties necessary to deploy an application.

Note: That file is the same configuration file commonly used to configure other aspects of an application, documented *here*.

29.1 Configuration

The configuration file can be defined in two ways:

- At package time, with the `--config` flag of the `holoscan package` command (Required/Default).
- At runtime, with the `--config` flag of the `holoscan run` command (Optional/Override).

29.2 Properties

The `holoscan run` command parses two specific YAML nodes from the configuration file:

- A required `application` parameter group to generate a *HAP-compliant*` container image for the application, including:
  - The `title` (name) and `version` of the application.
  - Optionally, `inputFormats` and `outputFormats` if the application expects any inputs or outputs respectively.
- An optional `resources` parameter group that defines the system resources required to run the application, such as the number of CPUs, GPUs and amount of memory required. If the application contains multiple fragments for distributed workloads, resource definitions can be assigned to each fragment.

29.3 Example

Below is an example configuration file with the `application` and optional `resources` parameter groups, for an application with two-fragments (`first-fragment` and `second-fragment`):

```yaml
application:
  title: My Application Title
  version: 1.0.1
  inputFormats: ["files"] # optional
  outputFormats: ["screen"] # optional

resources: # optional
  # non-distributed app
  cpu: 1 # optional
  cpuLimit: 5 # optional
  gpu: 1 # optional
  gpuLimit: 5 # optional
  memory: 1Mi # optional
  memoryLimit: 2Gi # optional
  gpuMemory: 1Gi # optional
  gpuMemoryLimit: 1.5Gi # optional
  sharedMemory: 1Gi # optional

  # distributed app
  fragments: # optional
    first-fragment: # optional
      cpu: 1 # optional
      cpuLimit: 5 # optional
      gpu: 1 # optional
      gpuLimit: 5 # optional
      memory: 100Mi # optional
      memoryLimit: 1Gi # optional
      gpuMemory: 1Gi # optional
      gpuMemoryLimit: 10Gi # optional
      sharedMemory: 1Gi # optional
    second-fragment: # optional
      cpu: 1 # optional
      cpuLimit: 2 # optional
      gpu: 1 # optional
      gpuLimit: 2 # optional
      memory: 1Gi # optional
      memoryLimit: 2Gi # optional
      gpuMemory: 1Gi # optional
      gpuMemoryLimit: 5Gi # optional
      sharedMemory: 10Mi # optional
```

For details, please refer to the *HAP specification*.

CHAPTER

THIRTY

GXF CORE CONCEPTS

Here is a list of the key GXF terms used in this section:

- **Applications** are built as compute graphs.
- **Entities** are nodes of the graph. They are nothing more than a unique identifier.
- **Components** are parts of an entity and provide their functionality.
- **Codelets** are special components which allow the execution of custom code. They can be derived by overriding the C++ functions `initialize`, `start`, `tick`, `stop`, `deinitialize`, and `registerInterface` (for defining configuration parameters).
- **Connections** are edges of the graph, which connect components.
- **Scheduler and Scheduling Terms**: components that determine how and when the `tick()` of a Codelet executes. This can be single or multithreaded, support conditional execution, asynchronous scheduling, and other custom behavior.
- **Memory Allocator**: provides a system for allocating a large contiguous memory pool up-front and then reusing regions as needed. Memory can be pinned to the device (enabling zero-copy between Codelets when messages are not modified) or host, or customized for other potential behavior.
- **Receivers, Transmitters, and Message Router**: a message passing system between Codelets that supports zero-copy.
- **Tensor**: the common message type is a tensor. It provides a simple abstraction for numeric data that can be allocated, serialized, sent between Codelets, etc. Tensors can be rank 1 to 7 supporting a variety of common data types like arrays, vectors, matrices, multi-channel images, video, regularly sampled time-series data, and higher dimensional constructs popular with deep learning flows.
- **Parameters**: configuration variables used by the Codelet. In GXF applications, they are loaded from the application YAML file and are modifiable without recompiling.

In comparison, the core concepts of the Holoscan SDK can be found here.

CHAPTER

THIRTYONE

HOLOSCAN AND GXF

31.1 Design differences

There are 2 main elements at the core of Holoscan and GXF designs:

1. How to define and execute application graphs.
2. How to define nodes' functionality.

How Holoscan SDK interfaces with GXF on those topics varies as Holoscan SDK evolves, as described below:

31.1.1 Holoscan SDK v0.2

Holoscan SDK was tightly coupled with GXF's existing interface:

1. GXF application graphs are defined in **YAML** configuration files. **GXE** (Graph Execution Engine) is used to execute AI application graphs. Its inputs are the YAML configuration file, and a list of GXF Extensions to load as plugins (manifest YAML file). This design allows entities to be swapped or updated without needing to recompile an application.
2. Components are made available by registering them within a **GXF extension**, each of which maps to a shared library and header(s).

Those concepts are illustrated in the *GXF by example* section.

The only additions that Holoscan provided on top of GXF were:

- Domain-specific reference applications
- New extensions
- CMake configurations for building extensions and applications

31.1.2 Holoscan SDK v0.3

The Holoscan SDK shifted to provide a more developer-friendly interface with C++:

1. GXF application graphs, memory allocation, scheduling, and message routing can be defined using a C++ API, with the ability to read parameters and required GXF extension names from a YAML configuration file. The backend used is still GXF as Holoscan uses the GXF C API, but this bypasses GXE and the full YAML definition.
2. The C++ **Operator** class was added to wrap and expose GXF extensions to that new application interface (See *dev guide*).

31.1.3 Holoscan SDK v0.4

The Holoscan SDK added Python wrapping and native operators to further increase ease of use:

1. The C++ API is also wrapped in Python. GXF is still used as the backend.
2. The Operator class supports **native operators**, i.e., operators that do not require that you implement and register a GXF Extension. An important feature is the ability to support messaging between native and GXF operators without any performance loss (i.e., zero-copy communication of tensors).

31.1.4 Holoscan SDK v0.5

1. The built-in Holoscan GXF extensions are loaded automatically and don't need to be listed in the YAML configuration file of Holoscan applications. This allows Holoscan applications to be defined without requiring a YAML configuration file.
2. No significant changes to build operators. However, most built-in operators were switched to native implementations, with the ability to convert native operators to GXF codelets for GXF application developers.

31.1.5 Holoscan SDK v1.0

1. The remaining GXF-based DemosaicOp operator was switched to a native implementation. Now all operators provided by the SDK are native operators.

31.1.6 Holoscan SDK v2.9

The Holoscan SDK introduces a method to wrap Holoscan SDK native operators, resources, and types as GXF codelets, components, and types, enabling their use in GXF applications. For more details, GXF application developers can refer to *Using Holoscan Operators/Resources/Types in GXF Applications*.

31.2 Current Limitations

The GXF capabilities below are not available in the Holoscan SDK either. There is no plan to support them at this time:

- *Graph Composer*
- *Behavior Trees*
- *Epoch Scheduler*
- *Target Time Scheduling Term*

CHAPTER

THIRTYTWO

GXF BY EXAMPLE

Warning: This section is legacy (0.2), as we recommend developing extensions and applications using the C++ or Python APIs. Refer to the developer guide for up-to-date recommendations.

32.1 Inner Workings of a GXF Entity

Let us look at an example of a GXF entity to try to understand its general anatomy. As an example let's start with the entity definition for an image format converter entity named `format_converter_entity` as shown below.

Listing 32.1: An example GXF Application YAML snippet

```yaml
%YAML 1.2
---
# other entities declared
---
name: format_converter_entity
components:
  - name: in_tensor
    type: nvidia::gxf::DoubleBufferReceiver
  - type: nvidia::gxf::MessageAvailableSchedulingTerm
    parameters:
      receiver: in_tensor
      min_size: 1
  - name: out_tensor
    type: nvidia::gxf::DoubleBufferTransmitter
  - type: nvidia::gxf::DownstreamReceptiveSchedulingTerm
    parameters:
      transmitter: out_tensor
      min_size: 1
  - name: pool
    type: nvidia::gxf::BlockMemoryPool
    parameters:
      storage_type: 1
      block_size: 4919040 # 854 * 480 * 3 (channel) * 4 (bytes per pixel)
      num_blocks: 2
  - name: format_converter_component
    type: nvidia::holoscan::formatconverter::FormatConverter
    parameters:
      in: in_tensor
```

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```yaml
      out: out_tensor
      out_tensor_name: source_video
      out_dtype: "float32"
      scale_min: 0.0
      scale_max: 255.0
      pool: pool
---
# other entities declared
---
components:
  - name: input_connection
    type: nvidia::gxf::Connection
    parameters:
      source: upstream_entity/output
      target: format_converter/in_tensor
---
components:
  - name: output_connection
    type: nvidia::gxf::Connection
    parameters:
      source: format_converter/out_tensor
      target: downstream_entity/input
---
name: scheduler
components:
  - type: nvidia::gxf::GreedyScheduler
```

Above:

1. The entity `format_converter_entity` receives a message in its `in_tensor` message from an upstream entity `upstream_entity` as declared in the `input_connection`.
2. The received message is passed to the `format_converter_component` component to convert the tensor element precision from `uint8` to `float32` and scale any input in the `[0, 255]` intensity range.
3. The `format_converter_component` component finally places the result in the `out_tensor` message so that its result is made available to a downstream entity (`downstream_ent` as declared in `output_connection`).
4. The `Connection` components tie the inputs and outputs of various components together, in the above case `upstream_entity/output -> format_converter_entity/in_tensor` and `format_converter_entity/out_tensor -> downstream_entity/input`.
5. The `scheduler` entity declares a `GreedyScheduler` "system component" which orchestrates the execution of the entities declared in the graph. In the specific case of `GreedyScheduler` entities are scheduled to run exclusively, where no more than one entity can run at any given time.

The YAML snippet above can be visually represented as follows.

In the image, as in the YAML, you will notice the use of `MessageAvailableSchedulingTerm`, `DownstreamReceptiveSchedulingTerm`, and `BlockMemoryPool`. These are components that play a "supporting" role to `in_tensor`, `out_tensor`, and `format_converter_component` components respectively. Specifically:

- `MessageAvailableSchedulingTerm` is a component that takes a `Receiver` (in this case `DoubleBufferReceiver` named `in_tensor`) and alerts the graph `Executor` that a message is available. This alert triggers `format_converter_component`.
- `DownstreamReceptiveSchedulingTerm` is a component that takes a `Transmitter` (in this case

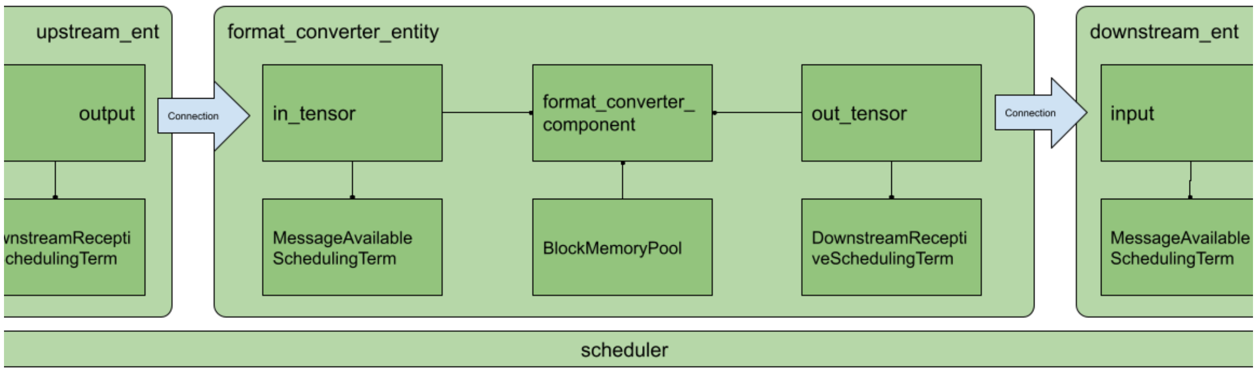

Fig. 32.1: Arrangement of components and entities in a Holoscan application

DoubleBufferTransmitter named out_tensor) and alerts the graph Executor that a message has been placed on the output.

- BlockMemoryPool provides two blocks of almost 5MB allocated on the GPU device and is used by format_converted_ent to allocate the output tensor where the converted data will be placed within the format converted component.

Together these components allow the entity to perform a specific function and coordinate communication with other entities in the graph, via the declared scheduler.

More generally, an entity can be thought of as a collection of components where components can be passed to one another to perform specific subtasks (e.g., event triggering or message notification, format conversion, memory allocation), and an application as a graph of entities.

The scheduler is a component of type nvidia::gxf::System which orchestrates the execution components in each entity at application runtime based on triggering rules.

32.2 Data Flow and Triggering Rules

Entities communicate with one another via messages which may contain one or more payloads. Messages are passed and received via a component of type nvidia::gxf::Queue from which both nvidia::gxf::Receiver and nvidia::gxf::Transmitter are derived. Every entity that receives and transmits messages has at least one receiver and one transmitter queue.

Holoscan uses the nvidia::gxf::SchedulingTerm component to coordinate data access and component orchestration for a Scheduler which invokes execution through the tick() function in each Codelet.

Tip: A SchedulingTerm defines a specific condition that is used by an entity to let the scheduler know when it's ready for execution.

In the above example, we used a MessageAvailableSchedulingTerm to trigger the execution of the components waiting for data from in_tensor receiver queue, namely format_converter_component.

Listing 32.2: MessageAvailableSchedulingTerm

```
- type: nvidia::gxf::MessageAvailableSchedulingTerm
  parameters:
```

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```
    receiver: in_tensor
    min_size: 1
```

Similarly, `DownStreamReceptiveSchedulingTerm` checks whether the `out_tensor` transmitter queue has at least one outgoing message in it. If there are one or more outgoing messages, `DownStreamReceptiveSchedulingTerm` will notify the scheduler, which in turn attempts to place the message in the receiver queue of a downstream entity. If, however, the downstream entity has a full receiver queue, the message is held in the `out_tensor` queue as a means to handle back-pressure.

Listing 32.3: DownstreamReceptiveSchedulingTerm

```
- type: nvidia::gxf::DownstreamReceptiveSchedulingTerm
  parameters:
    transmitter: out_tensor
    min_size: 1
```

If we were to draw the entity in *Fig. 32.1* in greater detail it would look something like the following.

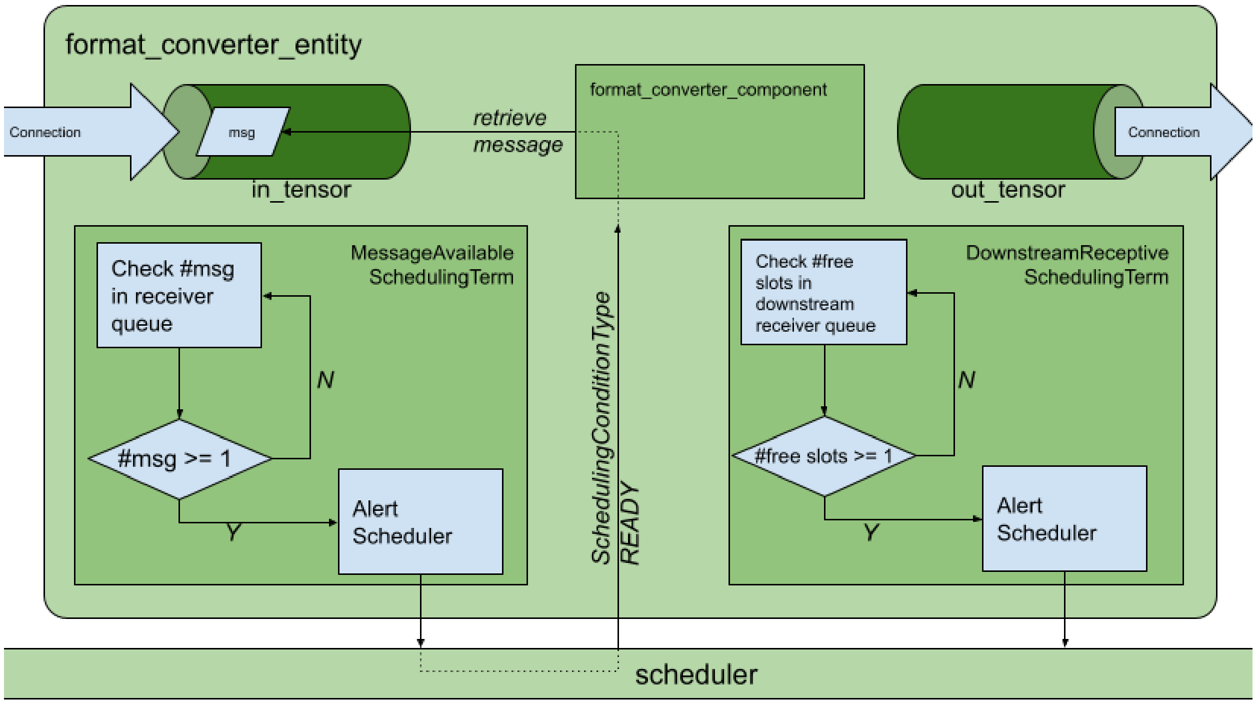
format_converter_entity
Connection
msg
in_tensor
retrieve message
format_converter_component
out_tensor
Connection
MessageAvailable SchedulingTerm
Check #msg in receiver queue
N
#msg >= 1
Y
Alert Scheduler
SchedulingConditionType READY
DownstreamReceptive SchedulingTerm
Check #free slots in downstream receiver queue
N
#free slots >= 1
Y
Alert Scheduler
scheduler

Fig. 32.2: Receive and transmit `Queues` and `SchedulingTerms` in entities.

Up to this point, we have covered the "entity component system" at a high level and showed the functional parts of an entity; namely, the messaging queues and the scheduling terms that support the execution of components in the entity. To complete the picture, the next section covers the anatomy and lifecycle of a component, and how to handle events within it.

32.3 Creating a GXF Extension

GXF components in Holoscan can perform a multitude of sub-tasks ranging from data transformations, to memory management, to entity scheduling. In this section, we will explore an `nvidia::gxf::Codelet` component which in Holoscan is known as a "GXF extension." *Holoscan (GXF) extensions* are typically concerned with application-specific sub-tasks such as data transformations, AI model inference, and the like.

32.3.1 Extension Lifecycle

The lifecycle of a `Codelet` is composed of the following five stages.

1. `initialize` - called only once when the codelet is created for the first time, and use of lightweight initialization.
2. `deinitialize` - called only once before the codelet is destroyed, and used for lightweight deinitialization.
3. `start` - called multiple times over the lifecycle of the codelet according to the order defined in the lifecycle, and used for heavy initialization tasks such as allocating memory resources.
4. `stop` - called multiple times over the lifecycle of the codelet according to the order defined in the lifecycle, and used for heavy deinitialization tasks such as deallocation of all resources previously assigned in `start`.
5. `tick` - called when the codelet is triggered, and is called multiple times over the codelet lifecycle; even multiple times between `start` and `stop`.

The flow between these stages is detailed in *Fig. 32.3*.

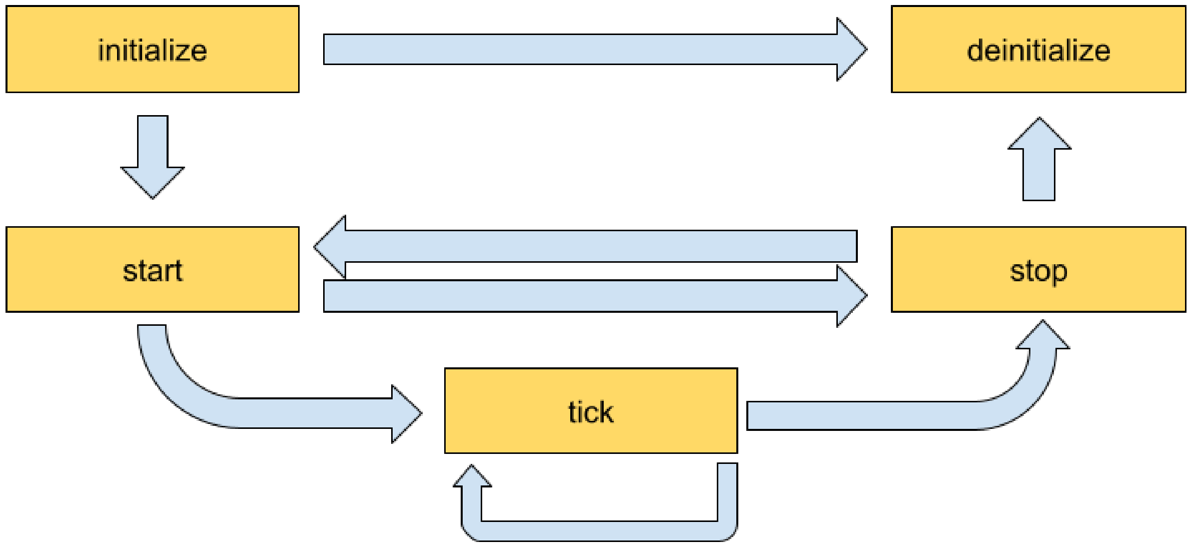

Fig. 32.3: Sequence of method calls in the lifecycle of a Holoscan extension

32.3.2 Implementing an Extension

In this section, we will implement a simple recorder that will highlight the actions we would perform in the lifecycle methods. The recorder receives data in the input queue and records the data to a configured location on the disk. The output format of the recorder files is the GXF-formatted index/binary replayer files (the format is also used for the data in the sample applications), where the `gxf_index` file contains timing and sequence metadata that refer to the binary/tensor data held in the `gxf_entities` file.

Declare the Class That Will Implement the Extension Functionality

The developer can create their Holoscan extension by extending the `Codelet` class, implementing the extension functionality by overriding the lifecycle methods, and defining the parameters the extension exposes at the application level via the `registerInterface` method. To define our recorder component, we would need to implement some of the methods in the `Codelet`.

First, clone the Holoscan project from here and create a folder to develop our extension such as under `gxf_extensions/my_recorder`.

Tip: Using Bash we create a Holoscan extension folder as follows.

```
git clone https://github.com/nvidia-holoscan/holoscan-sdk.git
cd clara-holoscan-embedded-sdk
mkdir -p gxf_extensions/my_recorder
```

In our extension folder, we create a header file `my_recorder.hpp` with a declaration of our Holoscan component.

Listing 32.4: gxf_extensions/my_recorder/my_recorder.hpp

```
#include <string>

#include "gxf/core/handle.hpp"
#include "gxf/std/codelet.hpp"
#include "gxf/std/receiver.hpp"
#include "gxf/std/transmitter.hpp"
#include "gxf/serialization/file_stream.hpp"
#include "gxf/serialization/entity_serializer.hpp"


class MyRecorder : public nvidia::gxf::Codelet {
 public:
  gxf_result_t registerInterface(nvidia::gxf::Registrar* registrar) override;
  gxf_result_t initialize() override;
  gxf_result_t deinitialize() override;

  gxf_result_t start() override;
  gxf_result_t tick() override;
  gxf_result_t stop() override;

 private:
  nvidia::gxf::Parameter<nvidia::gxf::Handle<nvidia::gxf::Receiver>> receiver_;
  nvidia::gxf::Parameter<nvidia::gxf::Handle<nvidia::gxf::EntitySerializer>> my_
↪serializer_;
```

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```cpp
  nvidia::gxf::Parameter<std::string> directory_;
  nvidia::gxf::Parameter<std::string> basename_;
  nvidia::gxf::Parameter<bool> flush_on_tick_;

  // File stream for data index
  nvidia::gxf::FileStream index_file_stream_;
  // File stream for binary data
  nvidia::gxf::FileStream binary_file_stream_;
  // Offset into binary file
  size_t binary_file_offset_;
};
```

Declare the Parameters to Expose at the Application Level

Next, we can start implementing our lifecycle methods in the `my_recorder.cpp` file, which we also create in `gxf_extensions/my_recorder` path.

Our recorder will need to expose the `nvidia::gxf::Parameter` variables to the application so the parameters can be modified by configuration.

Listing 32.5: registerInterface in gxf_extensions/my_recorder/my_recorder.cpp

```cpp
#include "my_recorder.hpp"

gxf_result_t MyRecorder::registerInterface(nvidia::gxf::Registrar* registrar) {
  nvidia::gxf::Expected<void> result;
  result &= registrar->parameter(
      receiver_, "receiver", "Entity receiver",
      "Receiver channel to log");
  result &= registrar->parameter(
      my_serializer_, "serializer", "Entity serializer",
      "Serializer for serializing input data");
  result &= registrar->parameter(
      directory_, "out_directory", "Output directory path",
      "Directory path to store received output");
  result &= registrar->parameter(
      basename_, "basename", "File base name",
      "User specified file name without extension",
      nvidia::gxf::Registrar::NoDefaultParameter(), GXF_PARAMETER_FLAGS_OPTIONAL);
  result &= registrar->parameter(
      flush_on_tick_, "flush_on_tick", "Boolean to flush on tick",
      "Flushes output buffer on every `tick` when true", false);  // default value `false`
  return nvidia::gxf::ToResultCode(result);
}
```

For pure GXF applications, our component's parameters can be specified in the following format in the YAML file:

Listing 32.6: Example parameters for MyRecorder component

```yaml
name: my_recorder_entity
components:
  - name: my_recorder_component
```

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```yaml
    type: MyRecorder
    parameters:
      receiver: receiver
      serializer: my_serializer
      out_directory: /home/user/out_path
      basename: my_output_file  # optional
      # flush_on_tick: false    # optional
```

Note that all the parameters exposed at the application level are mandatory except for `flush_on_tick`, which defaults to `false`, and `basename`, whose default is handled at `initialize()` below.

Implement the Lifecycle Methods

This extension does not need to perform any heavy-weight initialization tasks, so we will concentrate on `initialize()`, `tick()`, and `deinitialize()` methods, which define the core functionality of our component. At initialization, we will create a file stream and keep track of the bytes we write on `tick()` via `binary_file_offset`.

Listing 32.7: initialize in gxf_extensions/my_recorder/my_recorder.cpp

```cpp
gxf_result_t MyRecorder::initialize() {
  // Create path by appending receiver name to directory path if basename is not provided
  std::string path = directory_.get() + '/';
  if (const auto& basename = basename_.try_get()) {
    path += basename.value();
  } else {
    path += receiver_->name();
  }

  // Initialize index file stream as write-only
  index_file_stream_ = nvidia::gxf::FileStream("", path +␣
↪nvidia::gxf::FileStream::kIndexFileExtension);

  // Initialize binary file stream as write-only
  binary_file_stream_ = nvidia::gxf::FileStream("", path +␣
↪nvidia::gxf::FileStream::kBinaryFileExtension);

  // Open index file stream
  nvidia::gxf::Expected<void> result = index_file_stream_.open();
  if (!result) {
    return nvidia::gxf::ToResultCode(result);
  }

  // Open binary file stream
  result = binary_file_stream_.open();
  if (!result) {
    return nvidia::gxf::ToResultCode(result);
  }
  binary_file_offset_ = 0;

  return GXF_SUCCESS;
}
```

When de-initializing, our component will take care of closing the file streams that were created at initialization.

Listing 32.8: deinitialize in gxf_extensions/my_recorder/my_recorder.cpp

```cpp
gxf_result_t MyRecorder::deinitialize() {
  // Close binary file stream
  nvidia::gxf::Expected<void> result = binary_file_stream_.close();
  if (!result) {
    return nvidia::gxf::ToResultCode(result);
  }

  // Close index file stream
  result = index_file_stream_.close();
  if (!result) {
    return nvidia::gxf::ToResultCode(result);
  }

  return GXF_SUCCESS;
}
```

In our recorder, no heavyweight initialization tasks are required, so we implement the following; however, we would use `start()` and `stop()` methods for heavyweight tasks such as memory allocation and deallocation.

Listing 32.9: start/stop in gxf_extensions/my_recorder/my_recorder.cpp

```cpp
gxf_result_t MyRecorder::start() {
  return GXF_SUCCESS;
}

gxf_result_t MyRecorder::stop() {
  return GXF_SUCCESS;
}
```

Tip: For a detailed implementation of `start()` and `stop()`, and how memory management can be handled therein, please refer to the implementation of the UCX extension.

Finally, we write the component-specific functionality of our extension by implementing `tick()`.

Listing 32.10: tick in gxf_extensions/my_recorder/my_recorder.cpp

```cpp
gxf_result_t MyRecorder::tick() {
  // Receive entity
  nvidia::gxf::Expected<nvidia::gxf::Entity> entity = receiver_->receive();
  if (!entity) {
    return nvidia::gxf::ToResultCode(entity);
  }

  // Write entity to binary file
  nvidia::gxf::Expected<size_t> size = my_serializer_->serializeEntity(entity.value(), &
↪binary_file_stream_);
  if (!size) {
    return nvidia::gxf::ToResultCode(size);
  }
```

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```

  // Create entity index
  nvidia::gxf::EntityIndex index;
  index.log_time = std::chrono::system_clock::now().time_since_epoch().count();
  index.data_size = size.value();
  index.data_offset = binary_file_offset_;

  // Write entity index to index file
  nvidia::gxf::Expected<size_t> result = index_file_stream_.writeTrivialType(&index);
  if (!result) {
    return nvidia::gxf::ToResultCode(result);
  }
  binary_file_offset_ += size.value();

  if (flush_on_tick_) {
    // Flush binary file output stream
    nvidia::gxf::Expected<void> result = binary_file_stream_.flush();
    if (!result) {
      return nvidia::gxf::ToResultCode(result);
    }

    // Flush index file output stream
    result = index_file_stream_.flush();
    if (!result) {
      return nvidia::gxf::ToResultCode(result);
    }
  }

  return GXF_SUCCESS;
}
```

Register the Extension as a Holoscan Component

As a final step, we must register our extension so it is recognized as a component and loaded by the application executor. For this we create a simple declaration in `my_recorder_ext.cpp` as follows.

Listing 32.11: gxf_extensions/my_recorder/my_recorder_ext.cpp

```
#include "gxf/std/extension_factory_helper.hpp"

#include "my_recorder.hpp"

GXF_EXT_FACTORY_BEGIN()
GXF_EXT_FACTORY_SET_INFO(0xb891cef3ce754825, 0x9dd3dcac9bbd8483, "MyRecorderExtension",
                         "My example recorder extension", "NVIDIA", "0.1.0", "LICENSE");
GXF_EXT_FACTORY_ADD(0x2464fabf91b34ccf, 0xb554977fa22096bd, MyRecorder,
                    nvidia::gxf::Codelet, "My example recorder codelet.");
GXF_EXT_FACTORY_END()
```

`GXF_EXT_FACTORY_SET_INFO` configures the extension with the following information in order:

- UUID which can be generated using `scripts/generate_extension_uuids.py` which defines the **extension**

id

- extension name
- extension description
- author
- extension version
- license text

`GXF_EXT_FACTORY_ADD` registers the newly built extension as a valid `Codelet` component with the following information in order:

- UUID which can be generated using `scripts/generate_extension_uuids.py` which defines the **component id** (this must be different from the extension id),
- fully qualified extension class,
- fully qualifies base class,
- component description

To build a shared library for our new extension which can be loaded by a Holoscan application at runtime we use a CMake file under `gxf_extensions/my_recorder/CMakeLists.txt` with the following content.

Listing 32.12: gxf_extensions/my_recorder/CMakeLists.txt

```cmake
# Create library
add_library(my_recorder_lib SHARED
  my_recorder.cpp
  my_recorder.hpp
)
target_link_libraries(my_recorder_lib
  PUBLIC
    GXF::std
    GXF::serialization
    yaml-cpp
)

# Create extension
add_library(my_recorder SHARED
  my_recorder_ext.cpp
)
target_link_libraries(my_recorder
  PUBLIC my_recorder_lib
)

# Install GXF extension as a component 'holoscan-gxf_extensions'
install_gxf_extension(my_recorder) # this will also install my_recorder_lib
# install_gxf_extension(my_recorder_lib) # this statement is not necessary because this␣
↪library follows `<extension library name>_lib` convention.
```

Here, we create a library `my_recorder_lib` with the implementation of the lifecycle methods, and the extension `my_recorder` which exposes the C API necessary for the application runtime to interact with our component.

To make our extension discoverable from the project root we add the line:

```
add_subdirectory(my_recorder)
```

to the CMake file `gxf_extensions/CMakeLists.txt`.

Tip: To build our extension, we can follow the steps in the README.

At this point, we have a complete extension that records data coming into its receiver queue to the specified location on the disk using the GXF-formatted binary/index files.

32.4 Creating a GXF Application

For our application, we create the directory `apps/my_recorder_app_gxf` with the application definition file `my_recorder_gxf.yaml`. The `my_recorder_gxf.yaml` application is as follows:

Listing 32.13: apps/my_recorder_app_gxf/my_recorder_gxf.yaml

```yaml
%YAML 1.2
---
name: replayer
components:
  - name: output
    type: nvidia::gxf::DoubleBufferTransmitter
  - name: allocator
    type: nvidia::gxf::UnboundedAllocator
  - name: component_serializer
    type: nvidia::gxf::StdComponentSerializer
    parameters:
      allocator: allocator
  - name: entity_serializer
    type: nvidia::holoscan::stream_playback::VideoStreamSerializer   # inheriting from␣
↪nvidia::gxf::EntitySerializer
    parameters:
      component_serializers: [component_serializer]
  - type: nvidia::holoscan::stream_playback::VideoStreamReplayer
    parameters:
      transmitter: output
      entity_serializer: entity_serializer
      boolean_scheduling_term: boolean_scheduling
      directory: "/workspace/data/racerx"
      basename: "racerx"
      frame_rate: 0       # as specified in timestamps
      repeat: false       # default: false
      realtime: true      # default: true
      count: 0            # default: 0 (no frame count restriction)
  - name: boolean_scheduling
    type: nvidia::gxf::BooleanSchedulingTerm
  - type: nvidia::gxf::DownstreamReceptiveSchedulingTerm
    parameters:
      transmitter: output
      min_size: 1
```

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```yaml
---
name: recorder
components:
 - name: input
   type: nvidia::gxf::DoubleBufferReceiver
 - name: allocator
   type: nvidia::gxf::UnboundedAllocator
 - name: component_serializer
   type: nvidia::gxf::StdComponentSerializer
   parameters:
     allocator: allocator
 - name: entity_serializer
   type: nvidia::holoscan::stream_playback::VideoStreamSerializer   # inheriting from␣
↪nvidia::gxf::EntitySerializer
   parameters:
     component_serializers: [component_serializer]
 - type: MyRecorder
   parameters:
     receiver: input
     serializer: entity_serializer
     out_directory: "/tmp"
     basename: "tensor_out"
 - type: nvidia::gxf::MessageAvailableSchedulingTerm
   parameters:
     receiver: input
     min_size: 1
---
components:
  - name: input_connection
    type: nvidia::gxf::Connection
    parameters:
      source: replayer/output
      target: recorder/input
---
name: scheduler
components:
  - name: clock
    type: nvidia::gxf::RealtimeClock
  - name: greedy_scheduler
    type: nvidia::gxf::GreedyScheduler
    parameters:
      clock: clock
```

Above:

- The replayer reads data from `/workspace/data/racerx/racerx.gxf_[index|entities]` files, deserializes the binary data to a `nvidia::gxf::Tensor` using `VideoStreamSerializer`, and puts the data on an output message in the `replayer/output` transmitter queue.
- The `input_connection` component connects the `replayer/output` transmitter queue to the `recorder/input` receiver queue.
- The recorder reads the data in the `input` receiver queue, uses `StdEntitySerializer` to convert the received `nvidia::gxf::Tensor` to a binary stream, and outputs to the `/tmp/tensor_out.gxf_[index|entities]`

location specified in the parameters.

- The scheduler component, while not explicitly connected to the application-specific entities, performs the orchestration of the components discussed in the *Data Flow and Triggering Rules*.

Note the use of the component_serializer in our newly built recorder. This component is declared separately in the following entity:

```
- name: entity_serializer
  type: nvidia::holoscan::stream_playback::VideoStreamSerializer   # inheriting from␣
↪nvidia::gxf::EntitySerializer
  parameters:
    component_serializers: [component_serializer]
```

This is then passed into MyRecorder via the serializer parameter, which we exposed in the *extension development section (Declare the Parameters to Expose at the Application Level)*.

```
- type: MyRecorder
  parameters:
    receiver: input
    serializer: entity_serializer
    directory: "/tmp"
    basename: "tensor_out"
```

For our app to be able to load (and also compile where necessary) the extensions required at runtime, we need to declare a CMake file apps/my_recorder_app_gxf/CMakeLists.txt as follows.

Listing 32.14: apps/my_recorder_app_gxf/CMakeLists.txt

```
create_gxe_application(
  NAME my_recorder_gxf
  YAML my_recorder_gxf.yaml
  EXTENSIONS
    GXF::std
    GXF::cuda
    GXF::multimedia
    GXF::serialization
    my_recorder
    stream_playback
)

# Download the associated dataset if needed
if(HOLOSCAN_DOWNLOAD_DATASETS)
  add_dependencies(my_recorder_gxf racerx_data)
endif()
```

In the declaration of create_gxe_application we list:

- my_recorder component declared in the CMake file of the *extension development section* under the EXTENSIONS argument
- the existing stream_playback Holoscan extension which reads data from disk

To make our newly built application discoverable by the build, in the root of the repository, we add the following line to apps/CMakeLists.txt:

```
add_subdirectory(my_recorder_app_gxf)
```

We now have a minimal working application to test the integration of our newly built `MyRecorder` extension.

32.5 Running the GXF Recorder Application

To run our application in a local development container:

1. Follow the instructions under the Using a Development Container section steps 1-5 (try clearing the CMake cache by removing the `build` folder before compiling).

   You can execute the following commands to build:

   ```
   ./run build
   # ./run clear_cache # if you want to clear build/install/cache folders
   ```

2. Our test application can now be run in the development container using the command:

   ```
   ./apps/my_recorder_app_gxf/my_recorder_gxf
   ```

   from inside the development container.

   (You can execute `./run launch` to run the development container.)

   ```
   @LINUX:/workspace/holoscan-sdk/build$ ./apps/my_recorder_app_gxf/my_recorder_gxf
   2022-08-24 04:46:47.333 INFO  gxf/gxe/gxe.cpp@230: Creating context
   2022-08-24 04:46:47.339 INFO  gxf/gxe/gxe.cpp@107: Loading app: 'apps/my_recorder_
   ↪app_gxf/my_recorder_gxf.yaml'
   2022-08-24 04:46:47.339 INFO  gxf/std/yaml_file_loader.cpp@117: Loading GXF␣
   ↪entities from YAML file 'apps/my_recorder_app_gxf/my_recorder_gxf.yaml'...
   2022-08-24 04:46:47.340 INFO  gxf/gxe/gxe.cpp@291: Initializing...
   2022-08-24 04:46:47.437 INFO  gxf/gxe/gxe.cpp@298: Running...
   2022-08-24 04:46:47.437 INFO  gxf/std/greedy_scheduler.cpp@170: Scheduling 2␣
   ↪entities
   2022-08-24 04:47:14.829 INFO  /workspace/holoscan-sdk/gxf_extensions/stream_
   ↪playback/video_stream_replayer.cpp@144: Reach end of file or playback count␣
   ↪reaches to the limit. Stop ticking.
   2022-08-24 04:47:14.829 INFO  gxf/std/greedy_scheduler.cpp@329: Scheduler stopped:␣
   ↪Some entities are waiting for execution, but there are no periodic or async␣
   ↪entities to get out of the deadlock.
   2022-08-24 04:47:14.829 INFO  gxf/std/greedy_scheduler.cpp@353: Scheduler finished.
   2022-08-24 04:47:14.829 INFO  gxf/gxe/gxe.cpp@320: Deinitializing...
   2022-08-24 04:47:14.863 INFO  gxf/gxe/gxe.cpp@327: Destroying context
   2022-08-24 04:47:14.863 INFO  gxf/gxe/gxe.cpp@333: Context destroyed.
   ```

A successful run (it takes about 30 secs) will result in output files (`tensor_out.gxf_index` and `tensor_out.gxf_entities` in `/tmp`) that match the original input files (`racerx.gxf_index` and `racerx.gxf_entities` under `data/racerx`) exactly.

```
@LINUX:/workspace/holoscan-sdk/build$ ls -al /tmp/
total 821384
drwxrwxrwt 1 root root      4096 Aug 24 04:37 .
drwxr-xr-x 1 root root      4096 Aug 24 04:36 ..
```

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```
drwxrwxrwt 2 root root      4096 Aug 11 21:42 .X11-unix
-rw-r--r-- 1 1000 1000    729309 Aug 24 04:47 gxf_log
-rw-r--r-- 1 1000 1000 840054484 Aug 24 04:47 tensor_out.gxf_entities
-rw-r--r-- 1 1000 1000     16392 Aug 24 04:47 tensor_out.gxf_index

@LINUX:/workspace/holoscan-sdk/build$ ls -al ../data/racerx
total 839116
drwxr-xr-x 2 1000 1000      4096 Aug 24 02:08 .
drwxr-xr-x 4 1000 1000      4096 Aug 24 02:07 ..
-rw-r--r-- 1 1000 1000  19164125 Jun 17 16:31 racerx-medium.mp4
-rw-r--r-- 1 1000 1000 840054484 Jun 17 16:31 racerx.gxf_entities
-rw-r--r-- 1 1000 1000     16392 Jun 17 16:31 racerx.gxf_index
```

CHAPTER

THIRTYTHREE

USING HOLOSCAN OPERATORS, RESOURCES, AND TYPES IN GXF APPLICATIONS

For users who are familiar with the GXF development ecosystem, we provide an export feature to leverage native Holoscan code as GXF components to execute in GXF applications and Graph Composer.

For a streamlined approach wrapping a native C++ Holoscan operator as a GXF codelet, review the `wrap_operator_as_gxf_extension` example on GitHub as described below.

For a granular approach wrapping multiple operators and resources, review the `wrap_holoscan_as_gxf_extension` example on GitHub as described below.

33.1 Wrap An Operator as a GXF Extension

33.1.1 1. Creating compatible Holoscan Operators

Note: This section assumes you are already familiar with *how to create a native C++ operator*.

To ensure compatibility with GXF codelets, it is recommended to specify `holoscan::gxf::Entity` as the type for input and output ports in `Operator::setup(OperatorSpec& spec)`. This is demonstrated in the implementations of PingTxNativeOp and PingRxNativeOp. In contrast, the built-in operators PingTxOp and PingRxOp use different specifications. Note that specifying the type is currently for annotation purposes only, as the Holoscan SDK does not validate input and output types. However, this behavior may change in the future.

For more details regarding the use of `holoscan::gxf::Entity`, follow the documentation on *Interoperability between GXF and native C++ operators*.

33.1.2 2. Creating the GXF extension that wraps the operator

To wrap the native operator as a GXF codelet in a GXF extension, we provide the CMake `wrap_operator_as_gxf_extension` function in the SDK. An example of how it wraps `PingTxNativeOp` and `PingRxNativeOp` can be found here.

- It leverages the CMake target names of the operators defined in their respective `CMakeLists.txt` (ping_tx_native_op, ping_rx_native_op)
- The function parameters are documented at the top of the WrapOperatorAsGXFExtension.cmake file (ignore implementation below).

Note: Use the Holoscan SDK script `generate_extension_uuids.py` to generate UUIDs for GXF-wrapped components.

33.1.3 3. Using your wrapped operator in a GXF application

Note: This section assumes you are familiar with *how to create a GXF application*.

As shown in the `gxf_app/CMakeLists.txt` here, you need to list the following extensions in `create_gxe_application()` to use your wrapped codelets:

- `GXF::std`
- `gxf_holoscan_wrapper`
- The name of the CMake target for the created extension, defined by the `EXTENSION_TARGET_NAME` argument passed to `wrap_operator_as_gxf_extension` in the previous section.

The codelet class name (defined by the `CODELET_NAMESPACE::CODELET_NAME` arguments passed to `wrap_operator_as_gxf_extension` in the previous section) can then be used as a component `type` in a GXF application node, as shown in the YAML app definition of the example, connecting the two ping operators.

33.2 Wrap Multiple Components as a GXF Extension

Holoscan SDK provides several granular CMake macros to make resources and operators compatible with a GXF application.

33.2.1 1. Wrapping a `holoscan::Resource` as a `GXF::Component`

Holoscan SDK provides the CMake `generate_gxf_resource_wrapper` function to wrap a resource for GXF. The function takes a Holoscan SDK `Resource` class and applies a wrapper template to produce the following:

- C++ source and header code wrapping the resource for GXF;
- A CMake build target to compile the code to a shared library;
- GXF C++ macro source code to use in an extension.

For instance, the `wrap_holoscan_as_gxf_extension` example demonstrates wrapping a resource as follows:

```
generate_gxf_resource_wrapper(RESOURCE_HDRS RESOURCE_SRCS EXT_CPP_CONTENT
  RESOURCE_CLASS  myres::PingVarCustomNativeRes
  COMPONENT_NAME  PingVarCustomNativeResComponent
  COMPONENT_NAMESPACE myexts
  COMPONENT_TARGET_NAME gxf_wrapped_ping_variant_custom_native_res_lib
  HASH1  0xc4c16b8d6ef94a01
  HASH2  0x8014ce5b3e9602b1
  INCLUDE_HEADERS ping_variant_custom_native_res.hpp
  PUBLIC_DEPENDS ping_variant_custom_native_res
  COMPONENT_TARGET_PROPERTIES
    LIBRARY_OUTPUT_DIRECTORY ${CMAKE_CURRENT_BINARY_DIR}
)
```

The result of this function call in the example build context is as follows:

- Generates C++ source and header code wrapping the `myres::PingVarCustomNativeRes` resource in the GXF-compatible `myexts::PingVarCustomNativeResComponent` class. Output C++ file locations are stored in the `RESOURCE_HDRS` and `RESOURCE_SRCS` CMake variables.
- Defines a build target named `gxf_wrapped_ping_variant_custom_native_res_lib`. Running `cmake --build <build-dir> --target <gxf_wrapped_ping_variant_custom_native_res_lib>` will build the GXF resource wrapper depending on `ping_variant_custom_native_res`.
- Appends a GXF factory macro C++ code snippet to the `EXT_CPP_CONTENT` CMake variable for later use.

Repeat this step to wrap any other resources to include in your extension.

Note: Use the Holoscan SDK script `generate_extension_uuids.py` to generate UUIDs for GXF-wrapped components.

33.2.2 2. Wrapping a `holoscan::Operator` as a `GXF::Component`

Holoscan SDK provides the CMake `generate_gxf_operator_wrapper` function to wrap an operator for GXF. Like the Resource wrapper above, this function creates C++ source and header code wrapping the operator as well as a build target to build the operator wrapper's shared lib. Unlike the *earlier example*, this function does not itself generate a GXF extension.

The `wrap_holoscan_as_gxf_extension` example demonstrates wrapping an operator as follows:

```
generate_gxf_operator_wrapper(TX_CODELET_HDRS TX_CODELET_SRCS EXT_CPP_CONTENT
  OPERATOR_CLASS "myops::PingVarTxNativeOp"
  CODELET_NAME PingVarTxNativeOpCodelet
  CODELET_NAMESPACE myexts
  HASH1 0x35545ef8ae1541c5
  HASH2 0x8aef3c2078fc50b4
  CODELET_TARGET_NAME gxf_wrapped_ping_variant_tx_native_op_lib
  DESCRIPTION "Ping Tx Native Operator codelet"
  INCLUDE_HEADERS ping_variant_tx_native_op.hpp
  PUBLIC_DEPENDS ping_variant_tx_native_op
  CODELET_TARGET_PROPERTIES
    LIBRARY_OUTPUT_DIRECTORY ${CMAKE_CURRENT_BINARY_DIR}
)
```

The result of this function call in the example build context is as follows:

- Generates C++ source and header code wrapping the `myop::PingVarTxNativeOp` operator resource in the GXF-compatible `myexts::PingVarTxNativeOpCodelet` class. Output C++ file locations are stored in the `TX_CODELET_HDRS` and `TX_CODELET_SRCS` CMake variable.
- Defines a build target named `gxf_wrapped_ping_variant_tx_native_op_lib`. Running `cmake --build <build-dir> --target <gxf_wrapped_ping_variant_tx_native_op_lib>` will build the GXF ping operator wrapper depending on `ping_variant_tx_native_op`.
- Appends a GXF factory macro C++ code snippet to the `EXT_CPP_CONTENT` CMake variable for later use.

Repeat this step to wrap any other operators to include in your extension.

33.2.3 3. Generating a combined GXF Extension

Holoscan SDK provides the CMake `generate_gxf_extension` function to bundle wrapped components in a GXF extension template. The function accepts extension details and C++ GXF function content generated from the preceding sequence of wrapping function calls. Each component registered in the GXF extension can then be instantiated by the GXF component factory at application runtime.

The `wrap_holoscan_as_gxf_extension` example demonstrates generating a GXF extension as follows:

```
generate_gxf_extension(
  EXTENSION_TARGET_NAME gxf_wrapped_ping_variant_ext
  EXTENSION_NAME PingVarCustomNativeResExtension
  EXTENSION_DESCRIPTION
    "Ping Variant Custom Native extension. Includes wrapped Holoscan custom resource and␣
↪tx/rx operators"
  EXTENSION_AUTHOR "NVIDIA"
  EXTENSION_VERSION "${holoscan_VERSION}"
  EXTENSION_LICENSE "Apache-2.0"
  EXTENSION_ID_HASH1 0x2b8381ed5c2740a1
  EXTENSION_ID_HASH2 0xbe586c019eaa87be
  INCLUDE_HEADERS
    ${RESOURCE_HDRS}
    ${TX_CODELET_HDRS}
    ${RX_CODELET_HDRS}
  PUBLIC_DEPENDS
    gxf_wrapped_ping_variant_custom_native_res_lib
    gxf_wrapped_ping_variant_tx_native_op_lib
    gxf_wrapped_ping_variant_rx_native_op_lib
  EXTENSION_TARGET_PROPERTIES
    LIBRARY_OUTPUT_DIRECTORY ${CMAKE_CURRENT_BINARY_DIR}
  EXT_CPP_CONTENT "${EXT_CPP_CONTENT}"
)
```

The `generate_gxf_extension` function call generates a CMake build target `gxf_wrapped_ping_variant_ext` to build the GXF extension shared library. The resulting extension may be included in a GXF context to make the custom resource and Tx/Rx operators available to the GXF application.

33.2.4 4. Using your wrapped components in a GXF application

Note: This section assumes you are familiar with *how to create a GXF application*.

GXF extensions generated with Holoscan SDK wrappings rely on the Holoscan Wrapper extension. When listing extensions in your application manifest, please ensure dependencies are observed in order:

- `GXF::std`
- `ucx_holoscan_extension`
- `gxf_holoscan_wrapper`
- Your custom wrapper extension name

Review the example YAML app definition for a demonstration of how a custom resource can be used as a parameter to the tx operator in the app.

CHAPTER

THIRTYFOUR

GXF USER GUIDE

34.1 Graph Specification

Graph Specification is a format to describe high-performance AI applications in a modular and extensible way. It allows writing applications in a standard format and sharing components across multiple applications without code modification. Graph Specification is based on entity-composition pattern. Every object in graph is represented with entity (aka Node) and components. You can implement custom components, which can be added to entity to achieve the required functionality.

34.1.1 Concepts

The graph contains nodes which follow an entity-component design pattern implementing the "composition over inheritance" paradigm. A node itself is just a lightweight object which owns components. Components define how a node interacts with the rest of the applications. For example, nodes be connected to pass data between each other. A special component, called compute component, is used to execute the code based on certain rules. Typically a compute component would receive data, execute some computation, and publish data.

Graph

A graph is a data-driven representation of an AI application. Implementing an application by using programming code to create and link objects results in a monolithic and hard to maintain program. Instead, a graph object is used to structure an application. The graph can be created using specialized tools and it can be analyzed to identify potential problems or performance bottlenecks. The graph is loaded by the graph runtime to be executed.

The functional blocks of a graph are defined by the set of nodes which the graph owns. Nodes can be queried via the graph using certain query functions. For example, it is possible to search for a node by its name.

SubGraph

A subgraph is a graph with additional node for interfaces. It points to the components which are accessible outside this graph. In order to use a subgraph in an existing graph or subgraph, you need to create an entity where a component of the type `nvidia::gxf::Subgraph` is contained. Inside the Subgraph component, a corresponding subgraph can be loaded from the `yaml` file indicated by *location* property and instantiated in the parent graph.

The system makes the components from interface available to the parent graph when a sub-graph is loaded in the parent graph. It allows users to link subgraphs in parent with defined interface.

A subgraph interface can be defined as follows:

```
---
interfaces:
 - name: iname # the name of the interface for the access from the parent graph
   target: n_entity/n_component # the true component in the subgraph that is represented␣
↪by the interface
```

Node

Graph Specification uses an entity-component design principle for nodes. This means that a node is a lightweight object whose main purpose is to own components. A node is a composition of components. Every component is in exactly one node. In order to customize a node, you do not derive from node as a base class, but instead compose objects out of components. Components can be used to provide a rich set of functionality to a node and thus to an application.

Components

Components are the main functional blocks of an application. Graph runtime provides a couple of components which implement features like properties, code execution, rules and message passing. It also allows you to extend the runtime by injecting your own custom components with custom features to fit a specific use case.

The most common component is a codelet or compute component which is used for data processing and code execution. To implement a custom codelet, you'll need to implement a certain set of functions like *start* and *stop*. A special system – the *scheduler* – will call these functions at the specified time. Typical examples of triggering code execution are: receiving a new message from another node, or performing work on a regular schedule based on a time trigger.

Edges

Nodes can receive data from other nodes by connecting them with an edge. This essential feature allows a graph to represent a compute pipeline or a complicated AI application. An input to a node is called sink while an output is called source. There can be zero, one, or multiple inputs and outputs. A source can be connected to multiple sinks, and a sink can be connected to multiple sources.

Extension

An extension is a compiled shared library of a logical group of component type definitions and their implementations along with any other asset files that are required for execution of the components. Some examples of asset files are model files, shared libraries that the extension library links to and hence required to run, header and development files that enable development of additional components, and extensions that use components from the extension.

An extension library is a runtime loadable module compiled with component information in a standard format that allows the graph runtime to load the extension and retrieve further information from it to:

- Allow the runtime to create components using the component types in the extension.
- Query information regarding the component types in the extension:
  - The component type name
  - The base type of the component
  - A string description of the component
  - Information of parameters of the component – parameter name, type, description, etc.
- Query information regarding the extension itself – Name of the extension, version, license, author, and a string description of the extension.

The section :doc: *GraphComposer_Dev_Workflow* talks more about this with a focus on developing extensions and components.

34.1.2 Graph File Format

The graph file stores list of entities. Each entity has a unique name and list of components. Each component has a name, a type, and properties. Properties are stored as key-value pairs.

```
%YAML 1.2
---
name: source
components:
- name: signal
  type: sample::test::ping
- type: nvidia::gxf::CountSchedulingTerm
  parameters:
    count: 10
---
components:
- type: nvidia::gxf::GreedyScheduler
  parameters:
    realtime: false
    max_duration_ms: 1000000
```

34.2 Graph Execution Engine

Graph Execution Engine is used to execute AI application graphs. It accepts multiple graph files as input, and all graphs are executed in same process context. It also needs manifest files as input which includes list of extensions to load. It must list all extensions required for the graph.

```
gxe --help
  Flags from gxf/gxe/gxe.cpp:
    -app (GXF app file to execute. Multiple files can be comma-separated)
      type: string default: ""
    -graph_directory (Path to a directory for searching graph files.)
      type: string default: ""
    -log_file_path (Path to a file for logging.) type: string default: ""
    -manifest (GXF manifest file with extensions. Multiple files can be
      comma-separated) type: string default: ""
    -severity (Set log severity levels: 0=None, 1=Error, 2=Warning, 3=Info,
      4=Debug. Default: Info) type: int32 default: 3
```

34.3 Graph Specification TimeStamping

34.3.1 Message Passing

Once the graph is built, the communication between various entities occur by passing around messages (messages are entities themselves). Specifically, one component/codelet can publish a message entity and another can receive it. When publishing, a message should always have an associated `Timestamp` component with the name *"timestamp"*. A `Timestamp` component contains two different time values (See the `gxf/std/timestamp.hpp` header file for more information.):

1. `acqtime` - This is the time when the message entity is acquired; for instance, this would generally be the driver time of the camera when it captures an image. You must provide this timestamp if you are publishing a message in a codelet.
2. `pubtime` - This is the time when the message entity is published by a node in the graph. This will automatically get updated using the clock of the scheduler.

In a codelet, when publishing message entities using a `Transmitter (tx)`, there are two ways to add the required `Timestamp`:

1. `tx.publish(Entity message)`: You can manually add a component of type `Timestamp` with the name "timestamp" and set the `acqtime`. The `pubtime` in this case should be set to `0`. The message is published using the `publish(Entity message)`. **This will be deprecated in the next release.**
2. `tx.publish(Entity message, int64_t acqtime)`: You can simply call `publish(Entity message, int64_t acqtime)` with the `acqtime`. Timestamp will be added automatically.

34.4 The GXF Scheduler

The execution of entities in a graph is governed by the scheduler and the scheduling terms associated with every entity. A scheduler is a component responsible for orchestrating the execution of all the entities defined in a graph. A scheduler typically keeps track of the graph entities and their current execution states and passes them on to a `nvidia::gxf::EntityExecutor` component when ready for execution. The following diagram depicts the flow for an entity execution.

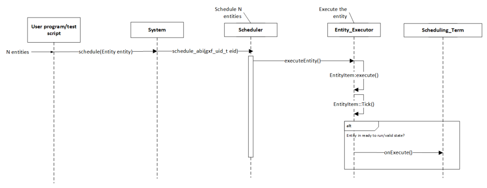


Figure: Entity execution sequence

As shown in the sequence diagram, the schedulers begin executing the graph entities via the `nvidia::gxf::System::runAsync\_abi()` interface, and continue this process until it meets the certain ending criteria. A single entity can have multiple codelets. These codelets are executed in the same order in which they were defined in the entity. A failure in execution of any single codelet stops the execution of all the entities. Entities are naturally unscheduled from execution when any one of their scheduling term reaches the `NEVER` state.

Scheduling terms are components used to define the execution readiness of an entity. An entity can have multiple scheduling terms associated with it and each scheduling term represents the state of an entity using SchedulingCondition.

The table below shows various states of `nvidia::gxf::SchedulingConditionType` described using `nvidia::gxf::SchedulingCondition`.

SchedulingConditionType	Description
NEVER	Entity will never execute again
READY	Entity is ready for execution
WAIT	Entity may execute in the future
WAIT_TIME	Entity will be ready for execution after specified duration
WAIT_EVENT	Entity is waiting on an asynchronous event with unknown time interval

Schedulers define deadlock as a condition when there are no entities which are in `READY`, `WAIT\_TIME` or `WAIT\_EVENT` states, which guarantee execution at a future point in time. This implies all the entities are in the `WAIT` state, for which the scheduler does not know if they ever will reach the `READY` state in the future. The scheduler can be configured to stop when it reaches such a state using the `stop\_on\_deadlock` parameter, else the entities are polled to check if any of them have reached the `READY` state. The `max\_duration` configuration parameter can be used to stop execution of all entities, regardless of their state, after a specified amount of time has elapsed.

There are two types of schedulers currently supported by GXF

1. Greedy Scheduler
2. Multithread Scheduler

34.4.1 Greedy Scheduler

This is a basic single threaded scheduler which tests scheduling term greedily. It is great for simple use cases and predictable execution, but may incur a large overhead of scheduling term execution, making it unsuitable for large applications. The scheduler requires a clock to keep track of time. Based on the choice of clock the scheduler will execute differently. If a Realtime clock is used, the scheduler will execute in real-time. This means pausing execution – sleeping the thread – until periodic scheduling terms are due again. If a ManualClock is used, scheduling will happen "time-compressed." This means the flow of time is altered to execute codelets in immediate succession.

The `GreedyScheduler` maintains a running count of entities which are in `READY`, `WAIT\_TIME` and `WAIT\_EVENT` states. The following activity diagram depicts the gist of the decision making for scheduling an entity by the Greedy Scheduler:

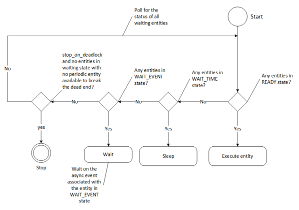

Poll for the status of all waiting entities
Start
No
stop_on_deadlock and no entities in waiting state with no periodic entity available to break the dead end?
Any entities in WAIT_EVENT state?
Any entities in WAIT_TIME state?
Any entities in READY state?
No
No
No
yes
Yes
Yes
Yes
Stop
Wait
Sleep
Execute entity
Wait on the async event associated with the entity in WAIT_EVENT state

Figure: Greedy Scheduler Activity Diagram

Greedy Scheduler Configuration

The Greedy Scheduler takes in the following parameters from the configuration file:

Parameter name	Description
clock	The clock used by the scheduler to define the flow of time. Typical choices are RealtimeClock or ManualClock
max_duration_ms	The maximum duration for which the scheduler will execute (in ms). If not specified, the scheduler will run until all work is done. If periodic terms are present this means the application will run indefinitely
stop_on_deadlock	If stop_on_deadlock is disabled, the GreedyScheduler constantly polls for the status of all the waiting entities to check if any of them are ready for execution.

Example usage – The following code snippet configures a Greedy Scheduler with a ManualClock option specified.

```yaml
name: scheduler
components:
- type: nvidia::gxf::GreedyScheduler
  parameters:
    max_duration_ms: 3000
    clock: misc/clock
    stop_on_deadlock: true
---
name: misc
components:
- name: clock
  type: nvidia::gxf::ManualClock
```

34.4.2 Multithread Scheduler

The MultiThread Scheduler is more suitable for large applications with complex execution patterns. The scheduler consists of a dispatcher thread which checks the status of an entity, and dispatches it to a thread pool of worker threads responsible for executing them. Worker threads enqueue the entity back on to the dispatch queue upon completion of execution. The number of worker threads can be configured using the `worker\_thread\_number` parameter. The MultiThread Scheduler also manages a dedicated queue and thread to handle asynchronous events. The following activity diagram demonstrates the gist of the multithread scheduler implementation.

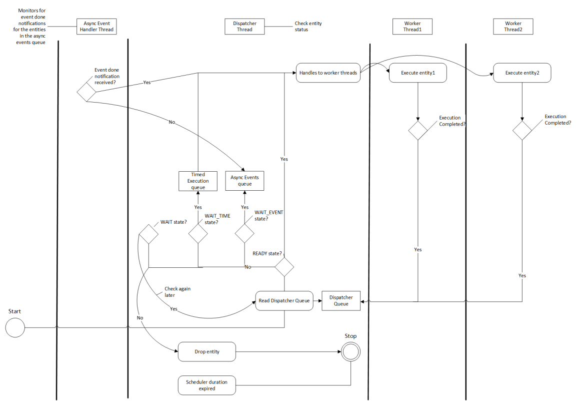


Figure: MultiThread Scheduler Activity Diagram

As depicted in the diagram, when an entity reaches the `WAIT\_EVENT` state, it's moved to a queue where they wait to receive event done notification. The asynchronous event handler thread is responsible for moving entities to the dispatcher upon receiving event done notification. The dispatcher thread also maintains a running count of the number of entities in `READY`, `WAIT\_EVENT` and `WAIT\_TIME` states, and uses these statistics to check if the scheduler has reached a deadlock. The scheduler also needs a clock component to keep track of time and it is configured using the `clock` parameter.

The MultiThread Scheduler is more resource efficient compared to the Greedy Scheduler, and does not incur any additional overhead for constantly polling the states of scheduling terms. The `check\_recession\_period\_ms` parameter can be used to configure the time interval the scheduler must wait to poll the state of entities which are in the `WAIT` state.

Multithread Scheduler Configuration

The Multithread Scheduler takes in the following parameters from the configuration file:

Parameter name	Description
clock	The clock used by the scheduler to define the flow of time. Typical choices are RealtimeClock or ManualClock.
max_duration_ms	The maximum duration for which the scheduler will execute (in ms). If not specified, the scheduler will run until all work is done. If periodic terms are present this means the application will run indefinitely.
check_recess_period_ms	Duration to sleep before checking the condition of an entity again [ms]. This is the maximum duration for which the scheduler would wait when an entity is not yet ready to run.
stop_on_deadlock	If enabled the scheduler will stop when all entities are in a waiting state, but no periodic entity exists to break the dead end. Should be disabled when scheduling conditions can be changed by external actors, for example by clearing queues manually.
worker_thread_number	Number of threads.

Example usage – The following code snippet configures a Multithread Scheduler with the number of worked threads and max duration specified:

```yaml
name: scheduler
components:
- type: nvidia::gxf::MultiThreadScheduler
  parameters:
    max_duration_ms: 5000
    clock: misc/clock
    worker_thread_number: 5
    check_recession_period_ms: 3
    stop_on_deadlock: false
---
name: misc
components:
- name: clock
  type: nvidia::gxf::RealtimeClock
```

34.4.3 Epoch Scheduler

The Epoch Scheduler is used for running loads in externally managed threads. Each run is called an Epoch. The scheduler goes over all entities that are known to be active and executes them one by one. If the epoch budget is provided (in ms), it would keep running all codelets until the budget is consumed or no codelet is ready. It might run over budget since it guarantees to cover all codelets in an epoch. In case the budget is not provided, it would go over all the codelets once and execute them only once.

The Epoch Scheduler takes in the following parameters from the configuration file:

Parameter name	Description
clock	The clock used by the scheduler to define the flow of time. Typical choice is a RealtimeClock.

Example usage – The following code snippet configures an Epoch Scheduler:

```
name: scheduler
components:
- name: clock
  type: nvidia::gxf::RealtimeClock
- name: epoch
  type: nvidia::gxf::EpochScheduler
  parameters:
    clock: clock
```

Note that the Epoch Scheduler is intended to run from an external thread. The `runEpoch(float budget_ms);` can be used to set the budget_ms and run the scheduler from the external thread. If the specified budget is not positive, all the nodes are executed once.

34.4.4 SchedulingTerms

A `SchedulingTerm` defines a specific condition that is used by an entity to let the scheduler know when it's ready for execution. There are various scheduling terms currently supported by GXF.

PeriodicSchedulingTerm

An entity associated with `nvidia::gxf::PeriodicSchedulingTerm` is ready for execution after periodic time intervals specified using its `recess\_period` parameter. The `PeriodicSchedulingTerm` can either be in `READY` or `WAIT\_TIME` state.

Example usage:

```
- name: scheduling_term
  type: nvidia::gxf::PeriodicSchedulingTerm
  parameters:
   recess_period: 50000000
```

CountSchedulingTerm

An entity associated with `nvidia::gxf::CountSchedulingTerm` is executed for a specific number of times specified using its `count` parameter. The `CountSchedulingTerm` can either be in `READY` or `NEVER` state. The scheduling term reaches the `NEVER` state when the entity has been executed `count` number of times.

Example usage:

```
- name: scheduling_term
  type: nvidia::gxf::CountSchedulingTerm
  parameters:
   count: 42
```

MessageAvailableSchedulingTerm

An entity associated with `nvidia::gxf::MessageAvailableSchedulingTerm` is executed when the associated receiver queue has at least a certain number of elements. The receiver is specified using the `receiver` parameter of the scheduling term. The minimum number of messages that permits the execution of the entity is specified by `min_size`. An optional parameter for this scheduling term is `front_stage_max_size`, the maximum front stage message count. If this parameter is set, the scheduling term will only allow execution if the number of messages in the queue does not exceed this count. It can be used for codelets which do not consume all messages from the queue.

In the example shown below, the minimum size of the queue is configured to be 4. This means the entity will not be executed until there are at least 4 messages in the queue.

```yaml
- type: nvidia::gxf::MessageAvailableSchedulingTerm
  parameters:
    receiver: tensors
    min_size: 4
```

MultiMessageAvailableSchedulingTerm

An entity associated with `nvidia::gxf::MultiMessageAvailableSchedulingTerm` is executed when a list of provided input receivers combined have at least a given number of messages. The `receivers` parameter is used to specify a list of the input channels/receivers. The minimum number of messages needed to permit the entity execution is set by `min_size` parameter.

Consider the example shown below. The associated entity will be executed when the number of messages combined for all the three receivers is at least the min_size; i.e., 5.

```yaml
- name: input_1
  type: nvidia::gxf::test::MockReceiver
  parameters:
    max_capacity: 10
- name: input_2
  type: nvidia::gxf::test::MockReceiver
  parameters:
    max_capacity: 10
- name: input_3
  type: nvidia::gxf::test::MockReceiver
  parameters:
    max_capacity: 10
- type: nvidia::gxf::MultiMessageAvailableSchedulingTerm
  parameters:
    receivers: [input_1, input_2, input_3]
    min_size: 5
```

BooleanSchedulingTerm

An entity associated with `nvidia::gxf::BooleanSchedulingTerm` is executed when its internal state is set to tick. The parameter `enable_tick` is used to control the entity execution. The scheduling term also has two APIs `enable_tick()` and `disable_tick()` to toggle its internal state. The entity execution can be controlled by calling these APIs. If `enable_tick` is set to false, the entity is not executed (Scheduling condition is set to `NEVER`). If `enable_tick` is set to true, the entity will be executed (Scheduling condition is set to `READY`). Entities can toggle the state of the scheduling term by maintaining a handle to it.

Example usage:

```yaml
- type: nvidia::gxf::BooleanSchedulingTerm
  parameters:
   enable_tick: true
```

AsynchronousSchedulingTerm

`AsynchronousSchedulingTerm` is primarily associated with entities which are working with asynchronous events happening outside of their regular execution performed by the scheduler. Since these events are non-periodic in nature, `AsynchronousSchedulingTerm` prevents the scheduler from polling the entity for its status regularly and reduces CPU utilization. `AsynchronousSchedulingTerm` can either be in `READY`, `WAIT`, `WAIT\_EVENT` or `NEVER` states based on asynchronous event it's waiting on.

The state of an asynchronous event is described using `nvidia::gxf::AsynchronousEventState` and is updated using the `setEventState` API.

AsynchronousEventState	Description
READY	Init state, first tick is pending
WAIT	Request to async service yet to be sent, nothing to do but wait
EVENT_WAITING	Request sent to an async service, pending event done notification
EVENT_DONE	Event done notification received, entity ready to be ticked
EVENT_NEVER	Entity does not want to be ticked again, end of execution

Entities associated with this scheduling term most likely have an asynchronous thread which can update the state of the scheduling term outside of its regular execution cycle performed by the GXF scheduler. When the scheduling term is in `WAIT` state, the scheduler regularly polls for the state of the entity. When the scheduling term is in `EVENT\_WAITING` state, schedulers will not check the status of the entity again until they receive an event notification which can be triggered using the `GxfEntityEventNotify` API. Setting the state of the scheduling term to `EVENT\_DONE` automatically sends this notification to the scheduler. Entities can use the `EVENT\_NEVER` state to indicate the end of its execution cycle.

Example usage:

```yaml
- name: async_scheduling_term
  type: nvidia::gxf::AsynchronousSchedulingTerm
```

DownsteamReceptiveSchedulingTerm

This scheduling term specifies that an entity shall be executed if the receiver for a given transmitter can accept new messages.

Example usage:

```
- name: downstream_st
  type: nvidia::gxf::DownstreamReceptiveSchedulingTerm
  parameters:
   transmitter: output
   min_size: 1
```

TargetTimeSchedulingTerm

This scheduling term permits execution at a user-specified timestamp. The timestamp is specified on the clock provided.

Example usage:

```
- name: target_st
  type: nvidia::gxf::TargetTimeSchedulingTerm
  parameters:
   clock: clock/manual_clock
```

ExpiringMessageAvailableSchedulingTerm

This scheduling waits for a specified number of messages in the receiver. The entity is executed when the first message received in the queue is expiring or when there are enough messages in the queue. The `receiver` parameter is used to set the receiver to watch on. The parameters `max_batch_size` and `max_delay_ns` dictate the maximum number of messages to be batched together and the maximum delay from first message to wait before executing the entity respectively.

In the example shown below, the associated entity will be executed when the number of messages in the queue is greater than `max_batch_size` (i.e., 5), or when the delay from the first message to current time is greater than `max_delay_ns` (i.e., 10000000).

```
- name: target_st
  type: nvidia::gxf::ExpiringMessageAvailableSchedulingTerm
  parameters:
   receiver: signal
   max_batch_size: 5
   max_delay_ns: 10000000
   clock: misc/clock
```

AND Combined

An entity can be associated with multiple scheduling terms which define its execution behavior. Scheduling terms are `AND` combined to describe the current state of an entity. For an entity to be executed by the scheduler, all the scheduling terms must be in `READY` state and conversely, the entity is unscheduled from execution whenever any one of the scheduling term reaches `NEVER` state. The priority of various states during `AND` combine follows the order `NEVER`, `WAIT\_EVENT`, `WAIT`, `WAIT\_TIME`, and `READY`.

Example usage:

```
components:
- name: integers
  type: nvidia::gxf::DoubleBufferTransmitter
- name: fibonacci
  type: nvidia::gxf::DoubleBufferTransmitter
- type: nvidia::gxf::CountSchedulingTerm
  parameters:
    count: 100
- type: nvidia::gxf::DownstreamReceptiveSchedulingTerm
  parameters:
    transmitter: integers
    min_size: 1
```

BTSchedulingTerm

A BT (Behavior Tree) scheduling term is used to schedule a behavior tree entity itself and its child entities (if any) in a Behavior tree.

Example usage:

```
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_codelet
  type: nvidia::gxf::SequenceBehavior
  parameters:
    children: [ child1/child1_st ]
    s_term: root_st
    controller: root_controller
```

34.5 Behavior Trees

Behavior tree codelets are one of the mechanisms to control the flow of tasks in GXF. They follow the same general behavior as classical behavior trees, with some useful additions for robotics applications. This document gives an overview of the general concept, the available behavior tree node types, and some examples of how to use them individually or in conjunction with each other.

34.5.1 General Concept

Behavior trees consist of n-ary trees of entities that can have zero or more children. The conditional execution of parent entity is based on the status of execution of the children. A behavior tree is graphically represented as a directed tree in which the nodes are classified as root, control flow nodes, or execution nodes (tasks). For each pair of connected nodes, the outgoing node is called parent and the incoming node is called child.

The execution of a behavior tree starts from the root which sends ticks with a certain frequency to its child. When the execution of a node in the behavior tree is allowed, it returns to the parent a status `running` if its execution has not finished yet, `success` if it has achieved its goal, or `failure` otherwise. The behavior tree also uses a controller component for controlling the entity's termination policy and the execution status. One of the controller behaviors currently implemented for Behavior Tree is `EntityCountFailureRepeatController`, which repeats the entity on failure up to `repeat_count` times before deactivating it.

GXF supports several behavior tree codelets which are explained in the following section.

34.5.2 Behavior Tree Codelets

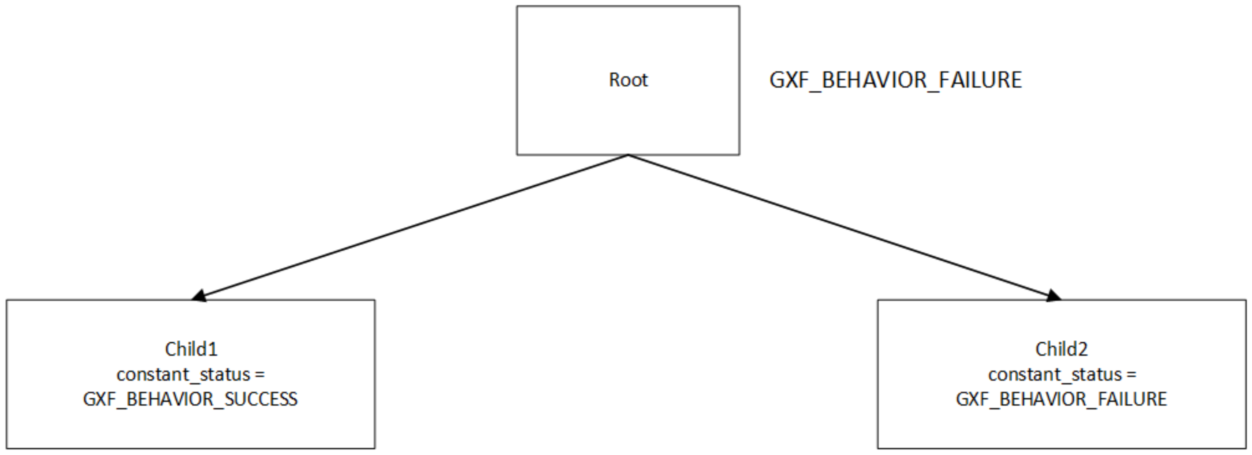
Each behavior tree codelet can have a set of parameters defining how it should behave. Note that in all the examples given below, the naming convention for configuring the `children` parameter for root codelets is `[child_codelet_name\child_codelet_scheduling_term]`.

Constant Behavior

After each tick period, switches its own status to the configured desired constant status.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
constant_status	The desired status to switch to during each tick time.

An example diagram depicting Constant behavior used in conjunction with a Sequence behavior defined for root entity is shown below:



Here, the child1 is configured to return a constant status of success (`GXF\_BEHAVIOR\_SUCCESS`) and child2 returns failure (`GXF\_BEHAVIOR\_FAILURE`), resulting into the root node (configured to exhibit sequence behavior) returning `GXF\_BEHAVIOR\_FAILURE`.

The controller for each child can be configured to repeat the execution on failure. A code snippet of configuring the example described is shown below.

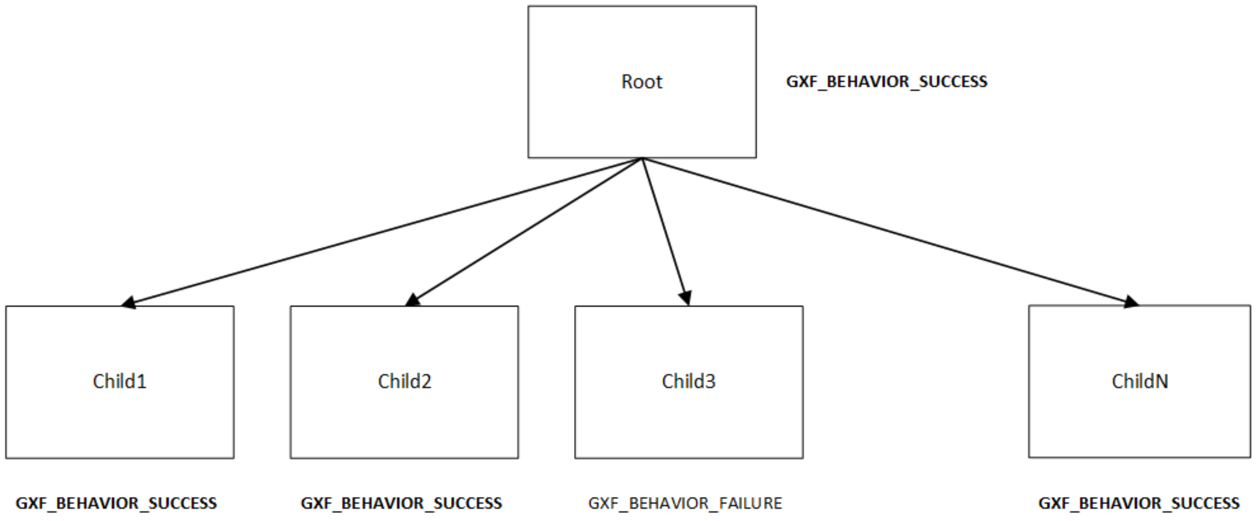
```yaml
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_codelet
  type: nvidia::gxf::SequenceBehavior
  parameters:
    children: [ child1/child1_st, child2/child2_st ]
    s_term: root_st
---
 name: child2
 components:
 - name: child2_controller
   type: nvidia::gxf::EntityCountFailureRepeatController
   parameters:
     max_repeat_count: 3
     return_behavior_running_if_failure_repeat: true
 - name: child2_st
   type: nvidia::gxf::BTSchedulingTerm
   parameters:
     is_root: false
 - name: child2_codelet
   type: nvidia::gxf::ConstantBehavior
   parameters:
     s_term: child2_st
     constant_status: 1
```

Parallel Behavior

Runs its child nodes in parallel. By default, succeeds when all child nodes succeed, and fails when all child nodes fail. This behavior can be customized using the parameters below.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
children	Child entities
success_threshold	Number of successful children required for success. A value of -1 means all children must succeed for this node to succeed.
failure_threshold	Number of failed children required for failure. A value of -1 means all children must fail for this node to fail.

The diagram below shows a graphical representation of a parallel behavior configured with `failure\_threshold` configured as `-1`. Hence, the root node returns `GXF\_BEHAVIOR\_SUCCESS` even if one child returns a `failure` status.



A code snippet to configure the example described is shown below.

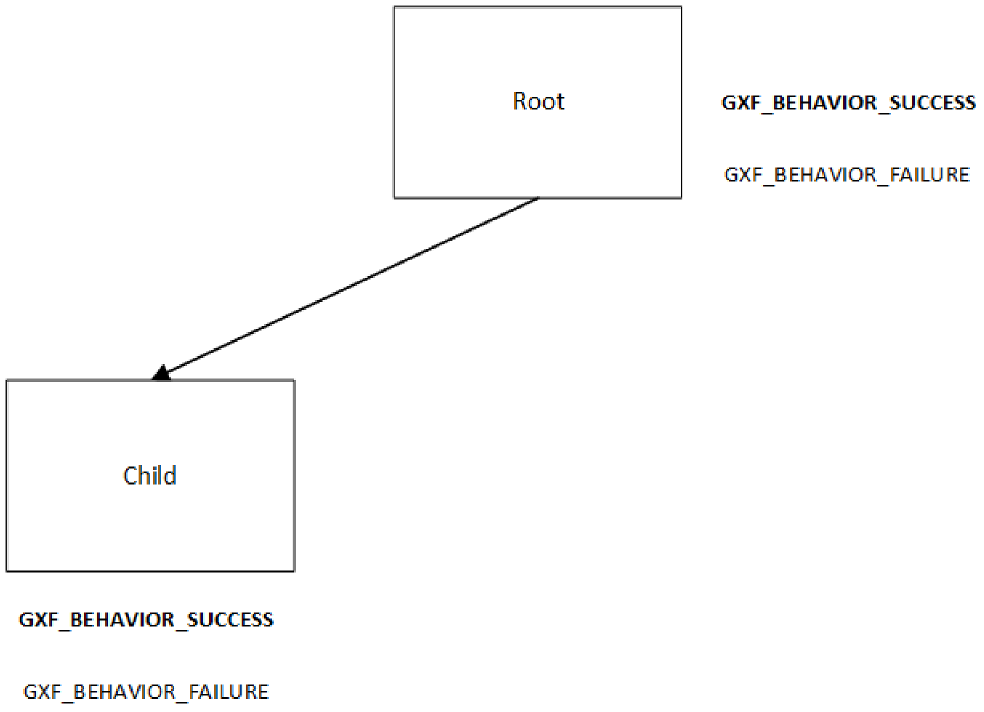
```
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_codelet
  type: nvidia::gxf::ParallelBehavior
  parameters:
    children: [ child1/child1_st, child2/child2_st ]
    s_term: root_st
    success_threshold: 1
    failure_threshold: -1
```

Repeat Behavior

Repeats its only child entity. By default, won't repeat when the child entity fails. This can be customized using the parameters below.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
repeat_after_failure	Denotes whether to repeat the child after it has failed.

The diagram below shows a graphical representation of a repeat behavior. The root entity can be configured to repeat the only child to repeat after failure. It succeeds when the child entity succeeds.



A code snippet to configure a repeat behavior is as shown below -

```yaml
name: repeat_knock
components:
- name: repeat_knock_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: repeat_knock_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: false
- name: repeat_codelet
  type: nvidia::gxf::RepeatBehavior
  parameters:
    s_term: repeat_knock_st
    children: [ knock_on_door/knock_on_door_st ]
    repeat_after_failure: true
```

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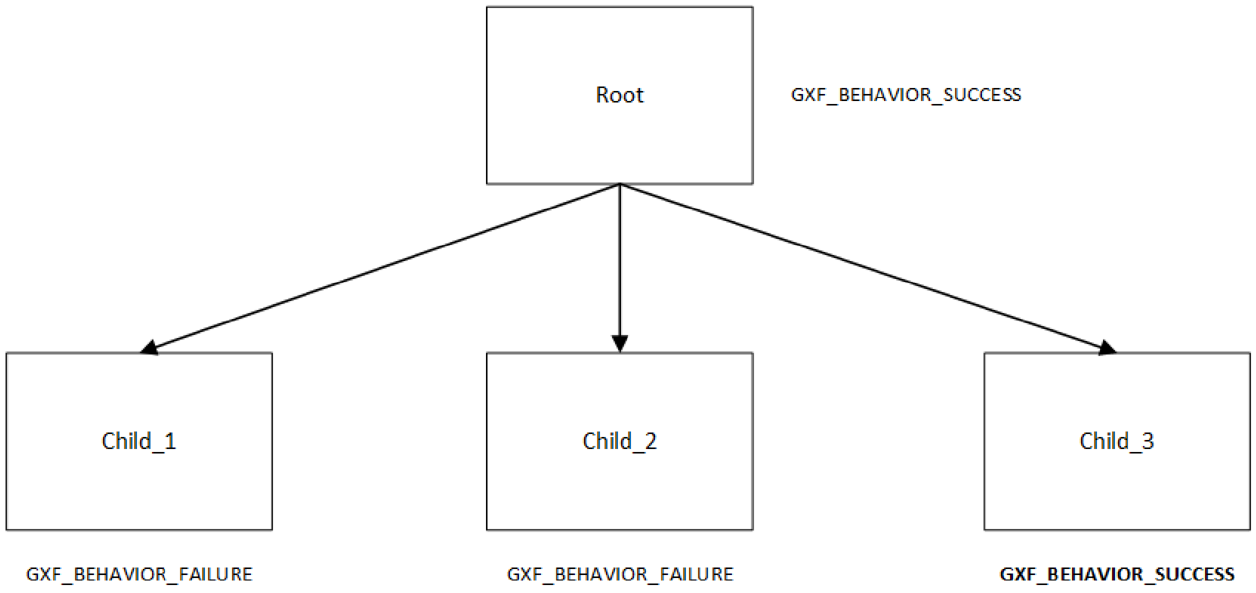
```
---
```

Selector Behavior

Runs all child entities in sequence until one succeeds, then reports success. If all child entities fail (or no child entities are present), this codelet fails.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
children	Child entities

The diagram below shows a graphical representation of a Selector behavior. The root entity starts `child\_1`, `child\_2`, and `child\_3` in a sequence. Although `child\_1` and `child\_2` fail, the root entity will return `success` since `child\_3` returns successfully.



A code snippet to configure a selector behavior is as shown below.

```
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_sel_codelet
  type: nvidia::gxf::SelectorBehavior
  parameters:
    children: [ door_distance/door_distance_st, door_detected/door_detected_st, knock/
↪knock_st ]
```

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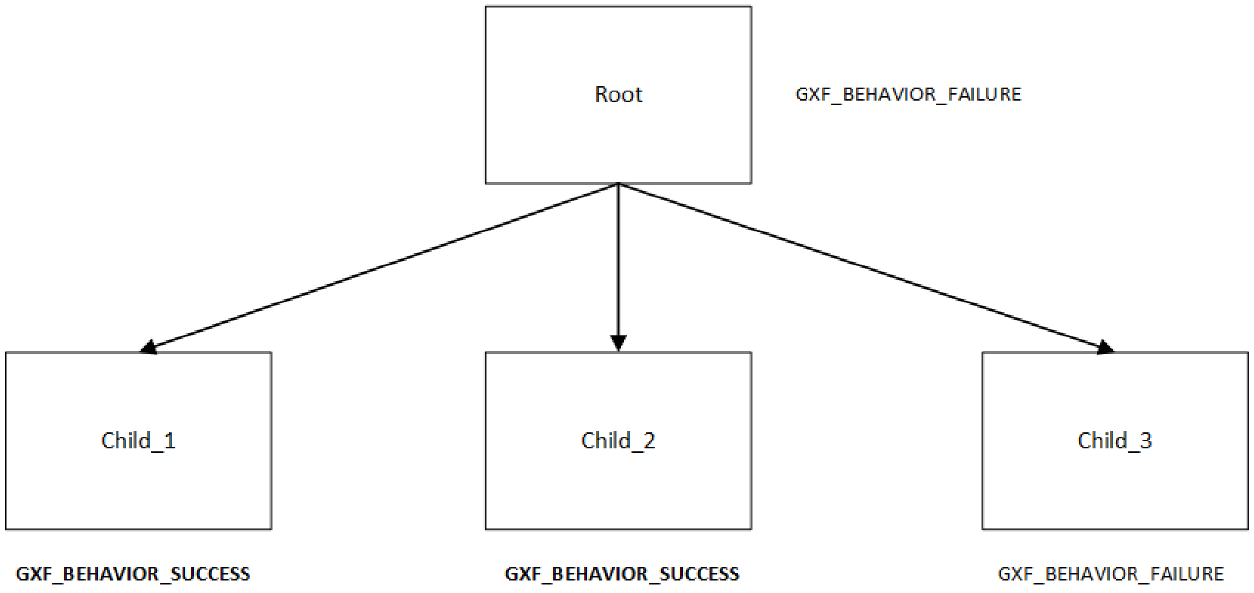
```yaml
    s_term: root_st
---
name: door_distance
components:
- name: door_distance_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: door_distance_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: false
- name: door_dist
  type: nvidia::gxf::SequenceBehavior
  parameters:
    children: []
    s_term: door_distance_st
---
```

Sequence Behavior

Runs its child entities in sequence, in the order in which they are defined. Succeeds when all child entities succeed or fails as soon as one child entity fails.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
children	Child entities

The diagram below shows a graphical representation of a Sequence behavior. The root entity starts `child\_1`, `child\_2` and `child\_3` in a sequence. Although `child\_1` and `child\_2` pass, the root entity will return failure since `child\_3` returns `failure`.



A code snippet to configure a sequence behavior is as shown below.

```
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_codelet
  type: nvidia::gxf::SequenceBehavior
  parameters:
    children: [ child1/child1_st, child2/child2_st ]
    s_term: root_st
```

Switch Behavior

Runs the child entity with the index defined as `desired\_behavior`.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
children	Child entities
desired_behavior	The index of child entity to switch to when this entity runs

In the code snippet shown below, the desired behavior of the root entity is designated to be the the child at index 1 (scene). Hence, that is the entity that is run.

```
name: root
components:
- name: root_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 0
- name: root_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: true
- name: root_switch_codelet
  type: nvidia::gxf::SwitchBehavior
  parameters:
    children: [ scene/scene_st, ref/ref_st ]
    s_term: root_st
    desired_behavior: 0
---
name: scene
components:
- name: scene_controller
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
```

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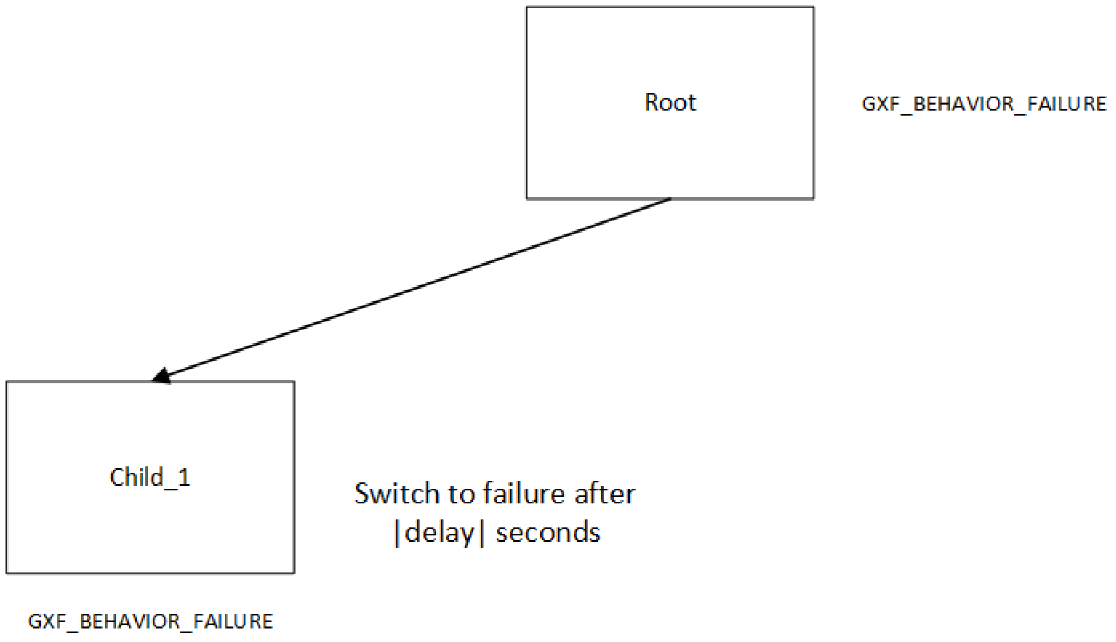
```
    max_repeat_count: 0
- name: scene_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: false
- name: scene_seq
  type: nvidia::gxf::SequenceBehavior
  parameters:
    children: [ pose/pose_st, det/det_st, seg/seg_st ]
    s_term: scene_st
---
```

Timer Behavior

Waits for a specified amount of time delay and switches to the configured result `switch\_status` afterwards.

Parameter	Description
s_term	scheduling term used for scheduling the entity itself
clock	Clock
switch_status	Configured result to switch to after the specified delay
delay	Configured delay

In the diagram shown below, the child entity switches to failure after a configured delay period. The root entity hence returns failure.



A code snippet for the same shown below.

```
name: knock_on_door
components:
- name: knock_on_door_controller
```

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```
  type: nvidia::gxf::EntityCountFailureRepeatController
  parameters:
    max_repeat_count: 10
- name: knock_on_door_st
  type: nvidia::gxf::BTSchedulingTerm
  parameters:
    is_root: false
- name: knock
  type: nvidia::gxf::TimerBehavior
  parameters:
    switch_status: 1
    clock: sched/clock
    delay: 1
    s_term: knock_on_door_st
---
```

34.6 GXF Core C APIs

34.6.1 Context

Create context

`gxf_result_t GxfContextCreate(gxf_context_t* context);`

Creates a new GXF context

A GXF context is required for all almost all GXF operations. The context must be destroyed with `GxfContextDestroy`. Multiple contexts can be created in the same process, however they can not communicate with each other.

> parameter: `context` The new GXF context is written to the given pointer.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Create a context from a shared context

`gxf_result_t GxfContextCreate1(gxf_context_t shared, gxf_context_t* context);`

Creates a new runtime context from shared context.

A shared runtime context is used for sharing entities between graphs running within the same process.

> parameter: `shared` A valid GXF shared context.
>
> parameter: `context` The new GXF context is written to the given pointer.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Destroy context

`gxf_result_t GxfContextDestroy(gxf_context_t context);`

Destroys a GXF context

Every GXF context must be destroyed by calling this function. The context must have been previously created with `GxfContextCreate`. This will also destroy all entities and components which were created as part of the context.

> parameter: `context` A valid GXF context.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.2 Extensions

> Maximum number of extensions in a context can be `1024`.

Load Extensions from a file

`gxf_result_t GxfLoadExtension(gxf_context_t context, const char* filename);`

Loads extension in the given context from file.

> parameter: `context` A valid GXF context.
>
> parameter: `filename` A valid filename.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

This function will be deprecated.

Load Extension libraries

`gxf_result_t GxfLoadExtensions(gxf_context_t context, const GxfLoadExtensionsInfo* info);`

Loads GXF extension libraries

Loads one or more extensions either directly by their filename or indirectly by loading manifest files. Before a component can be added to a GXF entity the GXF extension shared library providing the component must be loaded. An extension must only be loaded once.

To simplify loading multiple extensions at once the developer can create a manifest file which lists all extensions he needs. This function will then load all extensions listed in the manifest file. Multiple manifest may be loaded, however each extension may still be loaded only a single time.

A manifest file is a YAML file with a single top-level entry `extensions` followed by a list of filenames of GXF extension shared libraries.

Example: —– START OF FILE —– extensions: - gxf/std/libgxf_std.so - gxf/npp/libgxf_npp.so —– END OF FILE —–

> parameter: `context` A valid GXF context.
>
> parameter: `filename` A valid filename.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

```
gxf_result_t GxfLoadExtensionManifest(gxf_context_t context, const char*
manifest_filename);
```

Loads extensions from manifest file.

parameter: `context` A valid GXF context.

parameter: `filename` A valid filename.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

This function will be deprecated.

Load Metadata files

`gxf_result_t GxfLoadExtensionMetadataFiles(gxf_context_t context, const char* const* filenames, uint32_t count);`

Loads an extension registration metadata file.

Reads a metadata file of the contents of an extension used for registration. These metadata files can be used to resolve typename and TID's of components for other extensions which depend on them. Metadata files do not contain the actual implementation of the extension and must be loaded only to run the extension query API's on extension libraries which have the actual implementation and only depend on the metadata for type resolution.

If some components of extension B depend on some components in extension A: - Load metadata file for extension A. - Load extension library for extension B using `GxfLoadExtensions`. - Run extension query APIs on extension B and its components.

parameter: `context` A valid GXF context.

parameter: `filenames` absolute paths of metadata files.

parameter: `count` The number of metadata files to be loaded.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Register component

`gxf_result_t GxfRegisterComponent(gxf_context_t context, gxf_tid_t tid, const char* name, const char* base_name);`

Registers a component with a GXF extension.

A GXF extension need to register all of its components in the extension factory function. For convenience, the helper macros in `gxf/std/extension_factory_helper.hpp` can be used.

The developer must choose a unique GXF tid with two random 64-bit integers. The developer must ensure that every GXF component has a unique tid. The name of the component must be the fully qualified C++ type name of the component. A component may only have a single base class and that base class must be specified with its fully qualified C++ type name as the parameter `base_name`.

ref: gxf/std/extension_factory_helper.hpp ref: core/type_name.hpp

parameter: `context` A valid GXF context.

parameter: `tid` The chosen GXF tid.

parameter: `name` The type name of the component.

parameter: `base_name` The type name of the base class of the component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.3 Graph Execution

Loads a list of entities from YAML file

```
gxf_result_t GxfGraphLoadFile(gxf_context_t context, const char* filename, const char*
parameters_override[], const uint32_t num_overrides);
```

parameter: `context` A valid GXF context.

parameter: `filename` A valid YAML filename.

parameter: `params_override` An optional array of strings used for override parameters in YAML file.

parameter: `num_overrides` Number of optional override parameter strings.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Set the root folder for searching YAML files during loading

```
gxf_result_t GxfGraphSetRootPath(gxf_context_t context, const char* path);
```

parameter: `context` A valid GXF context.

parameter: `path` Path to root folder for searching YAML files during loading.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Loads a list of entities from YAML text

```
gxf_result_t GxfGraphParseString(gxf_context_t context, const char* tex, const char*
parameters_override[], const uint32_t num_overrides);
```

parameter: `context` A valid GXF context.

parameter: `text` A valid YAML text.

parameter: `params_override` An optional array of strings used for override parameters in yaml file.

parameter: `num_overrides` Number of optional override parameter strings.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Activate all system components

```
gxf_result_t GxfGraphActivate(gxf_context_t context);
```

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Deactivate all System components

`gxf_result_t GxfGraphDeactivate(gxf_context_t context);`

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Starts the execution of the graph asynchronously

`gxf_result_t GxfGraphRunAsync(gxf_context_t context);`

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Interrupt the execution of the graph

`gxf_result_t GxfGraphInterrupt(gxf_context_t context);`

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Waits for the graph to complete execution

`gxf_result_t GxfGraphWait(gxf_context_t context);`

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.`

Runs all System components and waits for their completion

`gxf_result_t GxfGraphRun(gxf_context_t context);`

parameter: `context` A valid GXF context.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.4 Entities

Create an entity

`gxf_result_t GxfEntityCreate(gxf_context_t context, gxf_uid_t* eid);`

Creates a new entity and updates the eid to the unique identifier of the newly created entity.

This method will be deprecated.

`gxf_result_t GxfCreateEntity((gxf_context_t context, const GxfEntityCreateInfo* info, gxf_uid_t* eid);`

Create a new GXF entity.

Entities are lightweight containers to hold components and form the basic building blocks of a GXF application. Entities are created when a GXF file is loaded, or they can be created manually using this function. Entities created with this function must be destroyed using `GxfEntityDestroy`. After the entity was created components can be added to it with `GxfComponentAdd`. To start execution of codelets on an entity, the entity needs to be activated first. This can happen automatically using `GXF_ENTITY_CREATE_PROGRAM_BIT` or manually using `GxfEntityActivate`.

parameter `context:` GXF context that creates the entity. parameter `info:` pointer to a GxfEntityCreateInfo structure containing parameters affecting the creation of the entity. parameter `eid:` pointer to a gxf_uid_t handle in which the resulting entity is returned. returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Activate an entity

`gxf_result_t GxfEntityActivate(gxf_context_t context, gxf_uid_t eid);`

Activates a previously created and inactive entity.

Activating an entity generally marks the official start of its lifetime and has multiple implications: - If mandatory parameters (i.e., parameters which do not have the flag `optional`) are not set, the operation will fail.

- All components on the entity are initialized.
- All codelets on the entity are scheduled for execution. The scheduler will start calling start, tick, and stop functions as specified by scheduling terms.
- After activation, trying to change a dynamic parameters will result in a failure.
- Adding or removing components of an entity after activation will result in a failure.

parameter: `context` A valid GXF context.

parameter: `eid` UID of a valid entity.

returns: GXF error code.

Deactivate an entity

`gxf_result_t GxfEntityDeactivate(gxf_context_t context, gxf_uid_t eid);`

Deactivates a previously activated entity.

Deactivating an entity generally marks the official end of its lifetime and has multiple implications:

- All codelets are removed from the schedule. Already running entities are run to completion.
- All components on the entity are deinitialized.
- Components can be added or removed again once the entity was deactivated.
- Mandatory and non-dynamic parameters can be changed again.

Note: In case that the entity is currently executing, this function will wait and block until

the current execution is finished.

parameter: `context` A valid GXF context.

parameter: `eid` UID of a valid entity.

returns: GXF error code.

Destroy an entity

`gxf_result_t GxfEntityDestroy(gxf_context_t context, gxf_uid_t eid);`

Destroys a previously created entity.

Destroys an entity immediately. The entity is destroyed even if the reference count has not yet reached 0. If the entity is active, it is deactivated first.

Note: This function can block for the same reasons as 'GxfEntityDeactivate'.

parameter: `context` A valid GXF context.

parameter: `eid` The returned UID of the created entity.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Find an entity

`gxf_result_t GxfEntityFind(gxf_context_t context, const char* name, gxf_uid_t* eid);`

Finds an entity by its name.

parameter: `context` A valid GXF context.

parameter: `name` A C string with the name of the entity. Ownership is not transferred.

parameter: `eid` The returned UID of the entity.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Find all entities

`gxf_result_t GxfEntityFindAll(gxf_context_t context, uint64_t* num_entities, gxf_uid_t* entities);`

Finds all entities in the current application.

Finds and returns all entity ids for the current application. If more than *max_entities* exist only *max_entities* will be returned. The order and selection of entities returned is arbitrary.

parameter: `context` A valid GXF context.

parameter: `num_entities` In/Out: the max number of entities that can fit in the buffer/the number of entities that exist in the application.

parameter: `entities` A buffer allocated by the caller for returned UIDs of all entities, with capacity for *num_entities*.

returns: GXF_SUCCESS if the operation was successful, GXF_QUERY_NOT_ENOUGH_CAPACITY if more entities exist in the application than *max_entities*, or otherwise one of the GXF error codes.

Increase reference count of an entity

`gxf_result_t GxfEntityRefCountInc(gxf_context_t context, gxf_uid_t eid);`

Increases the reference count for an entity by 1.

By default reference counting is disabled for an entity. This means that entities created with `GxfEntityCreate` are not automatically destroyed. If this function is called for an entity with disabled reference count, reference counting is enabled and the reference count is set to 1. Once reference counting is enabled an entity will be automatically destroyed if the reference count reaches zero, or if `GxfEntityCreate` is called explicitly.

> parameter: `context` A valid GXF context.
>
> parameter: `eid` The UID of a valid entity.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Decrease reference count of an entity.

`gxf_result_t GxfEntityRefCountDec(gxf_context_t context, gxf_uid_t eid);`

Decreases the reference count for an entity by 1.

See `GxfEntityRefCountInc` for more details on reference counting.

> parameter: `context` A valid GXF context.
>
> parameter: `eid` The UID of a valid entity.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get status of an entity

`gxf_result_t GxfEntityGetStatus(gxf_context_t context, gxf_uid_t eid, gxf_entity_status_t* entity_status);`

Gets the status of the entity.

See `gxf_entity_status_t` for the various status.

> parameter: `context` A valid GXF context.
>
> parameter: `eid` The UID of a valid entity.
>
> parameter: `entity_status` output; status of an entity eid.
>
> returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get state of an entity

`gxf_result_t GxfEntityGetState(gxf_context_t context, gxf_uid_t eid, entity_state_t* entity_state);`

Gets the state of the entity.

See `gxf_entity_status_t` for the various status.

> parameter: `context` A valid GXF context.
>
> parameter: `eid` The UID of a valid entity.
>
> parameter: `entity_state` output; behavior status of an entity eid used by the behavior tree parent codelet.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Notify entity of an event

`gxf_result_t GxfEntityEventNotify(gxf_context_t context, gxf_uid_t eid);`

Notifies the occurrence of an event and inform the scheduler to check the status of the entity

The entity must have an `AsynchronousSchedulingTerm` scheduling term component and it must be in the `EVENT_WAITING` state for the notification to be acknowledged.

See `AsynchronousEventState` for various states.

parameter: `context` A valid GXF context.

parameter: `eid` The UID of a valid entity.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.5 Components

Maximum number of components in an entity or an extension can be up to `1024`.

Get component type identifier

`gxf_result_t GxfComponentTypeId(gxf_context_t context, const char* name, gxf_tid_t* tid);`

Gets the GXF unique type ID (TID) of a component.

Get the unique type ID which was used to register the component with GXF. The function expects the fully qualified C++ type name of the component including namespaces.

Example of a valid component type name: `nvidia::gxf::test::PingTx`

parameter: `context` A valid GXF context.

parameter: `name` The fully qualified C++ type name of the component.

parameter: `tid` The returned TID of the component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get component type name

`gxf_result_t GxfComponentTypeName(gxf_context_t context, gxf_tid_t tid, const char** name);`

Gets the fully qualified C++ type name GXF component typename

Get the unique typename of the component with which it was registered using one of the `GXF_EXT_FACTORY_ADD*()` macros

parameter: `context` A valid GXF context.

parameter: `tid` The unique type ID (TID) of the component with which the component was registered.

parameter: `name` The returned name of the component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get component name

`gxf_result_t GxfComponentName(gxf_context_t context, gxf_uid_t cid, const char** name);`

Gets the name of a component.

Each component has a user-defined name which was used in the call to `GxfComponentAdd`. Usually the name is specified in the GXF application file.

parameter: `context` A valid GXF context.

parameter: `cid` The unique object ID (UID) of the component.

parameter: `name` The returned name of the component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get unique identifier of the entity of given component

`gxf_result_t GxfComponentEntity(gxf_context_t context, gxf_uid_t cid, gxf_uid_t* eid);`

Gets the unique object ID of the entity of a component

Each component has a unique ID with respect to the context and is stored in one entity. This function can be used to retrieve the ID of the entity to which a given component belongs.

parameter: `context` A valid GXF context.

parameter: `cid` The unique object ID (UID) of the component.

parameter: `eid` The returned UID of the entity.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Add a new component

`gxf_result_t GxfComponentAdd(gxf_context_t context, gxf_uid_t eid, gxf_tid_t tid, const char* name, gxf_uid_t* cid);`

Adds a new component to an entity.

An entity can contain multiple components and this function can be used to add a new component to an entity. A component must be added before an entity is activated, or after it was deactivated. Components must not be added to active entities. The order of components is stable and identical to the order in which components are added (see `GxfComponentFind`).

parameter: `context` A valid GXF context.

parameter: `eid` The unique object ID (UID) of the entity to which the component is added.

parameter: `tid` The unique type ID (TID) of the component to be added to the entity.

parameter: `name` The name of the new component. Ownership is not transferred.

parameter: `cid` The returned UID of the created component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Add component to entity interface

`gxf_result_t GxfComponentAddToInterface(gxf_context_t context, gxf_uid_t eid, gxf_uid_t cid, const char* name);`

Adds an existing component to the interface of an entity.

An entity can holds references to other components in its interface, so that when finding a component in an entity, both the component this entity holds and those it refers to will be returned. This supports the case when an entity contains a subgraph, then those components that has been declared in the subgraph interface will be put to the interface of the parent entity.

parameter: `context` A valid GXF context.

parameter: `eid` The unique object ID (UID) of the entity to which the component is added.

parameter: `cid` The unique object ID of the component.

parameter: `name` The name of the new component. Ownership is not transferred.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Find a component in an entity

`gxf_result_t GxfComponentFind(gxf_context_t context, gxf_uid_t eid, gxf_tid_t tid, const char* name, int32_t* offset, gxf_uid_t* cid);`

Finds a component in an entity.

Searches components in an entity which satisfy certain criteria: component type, component name, and component min index. All three criteria are optional; in case no criteria is given the first component is returned. The main use case for `component min index` is a repeated search which continues at the index which was returned by a previous search.

In case no entity with the given criteria was found `GXF_ENTITY_NOT_FOUND` is returned.

parameter: `context` A valid GXF context.

parameter: `eid` The unique object ID (UID) of the entity which is searched.

parameter: `tid` The component type ID (TID) of the component to find (optional).

parameter: `name` The component name of the component to find (optional). Ownership not transferred.

parameter: `offset` The index of the first component in the entity to search. Also contains the index of the component which was found.

parameter: `cid` The returned UID of the searched component.

returns: GXF_SUCCESS if a component matching the criteria was found, GXF_ENTITY_NOT_FOUND if no component matching the criteria was found, or otherwise one of the GXF error codes.

Get type identifier for a component

`gxf_result_t GxfComponentType(gxf_context_t context, gxf_uid_t cid, gxf_tid_t* tid);`

Gets the component type ID (TID) of a component.

parameter: `context` A valid GXF context.

parameter: `cid` The component object ID (UID) for which the component type is requested.

parameter: `tid` The returned TID of the component.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Gets pointer to component

`gxf_result_t GxfComponentPointer(gxf_context_t context, gxf_uid_t uid, gxf_tid_t tid, void** pointer);`

Verifies that a component exists, has the given type, gets a pointer to it.

parameter: `context` A valid GXF context.

parameter: `uid` The component object ID (UID).

parameter: `tid` The expected component type ID (TID) of the component.

parameter: `pointer` The returned pointer to the component object.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.6 Primitive Parameters

64-bit floating point

Set

`gxf_result_t GxfParameterSetFloat64(gxf_context_t context, gxf_uid_t uid, const char* key, double value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` a double value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

`gxf_result_t GxfParameterGetFloat64(gxf_context_t context, gxf_uid_t uid, const char* key, double* value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to get the double value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

64-bit signed integer

Set

`gxf_result_t GxfParameterSetInt64(gxf_context_t context, gxf_uid_t uid, const char* key, int64_t value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` 64-bit integer value to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

`gxf_result_t GxfParameterGetInt64(gxf_context_t context, gxf_uid_t uid, const char* key, int64_t* value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to get the 64-bit integer value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

64-bit unsigned integer

Set

`gxf_result_t GxfParameterSetUInt64(gxf_context_t context, gxf_uid_t uid, const char* key, uint64_t value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` unsigned 64-bit integer value to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

```
gxf_result_t GxfParameterGetUInt64(gxf_context_t context, gxf_uid_t uid, const char* key,
uint64_t* value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to get the unsigned 64-bit integer value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

32-bit signed integer

Set

```
gxf_result_t GxfParameterSetInt32(gxf_context_t context, gxf_uid_t uid, const char* key,
int32_t value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` 32-bit integer value to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

```
gxf_result_t GxfParameterGetInt32(gxf_context_t context, gxf_uid_t uid, const char* key,
int32_t* value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to get the 32-bit integer value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

String parameter

Set

```
gxf_result_t GxfParameterSetStr(gxf_context_t context, gxf_uid_t uid, const char* key,
const char* value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` A char array containing value to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

```
gxf_result_t GxfParameterGetStr(gxf_context_t context, gxf_uid_t uid, const char* key,
const char** value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to a char* array to get the value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Boolean

Set

```
gxf_result_t GxfParameterSetBool(gxf_context_t context, gxf_uid_t uid, const char* key,
bool value);
```

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` A boolean value to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

`gxf_result_t GxfParameterGetBool(gxf_context_t context, gxf_uid_t uid, const char* key, bool* value);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` pointer to get the boolean value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Handle

Set

`gxf_result_t GxfParameterSetHandle(gxf_context_t context, gxf_uid_t uid, const char* key, gxf_uid_t cid);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `cid` Unique identifier to set.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get

`gxf_result_t GxfParameterGetHandle(gxf_context_t context, gxf_uid_t uid, const char* key, gxf_uid_t* cid);`

parameter: `context` A valid GXF context.

parameter: `uid` A valid component identifier.

parameter: `key` A valid name of a component to set.

parameter: `value` Pointer to a unique identifier to get the value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.7 Vector Parameters

To set or get the vector parameters of a component, users can use the following C-APIs for various data types:

Set 1-D Vector Parameters

Users can call `gxf_result_t GxfParameterSet1D"DataType"Vector(gxf_context_t context, gxf_uid_t uid, const char* key, data_type* value, uint64_t length)`

`value` should point to an array of the data to be set of the corresponding type. The size of the stored array should match the `length` argument passed.

See the table below for all the supported data types and their corresponding function signatures.

parameter: `key` The name of the parameter.

parameter: `value` The value to set of the parameter.

parameter: `length` The length of the vector parameter.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Table 34.1: Supported Data Types to Set 1D Vector Parameters

Function Name	data_type
`GxfParameterSet1DFloat64Vector(...)`	`double`
`GxfParameterSet1DInt64Vector(...)`	`int64_t`
`GxfParameterSet1DUInt64Vector(...)`	`uint64_t`
`GxfParameterSet1DInt32Vector(...)`	`int32_t`

Set 2-D Vector Parameters

Users can call `gxf_result_t GxfParameterSet2D"DataType"Vector(gxf_context_t context, gxf_uid_t uid, const char* key, data_type** value, uint64_t height, uint64_t width)`

`value` should point to an array of array (and not to the address of a contiguous array of data) of the data to be set of the corresponding type. The length of the first dimension of the array should match the `height` argument passed, and similarly the length of the second dimension of the array should match the `width` passed.

See the table below for all the supported data types and their corresponding function signatures.

parameter: `key` The name of the parameter.

parameter: `value` The value to set of the parameter.

parameter: `height` The height of the 2-D vector parameter.

parameter: `width` The width of the 2-D vector parameter.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Table 34.2: Supported Data Types to Set 2D Vector Parameters

Function Name	data_type
`GxfParameterSet2DFloat64Vector(...)`	`double`
`GxfParameterSet2DInt64Vector(...)`	`int64_t`
`GxfParameterSet2DUInt64Vector(...)`	`uint64_t`
`GxfParameterSet2DInt32Vector(...)`	`int32_t`

Get 1-D Vector Parameters

Users can call `gxf_result_t GxfParameterGet1D"DataType"Vector(gxf_context_t context, gxf_uid_t uid, const char* key, data_type** value, uint64_t* length)` to get the value of a 1-D vector.

Before calling this method, users should call `GxfParameterGet1D"DataType"VectorInfo(gxf_context_t context, gxf_uid_t uid, const char* key, uint64_t* length)` to obtain the `length` of the vector parameter and then allocate at least that much memory to retrieve the `value`.

`value` should point to an array of size greater than or equal to `length` allocated by user of the corresponding type to retrieve the data. If the `length` doesn't match the size of stored vector then it will be updated with the expected size.

See the table below for all the supported data types and their corresponding function signatures.

parameter: `key` The name of the parameter.

parameter: `value` The value to set of the parameter.

parameter: `length` The length of the 1-D vector parameter obtained by calling `GxfParameterGet1D"DataType"VectorInfo(...)`.

Table 34.3: Supported Data Types to Get the Value of 1D Vector Parameters

Function Name	data_type
`GxfParameterGet1DFloat64Vector(...)`	`double`
`GxfParameterGet1DInt64Vector(...)`	`int64_t`
`GxfParameterGet1DUInt64Vector(...)`	`uint64_t`
`GxfParameterGet1DInt32Vector(...)`	`int32_t`

Get 2-D Vector Parameters

Users can call `gxf_result_t GxfParameterGet2D"DataType"Vector(gxf_context_t context, gxf_uid_t uid, const char* key, data_type** value, uint64_t* height, uint64_t* width)` to get the value of a -2D vector.

Before calling this method, users should call `GxfParameterGet1D"DataType"VectorInfo(gxf_context_t context, gxf_uid_t uid, const char* key, uint64_t* height, uint64_t* width)` to obtain the `height` and `width` of the 2D-vector parameter and then allocate at least that much memory to retrieve the `value`.

`value` should point to an array of array of height (size of first dimension) greater than or equal to `height` and width (size of the second dimension) greater than or equal to `width` allocated by user of the corresponding type to get the data. If the `height` or `width` don't match the height and width of the stored vector then they will be updated with the expected values.

See the table below for all the supported data types and their corresponding function signatures.

parameter": `key` The name of the parameter.

parameter": `value` Allocated array to get the value of the parameter.

parameter": `height` The height of the 2-D vector parameter obtained by calling `GxfParameterGet2D"DataType"VectorInfo(...)`.

parameter": `width` The width of the 2-D vector parameter obtained by calling `GxfParameterGet2D"DataType"VectorInfo(...)`.

Table 34.4: Supported Data Types to Get the Value of 2D Vector Parameters

Function Name	data_type
`GxfParameterGet2DFloat64Vector(...)`	`double`
`GxfParameterGet2DInt64Vector(...)`	`int64_t`
`GxfParameterGet2DUInt64Vector(...)`	`uint64_t`
`GxfParameterGet2DInt32Vector(...)`	`int32_t`

34.6.8 Information Queries

Get Meta Data about the GXF Runtime

```
gxf_result_t GxfRuntimeInfo(gxf_context_t context, gxf_runtime_info* info);
```

parameter: `context` A valid GXF context.

parameter: `info` pointer to gxf_runtime_info object to get the meta data.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get description and list of components in loaded Extension

```
gxf_result_t GxfExtensionInfo(gxf_context_t context, gxf_tid_t tid, gxf_extension_info_t*
info);
```

parameter: `context` A valid GXF context.

parameter: `tid` The unique identifier of the extension.

parameter: `info` pointer to gxf_extension_info_t object to get the meta data.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get description and list of parameters of Component

```
gxf_result_t GxfComponentInfo(gxf_context_t context, gxf_tid_t tid, gxf_component_info_t*
info);
```

Note: Parameters are only available after at least one instance is created for the Component.

parameter: `context` A valid GXF context.

parameter: `tid` The unique identifier of the component.

parameter: `info` pointer to gxf_component_info_t object to get the meta data.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Get parameter type description

Gets a string describing the parameter type.

`const char* GxfParameterTypeStr(gxf_parameter_type_t param_type);`

parameter: `param_type` Type of parameter to get info about.

returns: C-style string description of the parameter type.

Get flag type description

Gets a string describing the flag type.

`const char* GxfParameterFlagTypeStr(gxf_parameter_flags_t_ flag_type);`

parameter: `flag_type` Type of flag to get info about.

returns: C-style string description of the flag type.

Get parameter description

Gets description of specific parameter. Fails if the component is not instantiated yet.

`gxf_result_t GxfGetParameterInfo(gxf_context_t context, gxf_tid_t cid, const char* key, gxf_parameter_info_t* info);`

parameter: `context` A valid GXF context.

parameter: `cid` The unique identifier of the component.

parameter: `key` The name of the parameter.

parameter: `info` Pointer to a gxf_parameter_info_t object to get the value.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

Redirect logs to a file

Redirect console logs to the provided file.

`gxf_result_t GxfGetParameterInfo(gxf_context_t context, FILE* fp);`

parameter: `context` A valid GXF context.

parameter: `fp` File path for the redirected logs.

returns: GXF_SUCCESS if the operation was successful, or otherwise one of the GXF error codes.

34.6.9 Miscellaneous

Get string description of error

`const char* GxfResultStr(gxf_result_t result);`

Gets a string describing an GXF error code.

The caller does not get ownership of the return C string and must not delete it.

parameter: `result` A GXF error code.

returns: A pointer to a C string with the error code description.

34.7 CudaExtension

Extension for CUDA operations.

- UUID: d63a98fa-7882-11eb-a917-b38f664f399c
- Version: 2.0.0
- Author: NVIDIA
- License: LICENSE

34.7.1 Components

nvidia::gxf::CudaStream

Holds and provides access to native `cudaStream_t`.

`nvidia::gxf::CudaStream` handle must be allocated by `nvidia::gxf::CudaStreamPool`. Its lifecycle is valid until explicitly recycled through `nvidia::gxf::CudaStreamPool.releaseStream()` or implicitly until `nvidia::gxf::CudaStreamPool` is deactivated.

You may call `stream()` to get the native `cudaStream_t` handle, and to submit GPU operations. After the submission, GPU takes over the input tensors/buffers and keeps them in use. To prevent the host carelessly releasing these in-use buffers, CUDA Codelet needs to call `record(event, input_entity, sync_cb)` to extend `input_entity`'s lifecycle until the GPU completely consumes it. Alternatively, you may call `record(event, event_destroy_cb)` for native `cudaEvent_t` operations and free in-use resource via `event_destroy_cb`.

It is required to have a `nvidia::gxf::CudaStreamSync` in the graph pipeline after all the CUDA operations. See more details in `nvidia::gxf::CudaStreamSync`.

- Component ID: 5683d692-7884-11eb-9338-c3be62d576be
- Defined in: gxf/cuda/cuda_stream.hpp

nvidia::gxf::CudaStreamId

Holds CUDA stream Id to deduce `nvidia::gxf::CudaStream` handle.

`stream_cid` should be `nvidia::gxf::CudaStream` component id.

- Component ID: 7982aeac-37f1-41be-ade8-6f00b4b5d47c
- Defined in: gxf/cuda/cuda_stream_id.hpp

nvidia::gxf::CudaEvent

Holds and provides access to native `cudaEvent_t` handle.

When a `nvidia::gxf::CudaEvent` is created, you'll need to initialize a native `cudaEvent_t` through `init(flags, dev_id)`, or set third party event through `initWithEvent(event, dev_id, free_fnc)`. The event keeps valid until `deinit` is called explicitly otherwise gets recycled in destructor.

- Component ID: f5388d5c-a709-47e7-86c4-171779bc64f3
- Defined in: gxf/cuda/cuda_event.hpp

nvidia::gxf::CudaStreamPool

`CudaStream` allocation.

You must explicitly call `allocateStream()` to get a valid `nvidia::gxf::CudaStream` handle. This component would hold all the its allocated `nvidia::gxf::CudaStream` entities until `releaseStream(stream)` is called explicitly or the `CudaStreamPool` component is deactivated.

- Component ID: 6733bf8b-ba5e-4fae-b596-af2d1269d0e7
- Base Type: nvidia::gxf::Allocator

Parameters

dev_id

GPU device id.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32
- Default Value: 0

stream_flags

Flag values to create CUDA streams.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32
- Default Value: 0

stream_priority

Priority values to create CUDA streams.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32

- Default Value: 0

reserved_size

User-specified file name without extension.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32
- Default Value: 1

max_size

Maximum Stream Size.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32
- Default Value: 0, no limitation.

nvidia::gxf::CudaStreamSync

Synchronize all CUDA streams which are carried by message entities.

This codelet is required to get connected in the graph pipeline after all CUDA ops codelets. When a message entity is received, it would find all of the `nvidia::gxf::CudaStreamId` in that message, and extract out each `nvidia::gxf::CudaStream`. With each `CudaStream` handle, it synchronizes all previous `nvidia::gxf::CudaStream.record()` events, along with all submitted GPU operations before this point.

Note: `CudaStreamSync` must be set in the graph when `nvidia::gxf::CudaStream.record()` is used, otherwise it may cause a memory leak.

- Component ID: 0d1d8142-6648-485d-97d5-277eed00129c
- Base Type: nvidia::gxf::Codelet

Parameters

rx

Receiver to receive all messages carrying `nvidia::gxf::CudaStreamId`.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

tx

Transmitter to send messages to downstream.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

34.8 MultimediaExtension

Extension for multimedia related data types, interfaces and components in GXF Core.

- UUID: `6f2d1afc-1057-481a-9da6-a5f61fed178e`
- Version: `2.0.0`
- Author: `NVIDIA`
- License: `LICENSE`

34.8.1 Components

nvidia::gxf::AudioBuffer

AudioBuffer is similar to Tensor component in the standard extension and holds memory and metadata corresponding to an audio buffer.

- Component ID: `a914cac6-5f19-449d-9ade-8c5cdcebe7c3`

`AudioBufferInfo` structure captures the following metadata:

Field	Description
channels	Number of channels in an audio frame
samples	Number of samples in an audio frame
sampling_rate	sampling rate in Hz
bytes_per_sample	Number of bytes required per sample
audio_format	AudioFormat of an audio frame
audio_layout	AudioLayout of an audio frame

Supported `AudioFormat` types:

AudioFormat	Description
GXF_AUDIO_FORMAT_S16LE	16-bit signed PCM audio
GXF_AUDIO_FORMAT_F32LE	32-bit floating-point audio

Supported `AudioLayout` types:

AudioLayout	Description
GXF_AUDIO_LAYOUT_INTERLEAVED	Data from all the channels to be interleaved - LRLRLR
GXF_AUDIO_LAYOUT_NON_INTERLEAVED	Data from all the channels not to be interleaved - LLLRRR

nvidia::gxf::VideoBuffer

VideoBuffer is similar to Tensor component in the standard extension and holds memory and metadata corresponding to a video buffer.

- Component ID: `16ad58c8-b463-422c-b097-61a9acc5050e`

`VideoBufferInfo` structure captures the following metadata:

Field	Description
width	width of a video frame
height	height of a video frame
color_format	VideoFormat of a video frame
color_planes	ColorPlane(s) associated with the VideoFormat
surface_layout	SurfaceLayout of the video frame

Supported VideoFormat types:

VideoFormat	Description
GXF_VIDEO_FORMAT_YUV420	BT.601 multi planar 4:2:0 YUV
GXF_VIDEO_FORMAT_YUV420_ER	BT.601 multi planar 4:2:0 YUV ER
GXF_VIDEO_FORMAT_YUV420_709	BT.709 multi planar 4:2:0 YUV
GXF_VIDEO_FORMAT_YUV420_709_ER	BT.709 multi planar 4:2:0 YUV ER
GXF_VIDEO_FORMAT_NV12	BT.601 multi planar 4:2:0 YUV with interleaved UV
GXF_VIDEO_FORMAT_NV12_ER	BT.601 multi planar 4:2:0 YUV ER with interleaved UV
GXF_VIDEO_FORMAT_NV12_709	BT.709 multi planar 4:2:0 YUV with interleaved UV
GXF_VIDEO_FORMAT_NV12_709_ER	BT.709 multi planar 4:2:0 YUV ER with interleaved UV
GXF_VIDEO_FORMAT_RGBA	RGBA-8-8-8-8 single plane
GXF_VIDEO_FORMAT_BGRA	BGRA-8-8-8-8 single plane
GXF_VIDEO_FORMAT_ARGB	ARGB-8-8-8-8 single plane
GXF_VIDEO_FORMAT_ABGR	ABGR-8-8-8-8 single plane
GXF_VIDEO_FORMAT_RGBX	RGBX-8-8-8-8 single plane
GXF_VIDEO_FORMAT_BGRX	BGRX-8-8-8-8 single plane
GXF_VIDEO_FORMAT_XRGB	XRGB-8-8-8-8 single plane
GXF_VIDEO_FORMAT_XBGR	XBGR-8-8-8-8 single plane
GXF_VIDEO_FORMAT_RGB	RGB-8-8-8 single plane
GXF_VIDEO_FORMAT_BGR	BGR-8-8-8 single plane
GXF_VIDEO_FORMAT_R8_G8_B8	RGB - unsigned 8 bit multiplanar
GXF_VIDEO_FORMAT_B8_G8_R8	BGR - unsigned 8 bit multiplanar
GXF_VIDEO_FORMAT_GRAY	8 bit GRAY scale single plane

Supported SurfaceLayout types:

SurfaceLayout	Description
GXF_SURFACE_LAYOUT_PITCH_LINEAR	pitch linear surface memory
GXF_SURFACE_LAYOUT_BLOCK_LINEAR	block linear surface memory

34.9 NetworkExtension

Extension for communications external to a computation graph.

- UUID: `f50665e5-ade2-f71b-de2a-2380614b1725`
- Version: `1.0.0`
- Author: `NVIDIA`
- License: `LICENSE`

34.9.1 Interfaces

34.9.2 Components

nvidia::gxf::TcpClient

Codelet that functions as a client in a TCP connection.

- Component ID: `9d5955c7-8fda-22c7-f18f-ea5e2d195be9`
- Base Type: `nvidia::gxf::Codelet`

Parameters

receivers

List of receivers to receive entities from.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::Receiver>>`

transmitters

List of transmitters to publish entities to.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::Transmitter>>`

serializers

List of component serializers to serialize and de-serialize entities.

- Flags: `GXF_PARAMETER_FLAGS_NONE`

- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::ComponentSerializer>>`

address

Address of TCP server.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_STRING`

port

Port of TCP server.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_INT32`

timeout_ms

Time in milliseconds to wait before retrying connection to TCP server.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_UINT64`

maximum_attempts

Maximum number of attempts for I/O operations before failing.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_UINT64`

nvidia::gxf::TcpServer

Codelet that functions as a server in a TCP connection.

- Component ID: `a3e0e42d-e32e-73ab-ef83-fbb311310759`
- Base Type: `nvidia::gxf::Codelet`

Parameters

receivers

List of receivers to receive entities from.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::Receiver>>`

transmitters

List of transmitters to publish entities to.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::Transmitter>>`

serializers

List of component serializers to serialize and de-serialize entities.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::ComponentSerializer>>`

address

Address of TCP server.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_STRING`

port

Port of TCP server.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_INT32`

timeout_ms

Time in milliseconds to wait before retrying connection to TCP client.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_UINT64`

maximum_attempts

Maximum number of attempts for I/O operations before failing.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_UINT64`

34.10 SerializationExtension

Extension for serializing messages.

- UUID: `bc573c2f-89b3-d4b0-8061-2da8b11fe79a`
- Version: `2.0.0`
- Author: `NVIDIA`
- License: `LICENSE`

34.10.1 Interfaces

nvidia::gxf::ComponentSerializer

Interface for serializing components.

- Component ID: `8c76a828-2177-1484-f841-d39c3fa47613`
- Base Type: `nvidia::gxf::Component`
- Defined in: `gxf/serialization/component_serializer.hpp`

34.10.2 Components

nvidia::gxf::EntityRecorder

Serializes incoming messages and writes them to a file.

- Component ID: `9d5955c7-8fda-22c7-f18f-ea5e2d195be9`
- Base Type: `nvidia::gxf::Codelet`

Parameters

receiver

Receiver channel to log.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_HANDLE`
- Handle Type: `nvidia::gxf::Receiver`

serializers

List of component serializers to serialize entities.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::ComponentSerializer>>`

directory

Directory path for storing files.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_STRING`

basename

User specified file name without extension.

- Flags: `GXF_PARAMETER_FLAGS_OPTIONAL`
- Type: `GXF_PARAMETER_TYPE_STRING`

flush_on_tick

Flushes output buffer on every tick when true.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_BOOL`

nvidia::gxf::EntityReplayer

De-serializes and publishes messages from a file.

- Component ID: `fe827c12-d360-c63c-8094-32b9244d83b6`
- Base Type: `nvidia::gxf::Codelet`

Parameters

transmitter

Transmitter channel for replaying entities.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_HANDLE`
- Handle Type: `nvidia::gxf::Transmitter`

serializers

List of component serializers to serialize entities.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_CUSTOM`
- Custom Type: `std::vector<nvidia::gxf::Handle<nvidia::gxf::ComponentSerializer>>`

directory

Directory path for storing files.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_STRING`

batch_size

Number of entities to read and publish for one tick.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_UINT64`

ignore_corrupted_entities

If an entity could not be de-serialized, it is ignored by default; otherwise a failure is generated.

- Flags: `GXF_PARAMETER_FLAGS_NONE`
- Type: `GXF_PARAMETER_TYPE_BOOL`

nvidia::gxf::StdComponentSerializer

Serializer for Timestamp and Tensor components.

- Component ID: `c0e6b36c-39ac-50ac-ce8d-702e18d8bff7`
- Base Type: `nvidia::gxf::ComponentSerializer`

Parameters

allocator

Memory allocator for tensor components.

- Flags: `GXF_PARAMETER_FLAGS_OPTIONAL`
- Type: `GXF_PARAMETER_TYPE_HANDLE`
- Handle Type: `nvidia::gxf::Allocator`

34.11 StandardExtension

Most commonly used interfaces and components in Gxf Core.

- UUID: 8ec2d5d6-b5df-48bf-8dee-0252606fdd7e
- Version: 2.1.0
- Author: NVIDIA
- License: LICENSE

34.11.1 Interfaces

nvidia::gxf::Codelet

Interface for a component which can be executed to run custom code.

- Component ID: 5c6166fa-6eed-41e7-bbf0-bd48cd6e1014
- Base Type: nvidia::gxf::Component
- Defined in: gxf/std/codelet.hpp

nvidia::gxf::Clock

Interface for clock components which provide time.

- Component ID: 779e61c2-ae70-441d-a26c-8ca64b39f8e7
- Base Type: nvidia::gxf::Component
- Defined in: gxf/std/clock.hpp

nvidia::gxf::System

Component interface for systems which are run as part of the application run cycle.

- Component ID: d1febca1-80df-454e-a3f2-715f2b3c6e69
- Base Type: nvidia::gxf::Component

nvidia::gxf::Queue

Interface for storing entities in a queue.

- Component ID: 792151bf-3138-4603-a912-5ca91828dea8
- Base Type: nvidia::gxf::Component
- Defined in: gxf/std/queue.hpp

nvidia::gxf::Router

Interface for classes which are routing messages in and out of entities.

- Component ID: 8b317aad-f55c-4c07-8520-8f66db92a19e
- Defined in: gxf/std/router.hpp

nvidia::gxf::Transmitter

Interface for publishing entities.

- Component ID: c30cc60f-0db2-409d-92b6-b2db92e02cce
- Base Type: nvidia::gxf::Queue
- Defined in: gxf/std/transmitter.hpp

nvidia::gxf::Receiver

Interface for receiving entities.

- Component ID: a47d2f62-245f-40fc-90b7-5dc78ff2437e
- Base Type: nvidia::gxf::Queue
- Defined in: gxf/std/receiver.hpp

nvidia::gxf::Scheduler

A simple poll-based single-threaded scheduler which executes codelets.

- Component ID: f0103b75-d2e1-4d70-9b13-3fe5b40209be
- Base Type: nvidia::gxf::System
- Defined in: nvidia/gxf/system.hpp

nvidia::gxf::SchedulingTerm

Interface for terms used by a scheduler to determine if codelets in an entity are ready to step.

- Component ID: 184d8e4e-086c-475a-903a-69d723f95d19
- Base Type: nvidia::gxf::Component
- Defined in: gxf/std/scheduling_term.hpp

nvidia::gxf::Allocator

Provides allocation and deallocation of memory.

- Component ID: 3cdd82d0-2326-4867-8de2-d565dbe28e03
- Base Type: nvidia::gxf::Component
- Defined in: nvidia/gxf/allocator.hpp

nvidia::gxf::Monitor

Monitors entities during execution.

- Component ID: 9ccf9421-b35b-8c79-e1f0-97dc23bd38ea
- Base Type: nvidia::gxf::Component
- Defined in: nvidia/gxf/monitor.hpp

34.11.2 Components

nvidia::gxf::RealtimeClock

A real-time clock which runs based off a system steady clock.

- Component ID: 7b170b7b-cf1a-4f3f-997c-bfea25342381
- Base Type: nvidia::gxf::Clock

Parameters

initial_time_offset

The initial time offset used, until the time scale is changed manually.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_FLOAT64

initial_time_scale

The initial time scale used, until the time scale is changed manually.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_FLOAT64

use_time_since_epoch

If true, clock time is time since `epoch + initial_time_offset` at `initialize()`. Otherwise, clock time is `initial_time_offset` at `initialize()`.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL

nvidia::gxf::ManualClock

A manual clock which is instrumented manually.

- Component ID: 52fa1f97-eba8-472a-a8ca-4cff1a2c440f
- Base Type: nvidia::gxf::Clock

Parameters

initial_timestamp

The initial timestamp on the clock (in nanoseconds).

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

nvidia::gxf::SystemGroup

A group of systems.

- Component ID: 3d23d470-0aed-41c6-ac92-685c1b5469a0
- Base Type: nvidia::gxf::System

nvidia::gxf::MessageRouter

A router which sends transmitted messages to receivers.

- Component ID: 84fd5d56-fda6-4937-0b3c-c283252553d8
- Base Type: nvidia::gxf::Router

nvidia::gxf::RouterGroup

A group of routers.

- Component ID: ca64ee14-2280-4099-9f10-d4b501e09117
- Base Type: nvidia::gxf::Router

nvidia::gxf::DoubleBufferTransmitter

A transmitter which uses a double-buffered queue where messages are pushed to a backstage after they are published.

- Component ID: 0c3c0ec7-77f1-4389-aef1-6bae85bddc13
- Base Type: nvidia::gxf::Transmitter

Parameters

capacity

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64
- Default: 1

policy

0: pop, 1: reject, 2: fault.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64
- Default: 2

nvidia::gxf::DoubleBufferReceiver

A receiver which uses a double-buffered queue where new messages are first pushed to a backstage.

- Component ID: ee45883d-bf84-4f99-8419-7c5e9deac6a5
- Base Type: nvidia::gxf::Receiver

Parameters

capacity

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64
- Default: 1

policy

0: pop, 1: reject, 2: fault

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64
- Default: 2

nvidia::gxf::Connection

A component which establishes a connection between two other components.

- Component ID: cc71afae-5ede-47e9-b267-60a5c750a89a
- Base Type: nvidia::gxf::Component

Parameters

source

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

target

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::PeriodicSchedulingTerm

A component which specifies that an entity shall be executed periodically.

- Component ID: d392c98a-9b08-49b4-a422-d5fe6cd72e3e
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

recess_period

The recess period indicates the minimum amount of time which has to pass before the entity is permitted to execute again. The period is specified as a string containing of a number and an (optional) unit. If no unit is given, the value is assumed to be in nanoseconds. Supported units are: Hz, s, ms. Example: 10ms, 10000000, 0.2s, 50Hz.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_STRING

nvidia::gxf::CountSchedulingTerm

A component which specifies that an entity shall be executed exactly a given number of times.

- Component ID: f89da2e4-fddf-4aa2-9a80-1119ba3fde05
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

count

The total number of time this term will permit execution.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

nvidia::gxf::TargetTimeSchedulingTerm

A component where the next execution time of the entity needs to be specified after every tick.

- Component ID: e4aaf5c3-2b10-4c9a-c463-ebf6084149bf
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

clock

The clock used to define target time.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

nvidia::gxf::DownstreamReceptiveSchedulingTerm

A component which specifies that an entity shall be executed if receivers for a certain transmitter can accept new messages.

- Component ID: 9de75119-8d0f-4819-9a71-2aeaefd23f71
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

min_size

The term permits execution if the receiver connected to the transmitter has at least the specified number of free slots in its back buffer.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

transmitter

The term permits execution if this transmitter can publish a message; i.e., if the receiver which is connected to this transmitter can receive messages.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

nvidia::gxf::MessageAvailableSchedulingTerm

A scheduling term which specifies that an entity can be executed when the total number of messages over a set of input channels is at least a given number of messages.

- Component ID: fe799e65-f78b-48eb-beb6-e73083a12d5b
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

front_stage_max_size

If set, the scheduling term will only allow execution if the number of messages in the front stage does not exceed this count. For example, it can be used in combination with codelets which do not clear the front stage in every tick.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_UINT64

min_size

The scheduling term permits execution if the given receiver has at least the given number of messages available.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

receiver

The scheduling term permits execution if this channel has at least a given number of messages available.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::MultiMessageAvailableSchedulingTerm

A component which specifies that an entity shall be executed when a queue has at least a certain number of elements.

- Component ID: f15dbeaa-afd6-47a6-9ffc-7afd7e1b4c52
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

min_size

The scheduling term permits execution if all given receivers together have at least the given number of messages available.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

receivers

The scheduling term permits execution if the given channels have at least a given number of messages available.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::ExpiringMessageAvailableSchedulingTerm

A component which tries to wait for specified number of messages in queue for at most specified time.

- Component ID: eb22280c-76ff-11eb-b341-cf6b417c95c9
- Base Type: nvidia::gxf::SchedulingTerm

Parameters

clock

Clock to get time from.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

max_batch_size

The maximum number of messages to be batched together.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

max_delay_ns

The maximum delay from first message to wait before submitting workload anyway.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

receiver

Receiver to watch on.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::BooleanSchedulingTerm

A component which acts as a Boolean `AND` term that can be used to control the execution of the entity.

- Component ID: e07a0dc4-3908-4df8-8134-7ce38e60fbef
- Base Type: nvidia::gxf::SchedulingTerm

nvidia::gxf::AsynchronousSchedulingTerm

A component which is used to inform that an entity is dependent upon an async event for its execution.

- Component ID: 56be1662-ff63-4179-9200-3fcd8dc38673
- Base Type: nvidia::gxf::SchedulingTerm

nvidia::gxf::GreedyScheduler

A simple poll-based single-threaded scheduler which executes codelets.

- Component ID: 869d30ca-a443-4619-b988-7a52e657f39b
- Base Type: nvidia::gxf::Scheduler

Parameters

clock

The clock used by the scheduler to define flow of time. Typical choices are a `RealtimeClock` or a `ManualClock`.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

max_duration_ms

The maximum duration for which the scheduler will execute (in ms). If not specified the scheduler will run until all work is done. If periodic terms are present, this means the application will run indefinitely.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_INT64

realtime

This parameter is deprecated. Assign a clock directly.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL

- Type: GXF_PARAMETER_TYPE_BOOL

stop_on_deadlock

If enabled, the scheduler will stop when all entities are in a waiting state, but no periodic entity exists to break the dead end. Should be disabled when scheduling conditions can be changed by external actors; for example, by clearing queues manually.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL

nvidia::gxf::MultiThreadScheduler

A multi-thread scheduler that executes codelets for maximum throughput.

- Component ID: de5e0646-7fa5-11eb-a5c4-330ebfa81bbf
- Base Type: nvidia::gxf::Scheduler

Parameters

check_recession_perios_ms

The maximum duration for which the scheduler would wait (in ms) when an entity is not ready to run yet.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

clock

The clock used by the scheduler to define flow of time. Typical choices are a `RealtimeClock` or a `ManualClock`.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

max_duration_ms

The maximum duration for which the scheduler will execute (in ms). If not specified, the scheduler will run until all work is done. If periodic terms are present, this means the application will run indefinitely.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_INT64

stop_on_deadlock

If enabled, the scheduler will stop when all entities are in a waiting state, but no periodic entity exists to break the dead end. Should be disabled when scheduling conditions can be changed by external actors; for example, by clearing queues manually.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL

worker_thread_number

Number of threads.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64
- Default: 1

nvidia::gxf::BlockMemoryPool

A memory pool which provides a maximum number of equally sized blocks of memory.

- Component ID: 92b627a3-5dd3-4c3c-976c-4700e8a3b96a
- Base Type: nvidia::gxf::Allocator

Parameters

block_size

The size of one block of memory in byte. Allocation requests can only be fulfilled if they fit into one block. If less memory is requested, a full block is still issued.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

do_not_use_cuda_malloc_host

If enabled operator new will be used to allocate host memory instead of `cudaMallocHost`.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL
- Default: True

num_blocks

The total number of blocks which are allocated by the pool. If more blocks are requested, allocation requests will fail.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

storage_type

The memory storage type used by this allocator. Can be kHost (0) or kDevice (1) or kSystem (2).

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32
- Default: 0

nvidia::gxf::UnboundedAllocator

Allocator that uses dynamic memory allocation without an upper bound.

- Component ID: c3951b16-a01c-539f-d87e-1dc18d911ea0
- Base Type: nvidia::gxf::Allocator

Parameters

do_not_use_cuda_malloc_host

If enabled, a new operator will be used to allocate host memory instead of `cudaMallocHost`.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL
- Default: True

nvidia::gxf::Tensor

A component which holds a single tensor.

- Component ID: 377501d6-9abf-447c-a617-0114d4f33ab8
- Defined in: gxf/std/tensor.hpp

nvidia::gxf::Timestamp

Holds message publishing and acquisition related timing information.

- Component ID: d1095b10-5c90-4bbc-bc89-601134cb4e03
- Defined in: gxf/std/timestamp.hpp

nvidia::gxf::Metric

Collects, aggregates, and evaluates metric data.

- Component ID: f7cef803-5beb-46f1-186a-05d3919842ac
- Base Type: nvidia::gxf::Component

Parameters

aggregation_policy

Aggregation policy used to aggregate individual metric samples. Choices: {mean, min, max}.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_STRING

lower_threshold

Lower threshold of the metric's expected range.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_FLOAT64

upper_threshold

Upper threshold of the metric's expected range.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_FLOAT64

nvidia::gxf::JobStatistics

Collects runtime statistics.

- Component ID: 2093b91a-7c82-11eb-a92b-3f1304ecc959
- Base Type: nvidia::gxf::Component

Parameters

clock

The clock component instance to retrieve time from.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

codelet_statistics

If set to true, the `JobStatistics` component will collect performance statistics related to codelets.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_BOOL

json_file_path

If provided, all the collected performance statistics data will be dumped into a json file.

- Flags: GXF_PARAMETER_FLAGS_OPTIONAL
- Type: GXF_PARAMETER_TYPE_STRING

nvidia::gxf::Broadcast

Messages arrived on the input channel are distributed to all transmitters.

- Component ID: 3daadb31-0bca-47e5-9924-342b9984a014
- Base Type: nvidia::gxf::Codelet

Parameters

mode

The broadcast mode. Can be Broadcast or RoundRobin.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_CUSTOM

source

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::Gather

All messages arriving on any input channel are published on the single output channel.

- Component ID: 85f64c84-8236-4035-9b9a-3843a6a2026f
- Base Type: nvidia::gxf::Codelet

Parameters

sink

The output channel for gathered messages.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

tick_source_limit

Maximum number of messages to take from each source in one tick. `0` means no limit.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT64

nvidia::gxf::TensorCopier

Copies tensor either from host to device or from device to host.

- Component ID: c07680f4-75b3-189b-8886-4b5e448e7bb6
- Base Type: nvidia::gxf::Codelet

Parameters

allocator

Memory allocator for tensor data.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Allocator

mode

Configuration to select what tensors to copy:

1. kCopyToDevice (0) - copies to device memory, ignores device allocation.
2. kCopyToHost (1) - copies to pinned host memory, ignores host allocation.
3. kCopyToSystem (2) - copies to system memory, ignores system allocation.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_INT32

receiver

Receiver for incoming entities.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

transmitter

Transmitter for outgoing entities.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

nvidia::gxf::TimedThrottler

Publishes the received entity respecting the timestamp within the entity.

- Component ID: ccf7729c-f62c-4250-5cf7-f4f3ec80454b
- Base Type: nvidia::gxf::Codelet

Parameters

execution_clock

Clock on which the codelet is executed by the scheduler.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

receiver

Channel to receive messages that need to be synchronized.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

scheduling_term

Scheduling term for executing the codelet.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::TargetTimeSchedulingTerm

throttling_clock

Clock which the received entity timestamps are based on.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Clock

transmitter

Transmitter channel publishing messages at appropriate timesteps.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

nvidia::gxf::Vault

Safely stores received entities for further processing.

- Component ID: 1108cb8d-85e4-4303-ba02-d27406ee9e65
- Base Type: nvidia::gxf::Codelet

Parameters

drop_waiting

If too many messages are waiting, the oldest ones are dropped.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_BOOL

max_waiting_count

The maximum number of waiting messages. If exceeded, the codelet will stop pulling messages out of the input queue.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_UINT64

source

Receiver from which messages are taken and transferred to the vault.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

nvidia::gxf::Subgraph

Helper component to import a subgraph.

- Component ID: 576eedd7-7c3f-4d2f-8c38-8baa79a3d231
- Base Type: nvidia::gxf::Component

Parameters

location

`Yaml` source of the subgraph.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_STRING

nvidia::gxf::EndOfStream

A component which represents end-of-stream notification.

- Component ID: 8c42f7bf-7041-4626-9792-9eb20ce33cce
- Defined in: gxf/std/eos.hpp

nvidia::gxf::Synchronization

Component to synchronize messages from multiple receivers based on the `acq_time`.

- Component ID: f1cb80d6-e5ec-4dba-9f9e-b06b0def4443
- Base Type: nvidia::gxf::Codelet

Parameters

inputs

All the inputs for synchronization. Number of inputs must match that of the outputs.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Receiver

outputs

All the outputs for synchronization. Number of outputs must match that of the inputs.

- Flags: GXF_PARAMETER_FLAGS_NONE
- Type: GXF_PARAMETER_TYPE_HANDLE
- Handle Type: nvidia::gxf::Transmitter

signed char

- Component ID: 83905c6a-ca34-4f40-b474-cf2cde8274de

unsigned char

- Component ID: d4299e15-0006-d0bf-8cbd-9b743575e155

short int

- Component ID: 9e1dde79-3550-307d-e81a-b864890b3685

short unsigned int

- Component ID: 958cbdef-b505-bcc7-8a43-dc4b23f8cead

int

- Component ID: b557ec7f-49a5-08f7-a35e-086e9d1ea767

unsigned int

- Component ID: d5506b68-5c86-fedb-a2a2-a7bae38ff3ef

long int

- Component ID: c611627b-6393-365f-d234-1f26bfa8d28f

long unsigned int

- Component ID: c4385f5b-6e25-01d9-d7b5-6e7cadc704e8

float

- Component ID: a81bf295-421f-49ef-f24a-f59e9ea0d5d6

double

- Component ID: d57cee59-686f-e26d-95be-659c126b02ea

bool

- Component ID: c02f9e93-d01b-1d29-f523-78d2a9195128

CHAPTER

THIRTYFIVE

DATA FLOW TRACKING

The Holoscan SDK provides the Data Flow Tracking APIs as a mechanism to profile your application and analyze the fine-grained timing properties and data flow between operators in the graph of a fragment.

Currently, data flow tracking is only supported between the root operators and leaf operators of a graph and in simple cycles in a graph (support for tracking data flow between any pair of operators in a graph is planned for the future).

- A *root operator* is an operator without any predecessor nodes.
- A *leaf operator* (also known as a *sink operator*) is an operator without any successor nodes.

When data flow tracking is enabled, every message is tracked from the root operators to the leaf operators and in cycles. Then, the maximum (worst-case), average, and minimum end-to-end latencies of one or more paths can be retrieved using the Data Flow Tracking APIs.

Tip:

- The end-to-end latency between a root operator and a leaf operator is the time taken between the start of a root operator and the end of a leaf operator. Data Flow Tracking enables the support to track the end-to-end latency of every message being passed between a root operator and a leaf operator.
- The reported end-to-end latency for a cyclic path is the time taken between the start of the first operator of a cycle and the time when a message is again received by the first operator of the cycle.

The API also provides the ability to retrieve the number of messages sent from the root operators.

Tip:

- The Data Flow Tracking feature is also illustrated in the flow_tracker
- Look at the `C++` and `python` API documentation for exhaustive definitions

35.1 Enabling Data Flow Tracking

Before an application (`C++`/`python`) is run with the `run()` method, data flow tracking can be enabled. For single fragment applications, this can be done by calling the `track()` method in `C++` and using the `Tracker` class in `python`.

C++

```
auto app = holoscan::make_application<MyPingApp>();
auto& tracker = app->track(); // Enable Data Flow Tracking
// Change tracker and application configurations
...
app->run();
```

Python

```
from holoscan.core import Tracker
...
app = MyPingApp()
with Tracker(app) as tracker:
  # Change tracker and application configurations
  ...
  app.run()
```

35.2 Enabling Data Flow Tracking for Distributed Applications

For distributed (multi-fragment) applications, a separate tracker object is used for each Fragment so the API is slightly different than in the single fragment case.

C++

```
auto app = holoscan::make_application<MyPingApp>();
auto trackers = app->track_distributed(); // Enable data flow tracking for a distributed␣
↪app
// Change tracker and application configurations
...
app->run();
```

Note that instead of a returning a single `DataFlowTracker*` like `track`, the `track_distributed` method returns a `std::unordered_map<std::string, DataFlowTracker*>` where the keys are the names of the fragments.

Python

```
with Tracker(app) as trackers:
    app.run()
```

The `Tracker` context manager detects whether the app is distributed and returns a `dict[str, DataFlowTracker]` as `trackers` in the distributed case. For a single fragment application, the returned value is just a single `DataFlowTracker` object.

35.3 Retrieving Data Flow Tracking Results

After an application has been run, data flow tracking results can be accessed by various methods on the DataFlowTracker (C++/python) class.

1. `print()` (C++/python)
   - Prints all data flow tracking results including end-to-end latencies and the number of source messages to the standard output.
2. `get_num_paths()` (C++/python)
   - Returns the number of paths between the root operators and the leaf operators.
3. `get_path_strings()` (C++/python)
   - Returns a vector of strings, where each string represents a path between the root operators and the leaf operators. A path is a comma-separated list of operator names.
4. `get_metric()` (C++/python)
   - Returns the value of different metrics based on the arguments.
   - `get_metric(std::string pathstring, holoscan::DataFlowMetric metric)` returns the value of a metric `metric` for a path `pathstring`. The metric can be one of the following:
     - `holoscan::DataFlowMetric::kMaxE2ELatency` (python): the maximum end-to-end latency in the path.
     - `holoscan::DataFlowMetric::kAvgE2ELatency` (python): the average end-to-end latency in the path.
     - `holoscan::DataFlowMetric::kMinE2ELatency` (python): the minimum end-to-end latency in the path.
     - `holoscan::DataFlowMetric::kMaxMessageID` (python): the message number or ID which resulted in the maximum end-to-end latency.
     - `holoscan::DataFlowMetric::kMinMessageID` (python): the message number or ID which resulted in the minimum end-to-end latency.
   - `get_metric(holoscan::DataFlowMetric metric = DataFlowMetric::kNumSrcMessages)` returns a map of source operator and its edge, and the number of messages sent from the source operator to the edge.

In the above example, the data flow tracking results can be printed to the standard output like the following:

C++

```
auto app = holoscan::make_application<MyPingApp>();
auto& tracker = app->track(); // Enable Data Flow Tracking
// Change application configurations
...
app->run();
tracker.print();
```

Python

```python
from holoscan.core import Tracker
...
app = MyPingApp()
with Tracker(app) as trackers:
  # Change tracker and application configurations
  ...
  app.run()
  tracker.print()
```

If this was a distributed application, there would instead be a separate `DataFlowTracker` for each fragment. The overall flow tracking results for all fragments can be printed as in the following:

C++

```cpp
auto app = holoscan::make_application<MyPingApp>();
auto trackers = app->track_distributed(); // Enable data flow tracking for a distributed␣
↪app
// Change application configurations
...
app->run();
// print the data flow tracking results
for (const auto& [name, tracker] : trackers) {
  std::cout << "Fragment: " << name << std::endl;
  tracker->print();
}
```

Python

```python
from holoscan.core import Tracker
...
app = MyPingApp()
with Tracker(app) as trackers:
  # Change tracker and application configurations
  ...
  app.run()
  # print the data flow tracking results
  for fragment_name, tracker in trackers.items():
      print(f"Fragment: {fragment_name}")
      tracker.print()
```

35.4 Customizing Data Flow Tracking

Data flow tracking can be customized using a few optional configuration parameters. The `track()` method (`C++`/`/Python`) (or `track_distributed` method (`C++`/`Python`)` for distributed apps) can be configured to skip a few messages at the beginning of an application's execution as a *warm-up* period. It is also possible to discard a few messages at the end of an application's run as a *wrap-up* period. Additionally, outlier end-to-end latencies can be ignored by setting a latency threshold value (in ms) which is the minimum latency below which the observed latencies are ignored. Finally, it is possible to limit the timestamping of messages at all nodes except the root and leaf operators, so that the overhead of timestamping and sending timestamped messages are reduced. In this way, end-to-end latencies are still calculated, but pathwise fine-grained data are not stored for unique pairs of root and leaf operators.

For Python, it is recommended to use the `Tracker` context manager class instead of the `track` or `track_distributed` methods. This class will autodetect if the application is a single fragment or distributed app, using the appropriate method for each.

Tip: For effective benchmarking, it is common practice to include warm-up and cool-down periods by skipping the initial and final messages.

C++

Listing 35.1: Optional parameters to `track()`

```
Fragment::track(uint64_t num_start_messages_to_skip = kDefaultNumStartMessagesToSkip,
                         uint64_t num_last_messages_to_discard =␣
↪kDefaultNumLastMessagesToDiscard,
                         int latency_threshold = kDefaultLatencyThreshold,
                         bool is_limited_tracking = false);
```

Python

Listing 35.2: Optional parameters to `Tracker`

```
Tracker(num_start_messages_to_skip=num_start_messages_to_skip,
        num_last_messages_to_discard=num_last_messages_to_discard,
        latency_threshold=latency_threshold,
        is_limited_tracking=False)
```

The default values of these parameters of `track()` are as follows:

- `kDefaultNumStartMessagesToSkip`: 10
- `kDefaultNumLastMessagesToDiscard`: 10
- `kDefaultLatencyThreshold`: 0 (do not filter out any latency values)
- `is_limited_tracking`: false

These parameters can also be configured using the helper functions: `set_skip_starting_messages`, `set_discard_last_messages`, `set_skip_latencies`, and `set_limited_tracking`,

35.5 Logging

The Data Flow Tracking API provides the ability to log every message's graph-traversal information to a file. This enables you to analyze the data flow at a granular level. When logging is enabled, every message's received and sent timestamps at every operator between the root and the leaf operators are logged after a message has been processed at the leaf operator.

The logging is enabled by calling the `enable_logging` method in C++ and by providing the `filename` parameter to `Tracker` in python.

C++

```cpp
auto app = holoscan::make_application<MyPingApp>();
auto& tracker = app->track(); // Enable Data Flow Tracking
tracker.enable_logging("logging_file_name.log");
...
app->run();
```

Python

```python
from holoscan.core import Tracker
...
app = MyPingApp()
with Tracker(app, filename="logger.log") as tracker:
    ...
    app.run()
```

The logger file logs the paths of the messages after a leaf operator has finished its `compute` method. Every path in the logfile includes an array of tuples of the form:

> "(root operator name, message receive timestamp, message publish timestamp) -> ... -> (leaf operator name, message receive timestamp, message publish timestamp)".

This log file can further be analyzed to understand latency distributions, bottlenecks, data flow, and other characteristics of an application.

35.6 Configuring Clock Synchronization in Multiple Machines for Distributed Application Flow Tracking

For flow tracking in distributed applications that span multiple machines, system administrators must ensure that the clocks of all machines are synchronized. It is up to the administrator's preference on how to synchronize the clocks. Linux PTP is a popular and commonly used mechanism for clock synchronization.

Install the `linuxptp` package on all machines:

```
git clone http://git.code.sf.net/p/linuxptp/code linuxptp
cd linuxptp/
make
sudo make install
```

Tip: The Ubuntu `linuxptp` package can also be used. However, the above repository provides access to different PTP configurations.

35.6.1 Check PTP Hardware Timestamping Support

Check if your machine and network interface card supports PTP hardware timestamping:

```
$ sudo apt-get update && sudo apt-get install ethtool
$ ethtool -T <interface_name>
```

If the output of the above command is like the one provided below, it means PTP hardware timestamping may be supported:

```
$ ethtool -T eno1
Time stamping parameters for eno1:
Capabilities:
        hardware-transmit     (SOF_TIMESTAMPING_TX_HARDWARE)
        software-transmit     (SOF_TIMESTAMPING_TX_SOFTWARE)
        hardware-receive      (SOF_TIMESTAMPING_RX_HARDWARE)
        software-receive      (SOF_TIMESTAMPING_RX_SOFTWARE)
        software-system-clock (SOF_TIMESTAMPING_SOFTWARE)
        hardware-raw-clock    (SOF_TIMESTAMPING_RAW_HARDWARE)
PTP Hardware Clock: 0
Hardware Transmit Timestamp Modes:
        off                   (HWTSTAMP_TX_OFF)
        on                    (HWTSTAMP_TX_ON)
Hardware Receive Filter Modes:
        none                  (HWTSTAMP_FILTER_NONE)
        all                   (HWTSTAMP_FILTER_ALL)
        ptpv1-l4-sync         (HWTSTAMP_FILTER_PTP_V1_L4_SYNC)
        ptpv1-l4-delay-req    (HWTSTAMP_FILTER_PTP_V1_L4_DELAY_REQ)
        ptpv2-l4-sync         (HWTSTAMP_FILTER_PTP_V2_L4_SYNC)
        ptpv2-l4-delay-req    (HWTSTAMP_FILTER_PTP_V2_L4_DELAY_REQ)
        ptpv2-l2-sync         (HWTSTAMP_FILTER_PTP_V2_L2_SYNC)
        ptpv2-l2-delay-req    (HWTSTAMP_FILTER_PTP_V2_L2_DELAY_REQ)
        ptpv2-event           (HWTSTAMP_FILTER_PTP_V2_EVENT)
        ptpv2-sync            (HWTSTAMP_FILTER_PTP_V2_SYNC)
        ptpv2-delay-req       (HWTSTAMP_FILTER_PTP_V2_DELAY_REQ)
```

However, if the output is the one provided below, it means PTP hardware timestamping is not supported:

```
$ ethtool -T eno1
$ ethtool -T eno1
Time stamping parameters for eno1:
Capabilities:
        software-transmit
        software-receive
        software-system-clock
PTP Hardware Clock: none
Hardware Transmit Timestamp Modes: none
Hardware Receive Filter Modes: none
```

35.6.2 Without PTP Hardware Timestamping Support

Even if PTP hardware timestamping is not supported, it is possible to synchronize the clocks of different machines using software-based clock synchronization. Here, we show an example of how to synchronize the clocks of two machines using the automotive PTP profiles. Developers and administrators can use their own profiles.

Select one machine as the clock server and the others as the clients. On the server, run the following command:

```
sudo ptp4l -i eno1 -f linuxptp/configs/automotive-master.cfg -m -S
ptp4l[7526757.990]: port 1 (eno1): INITIALIZING to MASTER on INIT_COMPLETE
ptp4l[7526757.991]: port 0 (/var/run/ptp4l): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7526757.991]: port 0 (/var/run/ptp4lro): INITIALIZING to LISTENING on INIT_COMPLETE
```

On the clients, run the following command:

```
$ sudo ptp4l -i eno1 -f linuxptp/configs/automotive-slave.cfg -m -S
ptp4l[7370954.836]: port 1 (eno1): INITIALIZING to SLAVE on INIT_COMPLETE
ptp4l[7370954.836]: port 0 (/var/run/ptp4l): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7370954.836]: port 0 (/var/run/ptp4lro): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7370956.785]: rms 5451145770 max 5451387307 freq -32919 +/-   0 delay 72882 +/-   0
ptp4l[7370957.785]: rms 5451209853 max 5451525811 freq -32919 +/-   0 delay 71671 +/-   0
...
... wait until rms value drops in the range of orders of microseconds
ptp4l[7371017.791]: rms 196201 max 324853 freq -13722 +/- 34129 delay 73814 +/-   0
ptp4l[7371018.791]: rms 167568 max 249998 freq  +6509 +/- 30532 delay 73609 +/-   0
ptp4l[7371019.791]: rms 158762 max 216309 freq  -8778 +/- 28459 delay 73060 +/-   0
```

`CLOCK_REALTIME` on both the Linux machines are synchronized to the range of microseconds. Now, different fragments of a distributed application can be run on these machines, with flow tracking, end-to-end latency of an application can be measured across these machines.

Eventually, the `ptp4l` commands can be added as system-d services to start automatically on boot.

35.6.3 With PTP Hardware Timestamping Support

If PTP hardware timestamping is supported, the physical clock of the network interface card can be synchronized to the system clock, `CLOCK_REALTIME`. This can be done by running the following commands

```
$ sudo ptp4l -i eno1 -f linuxptp/configs/gPTP.cfg --step_threshold=1 -m &
ptp4l[7527677.746]: port 1 (eno1): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7527677.747]: port 0 (/var/run/ptp4l): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7527677.747]: port 0 (/var/run/ptp4lro): INITIALIZING to LISTENING on INIT_COMPLETE
ptp4l[7527681.663]: port 1 (eno1): LISTENING to MASTER on ANNOUNCE_RECEIPT_TIMEOUT_
↪EXPIRES
ptp4l[7527681.663]: selected local clock f02f74.fffe.cb3590 as best master
ptp4l[7527681.663]: port 1 (eno1): assuming the grand master role


$ sudo pmc -u -b 0 -t 1 "SET GRANDMASTER_SETTINGS_NP clockClass 248 \
        clockAccuracy 0xfe offsetScaledLogVariance 0xffff \
        currentUtcOffset 37 leap61 0 leap59 0 currentUtcOffsetValid 1 \
        ptpTimescale 1 timeTraceable 1 frequencyTraceable 0 \
        timeSource 0xa0"
sending: SET GRANDMASTER_SETTINGS_NP
```

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```
ptp4l[7527704.409]: port 1 (eno1): assuming the grand master role
        f02f74.fffe.cb3590-0 seq 0 RESPONSE MANAGEMENT GRANDMASTER_SETTINGS_NP
                clockClass              248
                clockAccuracy           0xfe
                offsetScaledLogVariance 0xffff
                currentUtcOffset        37
                leap61                  0
                leap59                  0
                currentUtcOffsetValid   1
                ptpTimescale            1
                timeTraceable           1
                frequencyTraceable      0
                timeSource              0xa0


$ sudo phc2sys -s eno1 -c CLOCK_REALTIME --step_threshold=1 --transportSpecific=1 -w -m
phc2sys[7527727.996]: ioctl PTP_SYS_OFFSET_PRECISE: Invalid argument
phc2sys[7527728.997]: CLOCK_REALTIME phc offset   7422791 s0 freq    +628 delay   1394
phc2sys[7527729.997]: CLOCK_REALTIME phc offset   7422778 s1 freq    +615 delay   1474
phc2sys[7527730.997]: CLOCK_REALTIME phc offset       118 s2 freq    +733 delay   1375
phc2sys[7527731.997]: CLOCK_REALTIME phc offset        57 s2 freq    +708 delay   1294
phc2sys[7527732.998]: CLOCK_REALTIME phc offset       -42 s2 freq    +626 delay   1422
phc2sys[7527733.998]: CLOCK_REALTIME phc offset        52 s2 freq    +707 delay   1392
phc2sys[7527734.998]: CLOCK_REALTIME phc offset       -65 s2 freq    +606 delay   1421
phc2sys[7527735.998]: CLOCK_REALTIME phc offset       -48 s2 freq    +603 delay   1453
phc2sys[7527736.999]: CLOCK_REALTIME phc offset        -2 s2 freq    +635 delay   1392
```

From here on, clocks on other machines can also be synchronized to the above server clock.

Further references:

- Synchronizing Time with Linux PTP
- Linux PTP Documentation and Configurations

CHAPTER

THIRTYSIX

GXF JOB STATISTICS

Holoscan can have the underlying graph execution framework (GXF) collect job statistics during application execution. Collection of these statistics causes a small amount of runtime overhead, so they are disabled by default, but can be enabled on request via the environment variables documented below. The job statistics will appear in the console on application shutdown, but can optionally also be saved to a JSON file.

The statistics collected via this method correspond to individual entities (operators) in isolation. To track execution times along specific paths through the computation graph, see the documentation on *flow tracking* instead.

Note: The job statistics will be collected by the underlying Graph Execution Framework (GXF) runtime. Given that, the terms used in the report correspond to GXF concepts (entity and codelet) rather than Holoscan classes.

From the GXF perspective, each Holoscan Operator is a unique entity which contains a single codelet as well as its associated components (corresponding to Holoscan Condition or Resource classes). Any additional entities and codelets that get implicitly created by Holoscan will also appear in the report. For example, if an output port of an operator connects to multiple downstream operators, you will see a corresponding implicit "broadcast" codelet appearing in the report).

36.1 Holoscan SDK environment variables related to GXF job statistics

Collection of GXF job statistics can be enabled by setting HOLOSCAN_ENABLE_GXF_JOB_STATISTICS.

- **HOLOSCAN_ENABLE_GXF_JOB_STATISTICS** : Determines if job statistics should be collected. Interprets values like "true", "1", or "on" (case-insensitive) as true (to enable job statistics). It defaults to false if left unspecified.
- **HOLOSCAN_GXF_JOB_STATISTICS_CODELET** : Determines if a codelet statistics summary table should be created in addition to the entitty stastics. Interprets values like "true", "1", or "on" (case-insensitive) as true (to enable codelet statistics). It defaults to false if left unspecified.
- **HOLOSCAN_GXF_JOB_STATISTICS_COUNT** : Count of the number of events to be maintained in history per entity. Statistics such as median and maximum correspond to a history of this length. If unspecified, it defaults to 100.
- **HOLOSCAN_GXF_JOB_STATISTICS_PATH** : Output JSON file name where statistics should be stored. The default if unspecified (or given an empty string) is to output the statistics only to the console. Statistics will still be shown in the console when a file path is specified.

CHAPTER

THIRTYSEVEN

NSIGHT SYSTEMS PROFILING

The Holoscan SDK has been annotated using the NVTX API to provide runtime tracing and profiling of key application calls such as the `start`, `compute`, and `stop` callbacks made to the operators used by the application. This profiling can be captured and visualized using the tools provided by NSight Systems.

To enable profiling and output the profile results of running an application, enable the `HOLOSCAN_ENABLE_PROFILE` environment variable and use the `nsys` runtime provided with NSight Systems to run the application. For example, the following command will profile the first 3 seconds of the `bring_your_own_model` example application and write the results to `byom_profile.nsys-rep`:

```
export HOLOSCAN_ENABLE_PROFILE=1
nsys profile -t cuda,nvtx,osrt -o byom_profile -f true -d 3 python3 ./examples/bring_
↪your_own_model/python/byom.py
```

The written profile can then be opened with the NSight Systems UI (`nsys-ui`) to visualize the results. This is a sample profile of the bring your own model example application, zoomed in to show the details of the CPU and CUDA runtime of the application's operators:

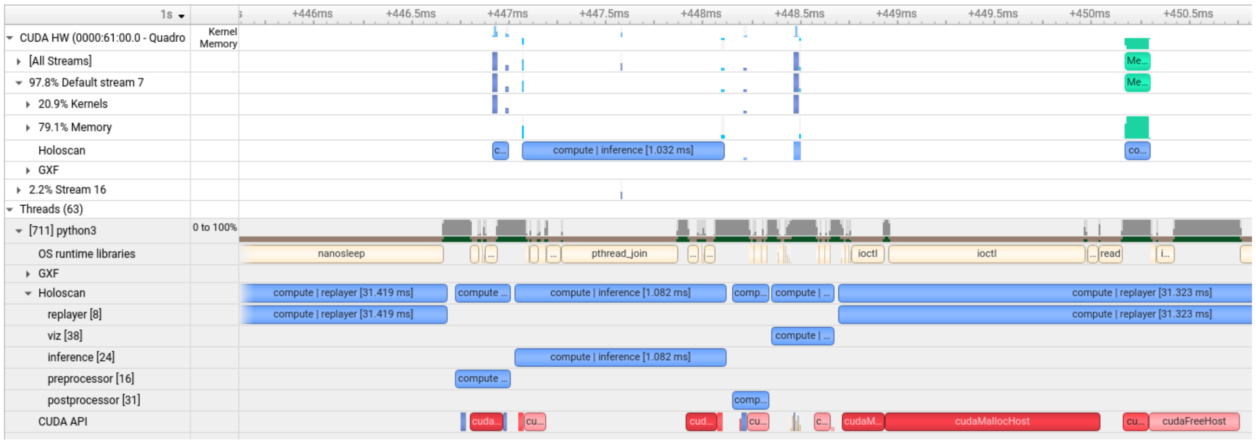


Fig. 37.1: Sample profile of the `bring_your_own_model` example application

CHAPTER

THIRTYEIGHT

HOLOSCAN SDK FAQS

38.1 General

Q1: What is the Holoscan SDK?

A1: The Holoscan SDK is a comprehensive software development kit from NVIDIA designed for developing real-time AI applications, particularly in the healthcare sector. It includes acceleration libraries, pre-trained AI models, and reference applications for various medical imaging modalities like ultrasound, endoscopy, surgical robotics, and more.

Q2: What are the core components of the Holoscan SDK?

A2: The core components include:

- **Application:** A collection of Fragments that acquire and process streaming data.A single fragment application executes in a single process while multi-fragment (distributed) applications can span multiple processes and/or physical nodes.
- **Fragments:** Directed graphs of Operators, which can be allocated to physical nodes in a Holoscan cluster.
- **Operators:** Basic units of work that process streaming data.
- **Conditions:** Components that determine conditions under which a given Operator will be considered ready to execute.
- **Resources:** Components that provide shared functionality which can be reused across operators. Examples are device memory pools, CUDA stream pools and components for serialization/deserialization of data.
- **Ports:** An operator's input ports are used to receive data from upstream operators. Input ports consist of a receiver and any associated conditions. An operator's output ports are used to emit data to downstream operators. An output port consists of a transmitter and any associated Conditions.

Q3: How is the Holoscan SDK different from other SDKs?

A3: The Holoscan SDK is a domain and sensor agnostic SDK optimized for the easy construction and deployment of high-performance, high bandwidth, and real-time AI applications. By marrying high speed instruments to NVIDIA software, Holoscan is the platform for a future of self-driving, software defined, and scalable sensor processing solutions, touching industries from scientific computing and instrumentation to medical devices.

38.2 Installation and Setup

Q1: How do I install the Holoscan SDK?

A1: There are multiple ways to install the Holoscan SDK:

- Using NGC containers :
  - For **dGPU** (x86_64, IGX Orin dGPU, Clara AGX dGPU, GH200)

```
docker pull nvcr.io/nvidia/clara-holoscan/holoscan:v3.1.0-dgpu
```

- For **iGPU** (Jetson, IGX Orin iGPU, Clara AGX iGPU)

```
docker pull nvcr.io/nvidia/clara-holoscan/holoscan:v3.1.0-igpu
```

For more information, please refer to details and usage instructions on NGC.

- Using Debian packages

```
sudo apt update
sudo apt install holoscan
```

If `holoscan` is not found, try the following before repeating the steps above:

- **IGX Orin**: Ensure the **compute stack is properly installed** which should configure the L4T repository source. If you still cannot install the Holoscan SDK, use the arm64-sbsa from the CUDA repository.
- **Jetson**: Ensure **JetPack is properly installed** which should configure the L4T repository source. If you still cannot install the Holoscan SDK, use the aarch64-jetson from the CUDA repository.
- **GH200**: Use the arm64-sbsa from the CUDA repository.
- **x86_64**: Use the x86_64 from the CUDA repository.

Please note that , to leverage the python module included in the debian package (instead of installing the python wheel), include the path below to your python path.

```
export PYTHONPATH="/opt/nvidia/holoscan/python/lib"
```

- Using Python wheels

```
pip install holoscan
```

For more details and troubleshooting , please refer to PyPI.For x86_64, ensure that the CUDA Toolkit is installed.

If you are unsure of which installation option to use, please refer to the considerations below:

- The **Holoscan container image on NGC** is the safest way to ensure all the dependencies are present with the expected versions (including Torch and ONNX Runtime), and should work on most Linux distributions. It is the simplest way to run the embedded examples, while still allowing you to create your own C++ and Python Holoscan applications on top of it. These benefits come at a cost:
  - Large image size due to the numerous (some of them optional) dependencies. If you need a lean runtime image, see the **section below**.
  - Standard inconveniences that exist when using Docker, such as more complex run instructions for proper configuration.

- If you are confident in your ability to manage dependencies on your own in your host environment, the **Holoscan Debian package** should provide all the capabilities needed to use the Holoscan SDK, assuming you are using Ubuntu 22.04.
- If you are not interested in the C++ API but just need to work in Python, or want to use a different version than Python 3.10, you can use the **Holoscan Python wheels** on PyPI. While they are the easiest solution for installing the SDK, they might require the most work to set up your environment with extra dependencies based on your needs. Finally, they are only formally supported on Ubuntu 22.04, though they should support other Linux distributions with glibc 2.35 or above.

Q2: What are the prerequisites for installing the Holoscan SDK?

A2: The prerequisites include:

- If you are installing Holoscan SDK on a Developer kit, please refer to the details below

Developer Kit	User Guide	OS	GPU mode
NVIDIA IGX Orin	Link to User Guide	IGX Software 1.1 Production Release	iGPU **or*** dGPU
NVIDIA Jetson AGX Orin and Orin Nano	Link to User Guide	JetPack 6.0	iGPU
NVIDIA Clara AGX	Link to User Guide	Holopack 1.2	iGPU **or*** dGPU

- If you are installing Holoscan SDK on NVIDIA SuperChips, please note that HSDK 2.2 has only been tested with the Grace-Hopper SuperChip (GH200) with Ubuntu 22.04. Follow setup instructions **here**.
- If you are installing Holsocan SDK on Linux x86_64 workstations, please refer to the details below for supported distributions

OS	NGC Container	Debian/RPM Package	Python wheel	Build from source
Ubuntu 22.04	Yes	Yes	Yes	No
RHEL 9.x	Yes	No	No	No
Other Linux distros	No	No	No	No

For specific NVIDIA discrete GPU (dGPU) requirements, please check below :

- Ampere or above recommended for best performance
- Quadro/NVIDIA RTX necessary for GPUDirect RDMA support
- Tested with NVIDIA Quadro RTX 6000 and NVIDIA RTX A6000
- NVIDIA dGPU drivers: 535 or above

Q3: Are there any additional setup steps required?

A3: Additional setup steps to achieve peak performance may include:

- Enabling RDMA
- Enabling G-SYNC
- Disabling Variable Backlight
- Enabling Exclusive Display Mode
- Use both Integrated and Discrete GPUs on NVIDIA Developer Kits
- Deployment Software Stack

38.3 Getting Started

Q1: How do I get started with developing applications using the Holoscan SDK?

A1: To get started:

1. Set up the SDK and your development environment.
2. Follow the "Getting Started" guide and tutorials provided in the SDK documentation.
3. Explore the example applications in Holohub to understand the framework and its capabilities.

Q2: Are there any pre-trained models available in the SDK?

A2: Yes, the SDK includes pre-trained AI models for various medical imaging tasks such as segmentation, classification, and object detection. These models can be fine-tuned or used directly in your applications. For more details, please refer to the endoscopy tool tracking example in Holohub and the body pose estimation example.

38.4 Development

Q1: How do I create a new application with the Holoscan SDK?

A1: To create a new application:

1. Define the core concepts such as Operators, Fragments, and their interactions.
2. Use the provided templates and examples as a starting point.

For more details, please refer to the *Holoscan by Example section*.

Q2: What are some example applications provided in the SDK?

A2: Example applications include:

- Hello World: Basic introduction to the SDK.
- Ping Simple and Ping Custom Op: Demonstrates simple data processing.
- Video Replayer: Shows how to process and display video streams.
- Medical imaging examples like ultrasound and endoscopy processing

For a list of example applications, please visit the *Holoscan by Example section*.

Q3: How can I integrate my own AI models into the Holoscan SDK?

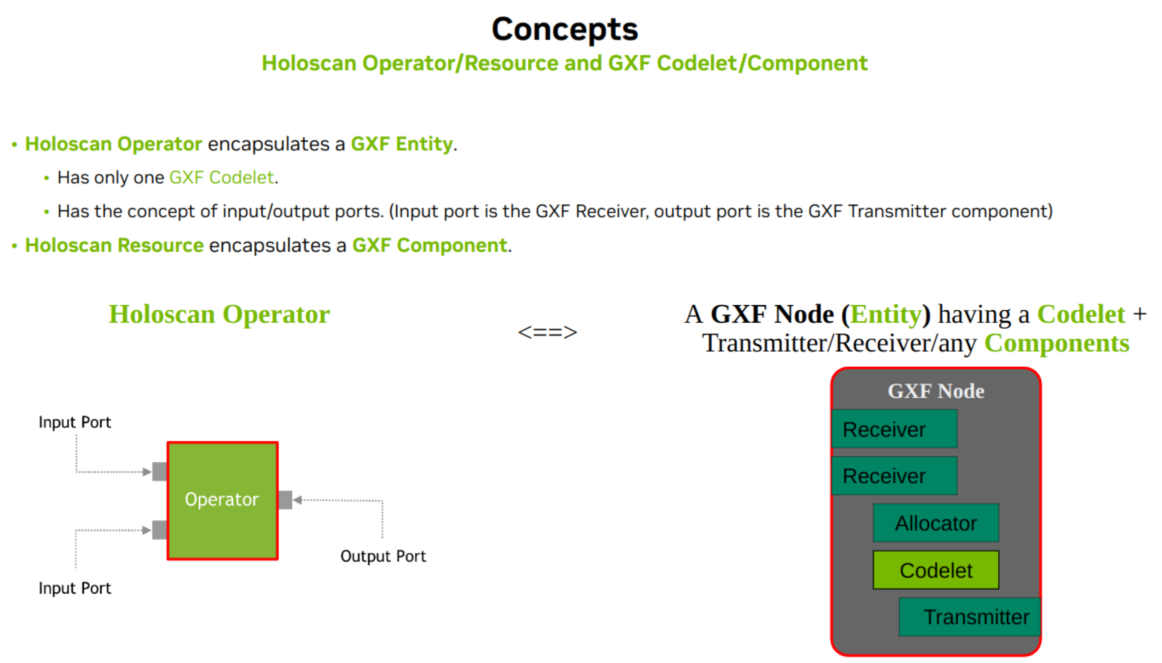
A3: Integrating your own AI models involves:

1. Converting your model to a compatible format (e.g., TensorRT, ONNX).
2. Ensuring that your data preprocessing and postprocessing steps align with the model's requirements.

For more information on how to bring your own model in Holsocan SDK and build an inference example, please refer to this example .

Q4: How can I update the VideoStreamReplayerOp and the VideoStreamRecorderOp to use a custom file format ?

A4: Holoscan SDK depends on GXF.GXF is using Entity-Component-System paradigm. Holoscan uses GXF as an execution engine and Holoscan's API abstracts Entity-Component-System and abstracts GXF node as Operator with input/output ports.



Concepts

Holoscan Operator/Resource and GXF Codelet/Component

- **Holoscan Operator** encapsulates a **GXF Entity**.
  - Has only one GXF Codelet.
  - Has the concept of input/output ports. (Input port is the GXF Receiver, output port is the GXF Transmitter component)
- **Holoscan Resource** encapsulates a **GXF Component**.

Holoscan Operator <==> A **GXF Node (Entity)** having a **Codelet** + Transmitter/Receiver/any **Components**

Most messages between Codelets(Operator in Holoscan) are also an entity object. An entity can hold multiple components/types. In VideoStreamReplayerOp and VideoStreamRecorderOp, an entity object that holds one or more GXF Tensor objects (as a component) is sent/received - you can think that an entity as a dictionary of objects – <key,object> map.For VideoStreamReplayerOp and VideoStreamRecorderOp, it currently uses a custom file type (`.gxf_entities` and `.gxf_index` files) to load and store a sequence of entity objects (in this case, an entity has one GXF Tensor object). `.gxf_index` file include a file offset/timestamp information for each entity and `.gxf_entities` includes a series of (serialized) entity data.Serializing/deserializing an entity object is done by using `nvidia::gxf::EntitySerializer` class (with StdEntitySerializer implementation), and nvidia::gxf::FileStream endpoint.The official way to support GDS in GXF would be to extend nvidia::gxf::FileStream class so it uses cufile(GDS) internally. However, setting the development environment wouldn't be straightforward. This are the steps you would need to follow:

- Update VideoStreamRecorderOp::compute() to use your own implementation to save an entity (as a single tensor) to the file system.
  - Example

```
auto in_message = op_input.receive<holoscan::TensorMap>("in").value();
```

- Update VideoStreamReplayerOp::compute() to use your own implementation to read the file (with the custom format) and emit it as an entity (holding tensor(s) as a component – it is called TensorMap).
  - Example:

```
nvidia::gxf::Expected<nvidia::gxf::Entity> out_message =
      CreateTensorMap(context.context(),
                      pool.value(),
                      {{out_tensor_name_.get(),
                        nvidia::gxf::MemoryStorageType::kDevice,
                        out_shape,
                        out_primitive_type_,
                        0,
                        nvidia::gxf::ComputeTrivialStrides(out_shape, dst_typesize)}},
                      false);
```

- You need to update initialize() and other methods to get rid of nvidia::gxf::FileStream and nvidia::gxf::FileStream endpoint.For testing VideoStreamReplayerOp, you can just use VideoReplayerApp example.You can develop/test/create operator (release) binaries by following the user guide: https://github.com/nvidia-holoscan/holoscan-sdk/blob/main/DEVELOP.md

```
class VideoReplayerApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    // Sets the data directory to use from the environment variable if it is set
    ArgList args;
    auto data_directory = std::getenv("HOLOSCAN_INPUT_PATH");
    if (data_directory != nullptr && data_directory[0] != '\0') {
      auto video_directory = std::filesystem::path(data_directory);
      video_directory /= "racerx";
      args.add(Arg("directory", video_directory.string()));
    }

    // Define the replayer and holoviz operators and configure using yaml configuration
    auto replayer =
        make_operator<ops::VideoStreamReplayerOp>("replayer", from_config("replayer"),␣
↪args);
    auto visualizer = make_operator<ops::HolovizOp>("holoviz", from_config("holoviz"));

    // Define the workflow: replayer -> holoviz
    add_flow(replayer, visualizer, {{"output", "receivers"}});
  }
};
```

```
./run build
./run launch
 # inside the container
 ./examples/video_replayer/cpp/video_replayer
```

- As an alternative, you can create a separate Holoscan Operator and apply it with other sample applications (such as endoscopy tool tracking app) by following HoloHub's guide (https://github.com/nvidia-holoscan/holohub).You can also use Holoscan SDK's installation binary with holoscan install dir created by ./run build with Holoscan SDK repo.

Q5: How can I use the Inference Operator with Python tensor?

A5: The Inference Operator accepts holoscan::Entity or holoscan::TensorMap (similar to the dictionary of Array-like objects in Python) as an input message.

For example, you can define an operator processing input video (as a tensor).You can find a more detailed example of this type of operator together with an example by referencing the tensor interop example.

```
This operator has:
    inputs:  "input_tensor"
    outputs: "output_tensor"

The data from each input is processed by a CuPy gaussian filter and
```

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~~~
the result is sent to the output.

```
def compute(self, op_input, op_output, context):
    # in_message is of dict
    in_message = op_input.receive("input_tensor")

    # smooth along first two axes, but not the color channels
    sigma = (self.sigma, self.sigma, 0)

    # out_message is of dict
    out_message = dict()

    for key, value in in_message.items():
        print(f"message received (count: {self.count})")
        self.count += 1

        cp_array = cp.asarray(value)

        # process cp_array
        cp_array = ndi.gaussian_filter(cp_array, sigma)

        out_message[key] = cp_array

    op_output.emit(out_message, "output_tensor")
```
~~~

Q6: Is there support in the Holoscan SDK, particularly for models written as Triton Python backends like NVIDIA's FoundationPose?

A6: Triton backends are not currently supported.The Inference Operator supports TensorRT (trt), ONNX Runtime (onnxrt), and Torch backends.

For more information on the Inference Operator please refer to the section in the User Guide regarding the Inference Operator .

Q7: Can I directly use a .pth (PyTorch) model file with the Holoscan SDK's inference operator? A7:No, you cannot use a .pth model file directly with the Holoscan SDK. Here's why and what you can do instead:

1. Holoscan SDK's Torch backend is based on libtorch, which requires models to be in TorchScript format.
2. Converting a .pth model to TorchScript is a manual process and cannot be done automatically within the SDK.
3. For the best performance and ease of use, it's recommended to: a) Use a TensorRT (TRT) model if available. b) If you have an ONNX model, you can convert it to TRT automatically within the SDK.
4. Using a TRT model (or converting from ONNX to TRT) will likely provide the fastest inference and be the easiest to set up with the Holoscan SDK.

In summary, while direct .pth file usage isn't supported, converting to TensorRT or using ONNX with automatic TRT conversion are the recommended approaches for optimal performance and compatibility with the Holoscan SDK.

Q8: Can I use multiple models with the Inference Operator?

A8: Yes, you can use multiple models by specifying them in the `model_path_map` parameter. For more information, please refer to the Parameters section of the Inference Operator in the Holoscan User Guide.

Q9: How can I enable parallel inference for multiple models?

A9: Parallel inference is enabled by default. To disable it, set `parallel_inference`: false in the parameter set. For more information, please refer to the Parameters section of the Inference Operator in the Holoscan User Guide.

Q9: Can I use different backends for different models in the same application?

A9: Yes, you can specify different backends for different models using the `backend_map` parameter.For more information, please refer to the Parameters section of the Inference Operator in the Holoscan User Guide.

Q10: Can I perform inference on the CPU?

A10: Yes, you can perform inference on the CPU by setting `infer_on_cpu`: true and use either the ONNX Runtime or PyTorch backend.For more information, please refer to the Parameters section of the Inference Operator in the Holoscan User Guide.

Q11:Can I control where the input and output data is stored (CPU vs GPU memory)?

A11: Yes, use the `input_on_cuda`, `output_on_cuda`, and `transmit_on_cuda` parameters to control data location.For more information, please refer to the Parameters section of the Inference Operator in the Holoscan User Guide.

Q12: How can I use the Optional flag?

A12: In Python, there are two ways to define parameter:

- Using spec.param() method in Python's setup() method of the operator , usually done when wrapping the existing C++ operator.
- Parameters are passed to the Constructor (`__init__()`) directly. In Python there is no `try_get()` method in the parameter. Instead, the default value is set to None, allowing us to check whether the parameter is set by users by verifying if the parameter value is None.

Q13:How can I define an Operator's creator for passing custom arguments?

A13:Feeding custom data to the constructor of an Operator in the `compose()` method is crucial. When you use the `make_operator<>()` template method in C++ or the Python Operator constructor, the `setup()` method is called internally, which prevents you from passing custom data (such as configuration values) after `make_operator<>()` is called. In C++, to pass non-condition/argument data to the constructor of a C++ Operator class, you need to define an additional constructor to accept your custom data. For example, you can define a constructor that accepts a `std::vector<std::string>` argument for the list of output port names as a second parameter.

Q14:How can I stop an application?

A14:There are two approaches to stopping an application:

- using BooleanCondition on replayer operator

```cpp
std::string op_name = "replayer";
std::string param_name = "boolean_scheduling_term";

// get the operator
holoscan::Operator* op = nullptr;
auto& app_graph = fragment()->graph();
if (!app_graph.is_empty()) { op = app_graph.find_node(op_name).get(); }
if (!op) {
    HOLOSCAN_LOG_ERROR("Operator '{}' is not defined", op_name);
    return;
}

  // Stop executing compute() for 'replayer' operator

auto boolean_condition = op->condition<holoscan::BooleanCondition>(param_name);
```

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```
    boolean_condition->disable_tick();

    // Stop executing compute() for this operator
    boolean_condition = condition<holoscan::BooleanCondition>(param_name);
    boolean_condition->disable_tick();
    return;
```

To terminate the application smoothly, it is recommended to rely on the stop-on-deadlock feature in the scheduler. By default, the `stop_on_deadlock` parameter of `GreedyScheduler` is set to true. In case the `VideoReplayer` Operator stops, the entire pipeline will stop.

- using interrupt()

```
fragment()->executor().interrupt();
```

Please note that using interrupt() forces to terminate the execution and can cause error messages, and the recommendation is using deadlock-based approach.

As an alternative, you can also use the `CountCondition`.Please refer to the section. At a high level, this is how attaching a `CountCondition` to an operator works:

The operator starts in a READY state. Each time the operator executes, the count decreases by 1. When the count reaches 0, the operator's state changes to NEVER. In the NEVER state, the operator stops executing.

For example, if you want to run the application 100 times and then stop it:

```
auto my_operator = make_operator<MyOperator>("my_operator", make_condition
↪<CountCondition>(100));
```

Q15:How can I loop an output.emit() call within the operator?

A15: Each input or output port has its own queue. Internally, the process works as follows:

1. Before the `compute()` method of an operator A is triggered, for each input port (usually backed by `DoubleBufferReceiver`), data (messages) in the backstage of the input port's queue are moved to the main stage of the queue. This is done using `router->syncInbox(entity)`.
2. The `compute()` method of operator A is triggered.
3. For each output port of operator A, data in the output port's queue are moved to the queue (backstage) of the downstream operator's input port using `router->syncOutbox(entity)`.

By default, the queue capacity of the input/output port is set to 1, although this can be configured in the `setup()` method. This is why we cannot call `output.emit()` multiple times in a `compute()` method, as doing so can cause a `GXF_EXCEEDING_PREALLOCATED_SIZE` error.

With the `GreedyScheduler`, which is the default scheduler using a single thread to trigger an operator's `compute()` method, no other operator can be scheduled until the `compute()` method of the current operator returns.

To address this challenge, we might consider creating a utility method or class designed to accept a generator or iterator object. This approach would be particularly effective within a `compute()` method, especially if the operator is a source operator without input ports. It would enable the method to preserve the state of the input and either call `output.emit()` for each yielded value in a single `compute()` invocation or return without blocking the thread.

The Python API code to override the connector would be something like this if we wanted a queue with capacity 20 and policy of "reject" (discard) the item if the queue is full:

```python
from holoscan.core import IOSpec

# and then within the setup method define the output using the connector method like this

spec.output("out1").connector(
    IOSpec.ConnectorType.DOUBLE_BUFFER, capacity=20, policy=1
)
```

For the policy options:

- 0 = pop (if the queue is full, remove an item from the queue to make room for the incoming one)
- 1 = reject (if the queue is full, reject the new item)
- 2 = fault (terminate the application if the queue is full and a new item is added)

For completeness, to explicitly specify both the connector and its conditions, the syntax should be:

```python
# The default setting for an output should be equivalent to explicitly specifying
spec.output("out1").connector(
    IOSpec.ConnectorType.DOUBLE_BUFFER, capacity=1, policy=2
).condition(
    ConditionType.DOWNSTREAM_MESSAGE_AFFORDABLE, min_size=1, front_stage_max_size=1
)
```

Q16: How can I add a green border and a small image to a corner to a Holoviz Operator?

A16: You can follow the Holoviz examples here:

- Holoviz geometry example : https://github.com/nvidia-holoscan/holoscan-sdk/blob/main/examples/holoviz/python/holoviz_geometry.py for border examples
- Holoviz views example https://github.com/nvidia-holoscan/holoscan-sdk/blob/main/examples/holoviz/python/holoviz_views.py for view/image example

Q17 : What is the difference between `setup` vs `initialize` vs `__init__` ?

A17: Since v0.6 release, Holoscan Operator does "lazy initialization" and Operator instance creation (`super().__init__(*args, **kwargs)`) doesn't initialize (calling Operator.initialize(self)) the corresponding GXF entity anymore. Currently, setting the class members in Python is done when Operator is initialized by GXF Executor.The purpose of setup method is for getting "operator's spec" by providing OperatorSpec object (spec param) to the method. When `__init__` is called, it calls C++'s `Operator::spec(const std::shared_ptr<OperatorSpec>& spec)` method (and also sets `self.spec` class member), and call `setup` method so that Operator's `spec()` method hold the operator's specification. Since setup method can be called multiple times with other OperatorSpec object (e.g., to enumerate the description of the operator), in the setup method, user shouldn't initialize something in the Operator object. Such initialization needs to be done in initialize method. `__init__` method is for creating Operator object. it can be used for initializing operator object itself by passing miscellaneous arguments, but it doesn't 'initialize' corresponding GXF entity object.

Q18:I'd like to use a CUDA stream allocated by the Holoscan SDK in a non-Holoscan library (OpenCV, CuPy, PyTorch). All these 3rd party libraries support CUDA streams, allocators etc. but they have different objects to represent that CUDA Stream (such as a `cupy.cuda.Stream`). I need to get the Holoscan CUDA stream and convert it to a `cupy.cuda.Stream` in a similar way a Holoscan Tensor is converted to a CuPy array with memory pointers.Please propose a solution.

A18:There is a CudaStreamHandler utility that works via GXF APIs in the C++ layer. We have not currently created a Python API to allow users to use it from the compute methods of native Python operators.In general, the underlying GXF library is currently refactoring how CUDA streams are handled and we plan to then improve the stream handling on Holoscan SDK after that.You can use CuPy or other 3rd party stream APIs within their own native operators and pass the stream objects as a Python object between your own native operators. I think this doesn't help with the issue you are facing as you want to reuse a stream allocated by some upstream wrapped C++ operator provided by the SDK there is currently no proper way to do that from Python.

Q19:What is the purpose of the `activation_map` parameter in the Holoscan Holoinfer operator? A19: The `activation_map` parameter allows users to enable or disable model inferences dynamically at runtime. It can be used to decide on which frames to run inference for each model.

Q20:Is there an existing example or template that demonstrates the simultaneous use of integrated GPU (iGPU) and discrete GPU (dGPU) in a Holoscan application pipeline? Specifically, I am looking for a sample workflow that includes:

1. **Receiving and processing data on the iGPU of an AGX Orin**
2. **Transferring the processed data to a dGPU**
3. **Running multiple AI models on the dGPU**
4. **Displaying results using the dGPU**

A20:To leverage both the integrated GPU (iGPU) and discrete GPU (dGPU) on your IGX system with Holoscan, please refer to the IGX user guide. This guide provides detailed instructions on utilizing the iGPU in containers when the IGX developer kit is configured in dGPU mode.

For Holoscan applications, there are two primary approaches to utilize both GPUs:

1. Concurrent Application Execution: Run separate applications simultaneously, as outlined in the IGX documentation. The iGPU application must be executed within the Holoscan iGPU container, while the dGPU application can be run either natively or within the Holoscan dGPU container.
2. Distributed Application: Develop a single distributed application that utilizes both GPUs by executing distinct fragments on the iGPU and dGPU respectively.

To illustrate the second approach, consider the following example using the 'ping' distributed application. This demonstrates communication between the iGPU and dGPU using Holoscan containers:

```
COMMON_DOCKER_FLAGS="--rm -i --init --net=host
--runtime=nvidia -e NVIDIA_DRIVER_CAPABILITIES=all
--cap-add CAP_SYS_PTRACE --ipc=host --ulimit memlock=-1 --ulimit stack=67108864
"
HOLOSCAN_VERSION=2.2.0
HOLOSCAN_IMG="nvcr.io/nvidia/clara-holoscan/holoscan:v$HOLOSCAN_VERSION"
HOLOSCAN_DGPU_IMG="$HOLOSCAN_IMG-dgpu"
HOLOSCAN_IGPU_IMG="$HOLOSCAN_IMG-igpu"

# Pull necessary images
docker pull $HOLOSCAN_DGPU_IMG
docker pull $HOLOSCAN_IGPU_IMG

# Execute ping distributed (Python) in dGPU container
# Note: This instance serves as the 'driver', but the iGPU could also fulfill this role
# The '&' allows for non-blocking execution, enabling subsequent iGPU command
docker run \
 $COMMON_DOCKER_FLAGS \
 $HOLOSCAN_DGPU_IMG \
 bash -c "python3 ./examples/ping_distributed/python/ping_distributed.py --gpu --worker -
↪-driver" &
```

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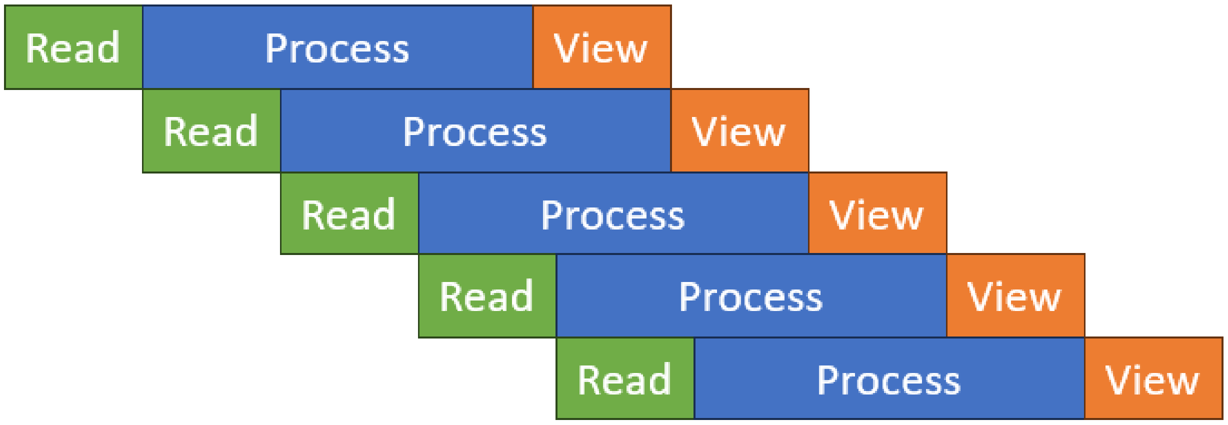
```
# Execute ping distributed (C++) in iGPU container
docker run \
 $COMMON_DOCKER_FLAGS \
 -e NVIDIA_VISIBLE_DEVICES=nvidia.com/igpu=0 \
 $HOLOSCAN_IMG-igpu \
 bash -c "./examples/ping_distributed/cpp/ping_distributed --gpu --worker"
```

Q21:Is there an efficient method to configure Holoscan to enable concurrent processing pipelines? My objective is to implement a system where frame acquisition and processing can occur simultaneously. Specifically, I aim to initiate the reading of a subsequent frame while the current frame is still undergoing processing through the InferenceOp.To illustrate:



1. **Is it possible to begin reading Frame N+1 while Frame N is still being processed by the InferenceOp?**
2. **Or does Holoscan require the completion of all operations on Frame N before initiating any operations on Frame N+1?**

If concurrent processing is achievable, what would be the recommended approach to implement such a system within the Holoscan framework?

A21: The NVIDIA GXF framework provides a `nvidia::gxf::BroadcastCodelet` with a "round robin" mode that offers an alternative to the standard broadcast behavior. This mode sequentially directs input messages to different output ports in rotation. While this functionality was accessible in Holoscan 2.1 through the GXFCodeletOp, we could also develop a native operator that provides equivalent utility.

The GXF source defines the modes as follows:

```
enum struct BroadcastMode {
  kBroadcast = 0,   // publishes incoming message to all transmitters
  kRoundRobin = 1,  // publishes incoming message to one transmitter in round-robin␣
↪fashion
};
```

For the gathering operation, GXF implements the `nvidia::gxf::Gather` codelet. This codelet transfers any messages from the receive ports to the output port. The `tick_source_limit` parameter can be configured to cease checking for additional received messages on other ports once a specified maximum number of messages to output has been reached.

It's important to note that the GXF Gather codelet may not inherently preserve the order in which inference operations were called. While messages might naturally be processed in the order they were received if inference operations complete sequentially, this behavior is not guaranteed.

To ensure strict ordering, we could develop a custom native operator. This operator would sequentially check for messages on each port, beginning with port 1, and only move to the next port once a message has been received on the current port. This approach would guarantee that frames are processed and displayed in the correct order.

This custom implementation would provide greater control over the message flow and ensure the integrity of the processing pipeline, particularly in scenarios where maintaining the original frame order is critical.

Q22: How can I use other libraries in my Holoscan SDK application pipeline? A22: Refer to the dedicated HoloHub tutorial for an overview of how to use external C++ or Python libraries in your custom Holoscan SDK application.

Q23: How can I ensure proper data flow and handling in a Holoscan pipeline with branching paths, especially when inline updates are performed on shared data?

A23:In a Holoscan pipeline with branching paths, such as:

```
A -> B -> C -> D
      \
       -> E
```

There are several considerations and potential solutions to ensure proper data flow and handling, especially when operators like C or D perform inline updates to the data.

1. Data Access Guarantee: E is guaranteed to access the data egressing from B. However, in a multithreaded scheduler, careful attention must be paid to potential data race conditions.
2. Execution Order: The current implementation maintains the order of root nodes, but the creation of GXF connections between B -> C and B -> E is randomly determined due to the use of `std::unordered_map` as the graph data structure. This randomness can affect which connection is prioritized in GXF.
3. Potential Solutions: a. PeriodicCondition: One approach is to use a PeriodicCondition to control the execution timing of operators. Here's an example:

```python
from holoscan.conditions import CountCondition, PeriodicCondition
from holoscan.core import Application
from holoscan.operators import PingRxOp, PingTxOp

class MyPingApp(Application):
    def compose(self):
        b = PingTxOp(self, CountCondition(self, 10), name="B")
        c = PingRxOp(self, PeriodicCondition(self, 20_000_000), name="C")
        e = PingRxOp(self, name="E")

        self.add_flow(b, c)
        self.add_flow(b, e)
```

In this example, the PeriodicCondition is used to ensure that C executes only after a specified period (20 milliseconds in this case) has elapsed. This can help control the timing of data processing between different branches. b. Custom Operator: Developing a custom native operator could provide more control over the message flow. This operator could sequentially check for messages on each port, ensuring that frames are processed and displayed in the correct order. c. Data Copying: To avoid issues with inline updates affecting shared data, consider implementing a mechanism to create copies of the data for each branch. This ensures that modifications in one branch don't unintentionally affect the other.

1. Limitations and Considerations:

- The GXF Gather codelet may not inherently preserve the order in which inference operations were called.
- When using mock objects for testing (as mentioned in the background information), modifying the original pipeline structure might be challenging. In such cases, focusing on data copying or careful timing control might be more feasible.

1. Future Improvements: Updating the graph structure to use std::map instead of `std::unordered_map` for `succ_` and `pred_` could potentially provide more predictable behavior in terms of connection creation order.

Q24:I'm inquiring about the availability of a Holoscan example that demonstrates distributed processing across two networked computers. Specifically, I'm interested in a scenario where:

1. **One computer captures a frame, potentially using an AJA capture card.**
2. **The captured frame is then transferred over a local network to a second computer.**
3. **The second computer receives and displays the frame.**

Additionally, I have some questions regarding the networking aspects of such a setup:

1. **Does Holoscan provide flexibility in selecting the transport layer for this inter-computer communication?**
2. **Is it possible to utilize WebRTC as the transport protocol in this scenario?**

A24: There are two relevant approaches:

1. WebRTC Implementation: A reference application demonstrating WebRTC-based video streaming is available in the HoloHub repository. You can find this example at: https://github.com/nvidia-holoscan/holohub/tree/main/applications/webrtc_video_server This application showcases how WebRTC can be utilized for inter-computer communication within the Holoscan framework.
2. Distributed Application Approach: An alternative method involves creating a distributed application with separate fragments running on each node. For more information, please refer to the section in the User guide on Creating Distributed applications .

Q25: How can I use `run_async()` to launch an application in a separate thread and stop the application?

A25:We can set the event state to `EVENT_WAITING` (request sent to an async service, pending event done notification) and then `EVENT_DONE` (event done notification received, entity ready to be ticked) to allow a specific operator to wait/resume its operation. In the example, it calls `AsynchronousCondition::event_state(AsynchronousEventState::EVENT_NEVER)` to set the status of the condition to NEVER. (BooleanCondition does the same by setting the status of the condition to NEVER when `BooleanCondition::disable_tick()` is called). This means the operator does not want to be ticked again (end of execution).Once the state of the condition goes to NEVER (internally, SchedulingConditionType::NEVER), it marks the end of execution and cannot be undone.

Q26:Are there any existing applications or examples in the Holoscan ecosystem that demonstrate the ability to utilize multiple GPUs concurrently within a single application?

A26:The multi ai ultrasound application has settings for multi GPU in a different YAML file. It can be controlled by the inference parameters.

Q27: What is the role of a scheduler in Holoscan?

A27: The scheduler is responsible for determining when each operator in an application will execute.

Q28: How many types of schedulers are available in the Holoscan SDK?

A28: There are three schedulers available: Greedy Scheduler, Multi-Thread Scheduler, and Event-Based Scheduler.

Q29:Which scheduler is used by default for non-distributed applications?

A29:Non-distributed applications use the Greedy Scheduler by default.

Q30:What is the main characteristic of the Greedy Scheduler?

A30: The Greedy Scheduler has only a single worker thread that executes operators sequentially in a deterministic order.

Q31:How does the Multi-Thread Scheduler work?

A31: It's a polling-based scheduler with a user-defined number of worker threads and a dedicated thread that polls operators at a user-defined interval.

Q32:What is unique about the Event-Based Scheduler?

A32:The Event-Based Scheduler waits for events indicating changes in operator readiness, rather than constantly polling.

Q33:How can the Event-Based Scheduler reduce CPU overhead?

A33:By eliminating the need for constant polling, it can significantly reduce CPU usage compared to the Multi-Thread Scheduler in certain scenarios.

Q34:In what situations do Multi-thread and Event-Based Schedulers show benefits?

A34:They show benefits in scenarios with multiple operators that can run simultaneously, potentially providing significant speedup compared to the Greedy Scheduler.

Q35:How do the Multi-Thread and Event-Based Schedulers compare in terms of performance?

A35:They often have similar runtime performance, but the Event-Based Scheduler tends to have lower CPU overhead on average.

Q36:Are there scenarios where using multi-thread schedulers might not be beneficial?

A36: Yes, for linear inference pipelines or applications with minimal computation per operator, multi-thread schedulers might not provide significant benefits and could even introduce overhead.

Q37: How does the number of worker threads affect performance in multi-thread schedulers?

A37: Increasing the number of worker threads can improve performance up to a point, but it also increases CPU usage.

Q38: Is there any memory pool (allocator) that supports both host and device memory?

Please use `RMMAllocator` for this purpose. It supports simultaneous memory pools for CUDA device memory and pinned host memory. A `BlockMemoryPool` can be used on either host or device memory, but cannot support both types at the same time. `UnboundedAllocator` also supports both host and device memory, but is not a memory pool (it allocates and frees new memory each time).

38.5 Performance

Q1: What performance tools are available in Holoscan SDK?

A1: Holoscan SDK provides several performance tools, including Data Flow Tracking and GXF job statistics.

Q2: What is Data Flow Tracking in Holoscan SDK?

A2: Data Flow Tracking is a mechanism to profile applications and analyze fine-grained timing properties and data flow between operators in a fragment's graph.For more detailed information, please refer to the Data Flow Tracking section in the Holoscan User Guide.

Q3: How do I enable Data Flow Tracking in my Holoscan application?

A3:You can enable Data Flow Tracking by calling the `track()` method in C++ or using the `Tracker` class in Python before running your application.

Q4: What metrics can I retrieve using Data Flow Tracking?

A4: You can retrieve metrics such as maximum, average, and minimum end-to-end latencies, as well as the number of messages sent from root operators.

Q5: How can I customize Data Flow Tracking?

A5:You can customize Data Flow Tracking by configuring parameters such as the number of messages to skip at the start and end, and setting a latency threshold to ignore outliers.

Q6: How do I enable GXF job statistics?

A6:You can enable GXF job statistics by setting the environment variable `HOLOSCAN_ENABLE_GXF_JOB_STATISTICS` to true.

Q7: Can I save GXF job statistics to a file?

A7:Yes, you can save GXF job statistics to a JSON file by setting the `HOLOSCAN_GXF_JOB_STATISTICS_PATH` environment variable. For more information on the GXF job statistics, please refer to this section in the User Guide.

Q11:How do NVTX markers work in Holoscan SDK?

A11:This is how NVTX markers added to a Holoscan application work:

- The multithreaded scheduler starts a worker thread, checks the status of entities (also known as Holoscan Operators), and executes each entity using `EntityExecutor::executeEntity()` method in GXF.
- `EntityExecutor::executeEntity()` calls the `EntityExecutor::EntityItem::execute()` GXF method for the given entity ID
- The `EntityExecutor::EntityItem::execute()` method checks the scheduling status of the entity (Holoscan Operator) and then calls the `EntityExecutor::EntityItem::tick()` method in GXF
- In the EntityExecutor::EntityItem::tick() method it is where the annotation happens, the following steps occur:

1. router->syncInbox(entity); is called to synchronize the inbox. For example, for the given Holoscan operator, UCXReceiver (input port) receives data from the network and pushes it into the queue in the UCXReceiver object. Data in the queue can be retrieved by calling the receive() method within the Operator::compute() method.
2. For each codelet in the entity (in Holoscan, an entity can have only one codelet), EntityExecutor::EntityItem::tickCodelet() is called, which in turn calls Codelet::tick() (in Holoscan, this is the Operator::compute() method) (Figure 5).
3. router->syncOutbox(entity); is called to synchronize the outbox. For example, for the given Holoscan operator, the data pushed to the queue in the UCXTransmitter object (output port) via emit() method calls in the Operator::compute() method is sent to the network using UCX.

During these calls, the system measures statistics, executes monitors (if any), and executes controllers (if any).

It is important to note that the tick codelet NVTX annotation doesn't cover router->syncInbox(entity); and router->syncOutbox(entity);. This means that the time range captured by NVTX measures only the duration for executing the Codelet::tick(). The time for sending and receiving data via UCXTransmitter/UCXReceiver is not measured by looking at the annotation range.

Q12:During the performance analysis of my Holoscan application, I've observed significant latency issues that are negatively impacting real-time performance. I've compiled a timing breakdown for each operator in the pipeline, which I've included below for reference.

Initially, I had assumed that each Holoscan Operator processed frames independently and concurrently. However, my observations suggest that the entire pipeline is processing each frame sequentially, which appears to be suboptimal for my real-time requirements.

Currently, my visualization component is only achieving approximately 15 fps, which falls short of my performance target. Given that my pipeline has a total execution time of approximately 70ms, I'm concerned that it may only be capable of processing one frame every 70ms.

Could you provide more detailed information about the implementation and potential benefits of Schedulers in Holoscan (as referenced in the NVIDIA documentation on Schedulers)? Specifically, I'm interested in understanding if and how Schedulers could be leveraged to address my performance concerns.

Here's the timing breakdown for each operator in my pipeline:

- **Replayer: 24.145 ms**
- **ImageProcessing: 18.289 ms**
- **Preprocessor: 1.213 ms**
- **Inference: 23.861 ms**
- **Postprocessor: 0.275 ms**
- **PostImageProcessing: 2.695 ms**
- **Viz: 1.575 ms**

A12: The following scheduler mechanisms can potentially impact the performance of your application:

1. Frame Processing Parallelization: The Multi-threaded Scheduler (MTS) and Event-based Scheduler (EBS) are designed to enable concurrent processing of multiple frames. These schedulers allow the initiation of processing for subsequent frames while preceding frames are still being processed by other operators in the pipeline.
2. Latency vs. Throughput Considerations: It's important to distinguish between end-to-end latency and throughput in the context of application performance. While MTS and EBS can potentially enhance the overall throughput of an application (defined as the number of frames processed per unit time), they do not necessarily reduce the end-to-end latency. End-to-end latency refers to the time required for a single frame to traverse the entire pipeline from source to sink.
3. Current Scheduler Implementation Status: Please note that the MTS and EBS are currently undergoing optimization. In their present state, they may exhibit higher latency compared to the greedy scheduler.
4. Inter-Operator Dependencies: It's crucial to understand that operators within a pipeline do not function in complete isolation. The pipeline architecture incorporates double-buffer queues between operators, with scheduling conditions applied to these queues. This design introduces data dependencies between adjacent nodes in the application graph, which influences the overall execution flow and timing.

Q13:How can I improve the performance of VideoStreamRecorderOp by reusing GPU memory?

A13:The VideoStreamReplayerOp can reuse the CUDA device buffers and avoid alloc/free for each frame by using BlockMemoryPool.

The VideoStreamReplayerOp does not have a parameter (such as allocator) to use a custom allocator, even though the user can specify `entity_serializer`.

- The current implementation always uses holoscan::StdEntitySerializer and holoscan::StdComponentSerializer with UnboundedAllocator, regardless of the user-specified `entity_serializer` parameter.
- The storage type of the tensor (GPU or CPU) created by the VideoStreamReplayerOp depends on the input video file to which the tensor object is serialized. Therefore, without updating the `holoscan::StdComponentSerializer` implementation, VideoStreamReplayerOp cannot blindly use a specific memory pool allocator that requires memory storage type, memory pool size, etc.

Q14: I've observed some CUPVA-CUDA interop-related latencies in this application that are not present in our CUPVA test applications. One notable difference between the Holohub application and the CUPVA test application lies in the method of CUDA stream creation.

In the CUPVA test application, we create the CUDA stream as follows:

```
cudaStreamCreateWithFlags(&cuStream, cudaStreamNonBlocking)
```

In contrast, the Holohub application utilizes a CudaStreamPool, created in this manner:

```
const std::shared_ptr<CudaStreamPool> cuda_stream_pool = make_resource<CudaStreamPool>(
↪"cuda_stream", 0, 0, 0, 1, 5);
// or
const std::shared_ptr<CudaStreamPool> cuda_stream_pool = make_resource<CudaStreamPool>(
↪"cuda_stream", 0, cudaStreamNonBlocking, 0, 1, 5);
```

The CUDA stream is then retrieved in the compute API using:

```
auto cudaStream = cuda_stream_handler_.get_cuda_stream(context.context());
```

I would like to clarify the following points:

1. **When calling `get_cuda_stream(..)`, will the default stream be utilized, or will it be a non-default stream?**
2. **Is there a method to ensure that the default CUDA stream is not used in the pool, given that we currently lack support for it in CUPVA?**

A14:It is important to know that CUDA stream management in both GXF and Holoscan is currently in a state of evolution.

In the current Holoscan implementation, CUDA streams are managed through the `holoscan::CudaStreamHandler` class. This class offers utility methods to define the operator specification with `CudaStreamPool`.

To utilize non-default streams, the application's `compose()` method should create a `cuda_stream_pool` as follows:

```
const std::shared_ptr<CudaStreamPool> cuda_stream_pool = make_resource<CudaStreamPool>(
↪"cuda_stream", 0, cudaStreamNonBlocking, 0, 1, 5);
```

Note that using 1 or `cudaStreamNonBlocking` for the flag parameter ensures the use of non-default streams.

For proper CUDA stream creation and sharing across operators in the application workflow:

1. In the Application's `compose()` method:
   - Create `CudaMemoryPool` and pass it as a parameter to the operators in the workflow graph.
2. For each operator in the workflow:
   - Define a `holoscan::CudaStreamHandler` member variable in the operator class (e.g., `cuda_stream_handler_`).
   - Call `cuda_stream_handler_.define_params(spec);` in the `setup(OperatorSpec& spec)` method.
   - In the `compute()` method, use the following calls:
     - `cuda_stream_handler_.from_message(context.context(), in_message);` to retrieve CUDA stream information from the input message.
     - `cuda_stream_handler_.get_cuda_stream(context.context());` to obtain the CUDA stream.
     - `cuda_stream_handler_.to_message(out_message);` to set the currently used CUDA stream to the output message for subsequent operators.

Regarding your specific concern about forcing non-use of the default CUDA stream in the pool due to lack of support in CUPVA, there are two potential approaches:

1. Ensure that your application uses an appropriate CUDA stream pool configuration.
2. Implement error handling or exceptions at the application/operator level to prevent the use of the default CUDA stream.

It's worth noting that the `VideoReplayerOp` currently doesn't support this CUDA stream handling. Consideration is being given to supporting it alongside CUDA memory pool support in future updates.

Q15:I'm seeking to understand the memory allocation strategies employed within the Holoscan framework. Specifically, I'd like clarification on the following points:

1. **How is memory allocated across different components of Holoscan?**
2. **What is the timing of memory allocation in relation to the compute() method execution? Is memory allocated: a) Each time compute() is called, or b) Once at the beginning of execution and then reused?**
3. **What types of CUDA memory are utilized in Holoscan operations? Specifically: a) Is pinned memory used? b) Is CUDA managed memory employed? c) Do all memory exchanges remain within device (GPU) memory?**

A15:Memory allocation can be done either once and reused or separately on each compute call. It depends on how the user write the compute method. We provide a BlockMemoryPool allocator class that allows reusing the same memory blocks on each call. Similarly there is ability to use CUDA streams and asynchronous memory allocation calls (CudaStreamPool). We hope to refactor over the coming months to make these easier to use than they are currently, but the capability is there now. BlockMemoryPool currently uses on device memory only. There is an UnboundedAllocator that can allocate on one of three places

- system memory (i.e. C++ new/delete)
- pinned host memory (cudaMallocHost / cudaFreeHost)
- device memory (cudaMalloc / cudaFree)

Q16: I'm running the endoscopy tool tracking application with a configuration that separates compute and graphics operations onto two distinct GPUs. I have a query about the data transfer mechanism between these GPUs:

1. **Is there an explicit use of memcpy for transferring data from the compute GPU to the graphics GPU?**
2. **In my analysis of the nsys profiler report, I've observed `MemcpyDToH` and `MemcpyHToD` operations. This leads me to question whether the inter-GPU data transfer is actually being routed through the host system.**

A16:The tool tracking post process is doing device to host copies here and here . This operations are also executed when the app is running on a single GPU. Holoviz is not doing any device to host operations, neither single nor multi GPU.

38.6 Troubleshooting

Q1: How can I debug Holoscan SDK examples and tests using Visual Studio Code?

A1: You can use the

```
./run vscode
```

command to launch VSCode in a development container. Configure CMake, build the source code, and use the Run and Debug view to start debugging sessions.

`-j <# of workers>` or `--parallel <# of workers>` can be used to specify the number of parallel jobs to run during the build process. For more information, refer to the instructions from `./run vscode -h`.

Q2: How can I get started with debugging my Holoscan application?

For debugging applications in Holoscan repo, refer to the Debugging Section. For debugging applications in Holohub, refer to HoloHub tutorials for strategies to set up debugging with Visual Studio Code or other tools such as GDB.

Q3: Is it possible to debug both C++ and Python components simultaneously in Holoscan SDK?

A3:Yes, you can use the Python C++ Debugger extension in VSCode to debug both C++ and Python components simultaneously. For more information, please refer to the Debugging section in the Holoscan SDK User Guide.

Q4: How do I analyze a core dump file when my application crashes?

A4:Use the gdb command with your application and core dump file, e.g.,

```
gdb <application> <coredump_file>
```

This will allow you to examine the stack trace and other debugging information.

Q5: What should I do if core dumps are not being generated?

A5: Enable core dumps by setting

```
ulimit -c unlimited
```

and configuring the `core_pattern value`. You may need to do this on the host system if working in a Docker container. For more information, please refer to the Debugging section in the Holoscan User Guide.

Q6: How can I debug a distributed application using UCX?

A6: Set the `UCX_HANDLE_ERRORS` environment variable to control UCX's behavior during crashes. Options include printing backtraces, attaching a debugger, or freezing the application. For more information, please refer to the Debugging section in the Holoscan User Guide.

The `UCX_LOG_LEVEL` environment variable can be set to "info" or higher level to see more detailed information about UCX transports used (the default level for UCX logging is "warn"). The full set of available UCX logging levels correspond to the list here.

Q7: What tools are available for profiling Python applications in Holoscan?

A7: You can use tools like pyinstrument, pprofile, yappi, cProfile, or line_profiler. Each has different strengths and may be more suitable depending on your specific needs. For more information , please refer to the Python debugging section in the Holoscan User Guide.

Each profiler has its strengths and is suitable for different debugging scenarios, from high-level overviews to detailed line-by-line analysis.Please find below more details:

1. pyinstrument:
    - Call stack profiler that highlights performance bottlenecks
    - Provides easily understandable output directly in the terminal
    - Multithreading-aware, suitable for use with multithreaded schedulers
    - Visualizes the execution tree, showing time spent in each function
2. pprofile:
    - Line-granularity profiler
    - Thread-aware and deterministic
    - Provides detailed statistics for each line of code
    - Shows hit counts, time per hit, and percentage of total time for each line
3. yappi:
    - Tracing profiler that is multithreading, asyncio, and gevent aware
    - Can handle complex threading scenarios in Holoscan applications
    - Provides hit counts for methods across different threads

   - Requires setting a context ID callback for accurate thread identification

4. cProfile:
   - Deterministic profiling module built into Python
   - Provides a high-level overview of function calls and time spent
   - Easy to use with minimal setup
   - Good for identifying which functions are taking the most time overall

5. line_profiler:
   - Offers line-by-line profiling of specific functions
   - Provides detailed timing information for each line within a function
   - Useful for pinpointing exact lines causing performance issues
   - Requires adding @profile decorators to functions of interest

Q8: How do I measure code coverage for my Holoscan Python application?

A8: You can use

```
Coverage.py
```

to measure code coverage.

- install it with pip
- run your application with coverage
- generate reports using commands like coverage report or coverage html

For more detailed information, please refer to Measuring Code Coverage section in the Holoscan User Guide.

Q9: How can I trace function calls in my Python application?

A9: You can use the trace module to track function calls. Run your application with

```
python -m trace --trackcalls
```

or use the trace module programmatically in your code.

Q10: How can I leverage a large language model (LLM) to assist in debugging a complex and lengthy task implemented with the Holoscan SDK?

A10: Holoscan SDK offers to do the task piecemeal and get feedback from you as it completes each part of the task. This allows for step-by-step debugging of complex, lengthy processes. For Holochat links , please refer to to Holochat-GPT to ask questions and receive feedback on building and debugging Holoscan SDK applications. Note that Holochat-GPT is not confidential and may not be trained on the latest Holoscan SDK release. Please refer to the Holoscan SDK User Guide for latest APIs.

Q11: How can I use Python's `coverage.py` with the Holoscan SDK?

A4:In Python, both coverage measurement and Python debugger is using sys.settrace() or PyEval_SetTrace() method to register a trace method for the current thread. When coverage.py or Python debugger is running, it calls those method (and threading.settrace for newly-created threads) for tracing Python code execution.However, when Python methods (such as compute()) are called by the threads (worker(s) of GreedyScheduler/MultiThreadScheduler) in Holoscan SDK, which is not derived from the Python's main thread, sys.settrace() (or PyEval_SetTrace()) is not called properly for those threads.The resolution is:

1. Capture the current trace method (by using sys.gettrace(), let's say `CURR_TRACE_METHOD`- if it exists when `Application.run()` method is called. 2. When Python methods (such as Operator.compute()/Fragment.compose()/Operator.initialize()/Operator.start()/Operator.stop()) are called, get current trace method (by using sys.gettrace()) and call sys.settrace(`CURR_TRACE_METHOD`) and set current stack frame's `f_trace` to `CURR_TRACE_METHOD` (current stack frame is available through inspect.currentframe()) if no trace method was set before.

- This process can be sped up by storing thread id-> <trace method> map (or using thread local variable) and checking if trace method is already registered to the current thread.

Python's cProfile module is using sys.setprofile() instead of sys.settrace() (because the profile method is called per method, which is more effective), and we can apply similar approach for enabling profiler on Holoscan's Python Operator methods.

Q12:How does Holoscan SDK reconcile command line arguments for multi-fragment applications?

A12: The CLI arguments (such as –driver, –worker, –fragments) are parsed by the Application class and the remaining arguments are available as app.argv property.

```python
import argparse
import sys
from holoscan.core import Application

class MyApp(Application):
    def compose(self):
        pass

if __name__ == "__main__":
    app = MyApp()

    print("sys.argv:", sys.argv)
    print("app.argv:", app.argv)

    parser = argparse.ArgumentParser()
    parser.add_argument("--input")
    args = parser.parse_args(app.argv[1:])
    print("args:", args)

    app.run()

# $ python cli_test.py --address 12.3.0 --input a
# sys.argv: ['cli_test.py', '--address', '12.3.0', '--input', 'a']
# app.argv: ['cli_test.py', '--input', 'a']
args: Namespace(input='a')
```

Q13:Why is the Inference Operator rejecting the input shape for a CNN-LSTM model with a 5-dimensions input (batch, temporal_dim, channels, width, height) ? A13: In Holoscan SDK v2.4 and earlier, the InferenceOp supports rank only between 2 and 4.

Q14: I am attempting to profile a Holoscan application in a container using NVIDIA NSight Systems. I'm following the documentation available at https://github.com/nvidia-holoscan/holohub/blob/main/doc/developer.md and using a recent checkout of Holohub with the Holoscan v2.1 NGC image.

My process is as follows:

1. **Initiate the development container with NSight profiling enabled:**

```
./dev_container launch --nsys_profile
```

1. **Launch the endoscopy tool tracking application with NSight profiling:**

```
./run launch endoscopy_tool_tracking python --nsys_profile
```

However, I encounter the following error:

```
ERROR: For Nsight Systems profiling the Linux operating system's perf_event_paranoid␣
↪level must be 2 or less.
See https://docs.nvidia.com/nsight-systems/InstallationGuide/index.html#linux-
↪requirements for more information.
```

How can I fix it ?

A14: The

```

sudo sh -c 'echo 2 >/proc/sys/kernel/perf_event_paranoid'
```

command needs to be executed on the host system, not inside the container.

- Check the current value

```
cat /proc/sys/kernel/perf_event_paranoid
```

- To temporarily change the value to 2 (which allows kernel profiling by unprivileged users):

```
sudo sh -c 'echo 2 >/proc/sys/kernel/perf_event_paranoid'
```

- To make the change permanent, edit `/etc/sysctl.conf`: Add or modify the line:

```
update /etc/sysctl.conf
```

- Then apply the changes:

```
sudo sysctl -p
```

- If you need to allow use of almost all events by all users, you can set the value to -1 instead of 2.
- The values and their meanings:
  - -1: Allow use of (almost) all events by all users
  - 0 or higher: Disallow ftrace function tracepoint by users without CAP_SYS_ADMIN
  - 1 or higher: Also disallow CPU event access by users without CAP_SYS_ADMIN
  - 2 or higher: Also disallow kernel profiling by users without CAP_SYS_ADMIN
- After making changes, you may need to restart your application or services that depend on these performance events.
- Refer to the perf_event_open manpage for more detailed information.

Remember that lowering this value increases the access unprivileged users have to performance data, which could potentially be a security concern in some environments. Always consider the security implications before making such changes. Refer to the NVIDIA Nsight Systems installation guide for more information.

Q15: I am developing an application utilizing two distinct processing graphs:

1. **VideoReplayerOp -> HolovizOp**
2. **CameraOp -> HolovizOp**

The first graph displays source video for camera observation, while the second applies AI processing to enhance camera input. Currently, I am employing two separate Holoviz instances, with the instance for source video (graph 1) exclusively utilizing the second monitor (DP-4).

I've encountered an issue during application termination: when pressing 'Esc' to exit, the main Holoviz instance on the primary screen closes as expected, but the source video continues playing on the secondary screen. While I can force quit the application using 'Ctrl+C', I am seeking a more elegant solution for proper termination.

Is there a recommended method for gracefully closing the entire application?

A15:To address your concerns about graceful application termination with multiple Holoviz instances, let's first understand how the ESC key functions in Holoviz:

1. ESC Key Behavior:
   - Holoviz monitors for window closure requests via the ESC key.
   - When pressed, it deactivates the associated HolovizOp by setting a boolean scheduling term to false.
2. Termination Scenarios:
   - Single HolovizOp: ESC key press closes the entire application.
   - Multiple HolovizOps: ESC only terminates the specific Holoviz instance, leaving others running.

Proposed Solution:

To achieve synchronized termination across all Holoviz instances:

1. Create a shared boolean scheduling condition.
2. For each HolovizOp in your application:
   - Set this condition as a general execution condition.
   - Importantly, also set it as the `window_close_condition` parameter (Note: this parameter was named `window_close_scheduling_term` in releases prior to v2.7).

Q16:I'm trying to use the `render_buffer_output` from Holoviz Python operator, but I get the following error :

```
[error] [entity.hpp:90] Unable to find component from the name 'render_buffer_output'␣
↪(error code: 24)
```

A16:The reason why you are getting this error is because HolovizOp returns a gxf::VideoBuffer which is not yet supported by Python in Holoscan SDK.

Q17:I am using an AGX Orin with an MST board, with 2 display monitors - DP-0.1 (touch screen) and DP-0.2 (an external main display). I am trying to force Holoviz to display on monitor DP-0.2, by setting `use_exclusive_display = True`, `display_name = "DP-0.2"`. But this results in error below:

```
[info] [exclusive_window.cpp:125] _____________________
[info] [exclusive_window.cpp:126] Available displays :
[info] [exclusive_window.cpp:129] ADA (DP-0.1)
[info] [exclusive_window.cpp:129] LG Electronics LG ULTRAWIDE (DP-0.2)
[info] [exclusive_window.cpp:134]
[info] [exclusive_window.cpp:135] Using display "LG Electronics LG ULTRAWIDE (DP-0.2)"
[info] [exclusive_window.cpp:148] X server is running, trying to acquire display
```

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```
[error] [context.cpp:56] VkResult -13 - unknown
[error] [gxf_wrapper.cpp:57] Exception occurred when starting operator: 'holoviz' -␣
↪Failed to acquire display from X-Server.
```

As a potential fix, I have disabled the main display in nvidia-settings for the compositor, but the application still crashes with the following error:

```
[error] [context.cpp:56] /workspace/holoscan-sdk/modules/holoviz/thirdparty/nvpro_core/
↪nvvk/swapchain_vk.cpp(172): Vulkan Error : unknown
[error] [context.cpp:56] /workspace/holoscan-sdk/modules/holoviz/thirdparty/nvpro_core/
↪nvvk/swapchain_vk.cpp(172): Vulkan Error : unknown
[error] [context.cpp:56] /workspace/holoscan-sdk/modules/holoviz/thirdparty/nvpro_core/
↪nvvk/swapchain_vk.cpp(172): Vulkan Error : unknown
[error] [gxf_wrapper.cpp:57] Exception occurred when starting operator: 'holoviz' -␣
↪Failed to update swap chain.
```

A17:The progress indicated by the message “[info] [exclusive_window.cpp:161] Using display mode 1920x1080 60.000 Hz” is a positive sign. However, the failure of Vulkan swap chain creation with an unknown error is concerning. While we regularly test exclusive display with discrete GPUs (dGPUs), this is seldom tested with integrated GPUs (iGPUs). In the past, we’ve encountered issues with Vulkan features on iGPUs.

An alternative option would be to use fullscreen mode, which is known to work on iGPUs. It’s important to note that Holoviz always opens in fullscreen mode on the primary display, and display name selection is not currently supported.

Given that the display they want to use for Holoviz appears to be the primary display, you could try setting `fullscreen = True` instead of `use_exclusive_display = True`.

Q18: How can I use CuPy arrays with Holoscan SDK’s InferenceOp? A18: Both CuPy and Holoscan SDK support `_cuda_array_interface` to facilitate seamless array integration among libraries. Refer to the HoloHub library integration tutorial CuPy section for details on using CuPy arrays in a Holoscan SDK application.

Q19:I am running into these errors when using the Holoscan Packager in my networking environment:

```
curl: (6) Could not resolve host: github.com.
Failed to establish a new connection:: [Errno -3] Temporary failure in name solution...
```

A19:To resolve these errors, edit the `/etc/docker/daemon.json` file to include `dns` and `dns-search` fields as follows:

```
{
    "default-runtime": "nvidia",
    "runtimes": {
        "nvidia": {
            "args": [],
            "path": "nvidia-container-runtime"
        }
    },
    "dns": ["IP-1", "IP-n"],
    "dns-search": ["DNS-SERVER-1", "DNS-SERVER-n"]
}
```

You may need to consult your IT team and replace `IP-x` and `DNS-SERVER-x` with the provided values.

Q20:I am seeing the following error when trying to use the `RMMAllocator`

When running the application, if it fails to start with an error like the following being logged:

```
[error] [rmm_allocator.cpp:74] Unexpected error while initializing RMM Allocator rmm_
↪allocator: std::bad_alloc: out_of_memory: RMM failure at:bazel-out/k8-opt/bin/external/
↪rmm/_virtual_includes/rmm/rmm/mr/device/pool_memory_resource.hpp:424: Maximum pool␣
↪size exceeded
```

This indicates that the requested memory sizes on host and/or device exceed the available memory. Please make sure that your device supports the specified memory size. Also check that the specified the values for `device_memory_initial_size`, `device_memory_max_size`, `host_memory_initial_size` and `host_memory_max_size` were specified using the intended units (B, KB, MB, GB or TB).

38.7 Miscellaneous

Q1: Can I use DLA cores with the Holoscan SDK?

A1: There are 2 situations in which Holsocan SDK can support Deep Learning Accelerator (DLA) cores. You can configure your application to offload certain inference tasks to DLA cores to improve performance and efficiency.

- User created engine file: If the TensorRT engine file is created with `-useDLACore=0` and the engine file is used in the Holsocan SDK inference framework, then it will use DLA (core 0) as HoloInfer just guides the execution to TensorRT and it will automatically pick it up.The user must give the path to engine file in `model_path_map` and enable the flag `is_engine_path=true` in the inference parameter set.
- If user is creating engine file via HoloInfer: HoloInfer currently does not support using any DLA cores for engine creation (even if it's available) and it defaults to GPU.

Q2: How can I generate HSDK applications from Graph Composer?

A2:In Graph Composer, graph nodes (entities) are based on GXF Codelets/Components (from GXF extensions) that are registered in the Graph Composer registry. Currently, none of the Holoscan operators are registered in this registry. However, we have a method to convert Holoscan Operators into GXF extensions. Please find example code below :

- https://github.com/nvidia-holoscan/holoscan-sdk/tree/main/examples/wrap_operator_as_gxf_extensio
- https://github.com/nvidia-holoscan/holoscan-sdk/tree/main/gxf_extensions/gxf_holoscan_wrapper

To generate or run an application graph (pipeline) described in Graph Composer, we need a method to import GXF Codelets/Components as Holoscan Operators/Resources. Currently, users need to manually wrap GXF Codelets/Resources to convert them into Holoscan Operators/Resources.

Q3: How can I support external events like React?

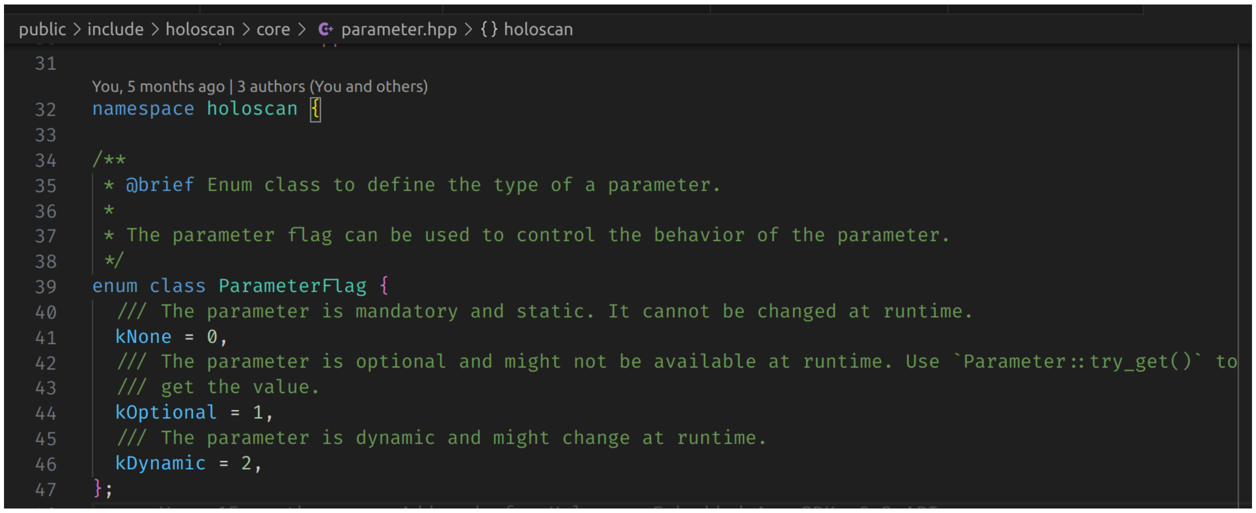
A3:Regarding parameter flags, we support GXF's optional/dynamic parameter flag (Figure 1) and can set it in the `Operator::setup(OperatorSpec& spec)` method using `spec.param(..., ParameterFlag::kDynamic);` (Figure 2). However, this parameter flag is primarily for wrapping GXF Codelets. When implementing a Holoscan Native operator, there is no runtime check for parameter value changes, allowing us to update parameter values and use them without setting the parameter flag (`holoscan::Parameter<T>` simply acts as a value holder using `std::any`).

To support external events/controls (such as for Qt), we can implement a Holoscan Resource (GXF Component) that handles events and state management. This would allow a Holoscan operator to update the state based on events and use it, similar to React's state management approach. QtHoloscanVideo (Figure 3) could be a good candidate for such a Holoscan Resource.

For reference, CudaStreamPool is an example of a Holoscan Resource (wrapping the GXF CudaStreamPool component), and the object is passed to the operator as an argument (Figure 4). However, it's not necessary to pass Holoscan resources as arguments. Instead, we can provide them to the operator (Figure 5) and access them through the `resource<T>()` method inside the `compute()` method (Figure 6). In Python, resources can be accessed via the `op.resources` property (which is of type `dict[str, Resource]`).

Holoscan supports Native Resources for C++ (with an example demonstrating this feature), but Native Python resources have not been implemented yet.

Given this situation, it might be preferable to implement it as a GXF Component and expose it as a C++/Python Holoscan Resource. This approach would allow QtVideoOp (in Figure 3) to define a public method for accessing the event/control Holoscan resource object from the Qt app logic (possibly through a `HoloscanVideo*` object in QtVideoOp).

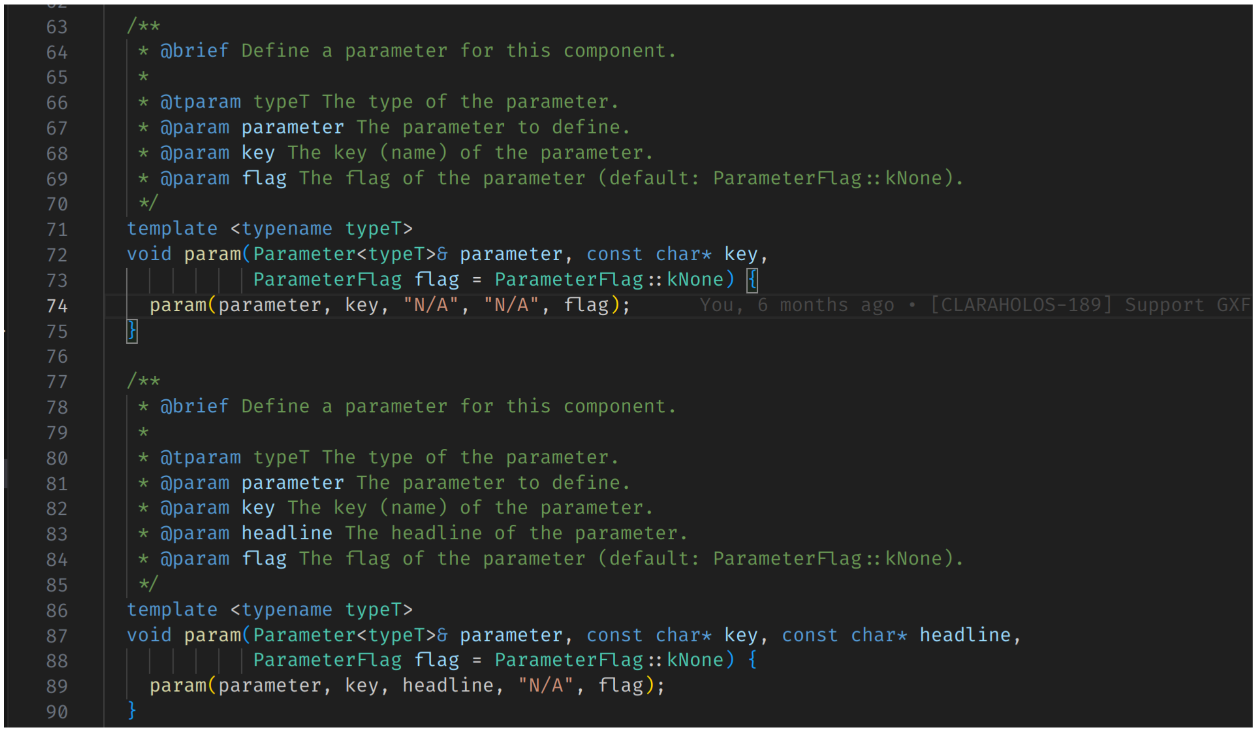


public > include > holoscan > core > parameter.hpp > {} holoscan

```
You, 5 months ago | 3 authors (You and others)
namespace holoscan {

/**
 * @brief Enum class to define the type of a parameter.
 *
 * The parameter flag can be used to control the behavior of the parameter.
 */
enum class ParameterFlag {
  /// The parameter is mandatory and static. It cannot be changed at runtime.
  kNone = 0,
  /// The parameter is optional and might not be available at runtime. Use `Parameter::try_get()` to
  /// get the value.
  kOptional = 1,
  /// The parameter is dynamic and might change at runtime.
  kDynamic = 2,
};
```

Figure 1



```
  /**
   * @brief Define a parameter for this component.
   *
   * @tparam typeT The type of the parameter.
   * @param parameter The parameter to define.
   * @param key The key (name) of the parameter.
   * @param flag The flag of the parameter (default: ParameterFlag::kNone).
   */
  template <typename typeT>
  void param(Parameter<typeT>& parameter, const char* key,
             ParameterFlag flag = ParameterFlag::kNone) {
    param(parameter, key, "N/A", "N/A", flag);       You, 6 months ago • [CLARAHOLOS-189] Support GXF
  }

  /**
   * @brief Define a parameter for this component.
   *
   * @tparam typeT The type of the parameter.
   * @param parameter The parameter to define.
   * @param key The key (name) of the parameter.
   * @param headline The headline of the parameter.
   * @param flag The flag of the parameter (default: ParameterFlag::kNone).
   */
  template <typename typeT>
  void param(Parameter<typeT>& parameter, const char* key, const char* headline,
             ParameterFlag flag = ParameterFlag::kNone) {
    param(parameter, key, headline, "N/A", flag);
  }
```

Figure 2

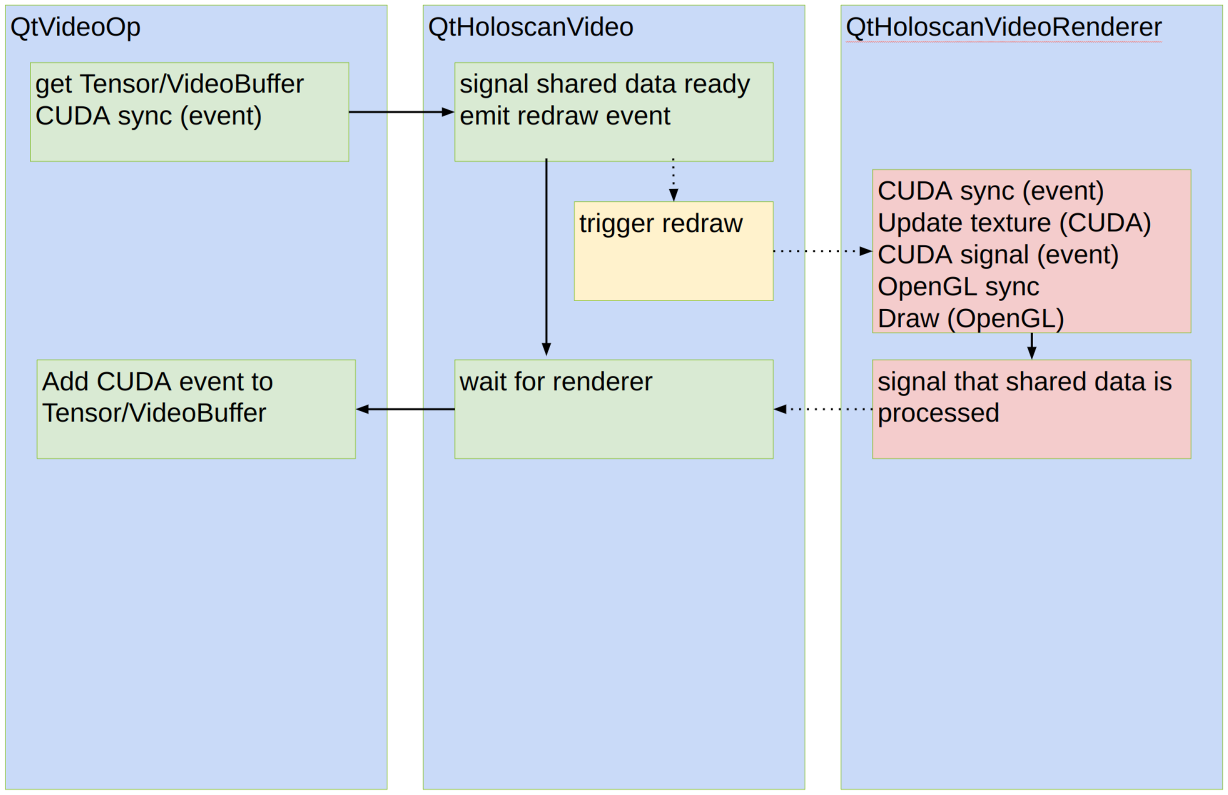
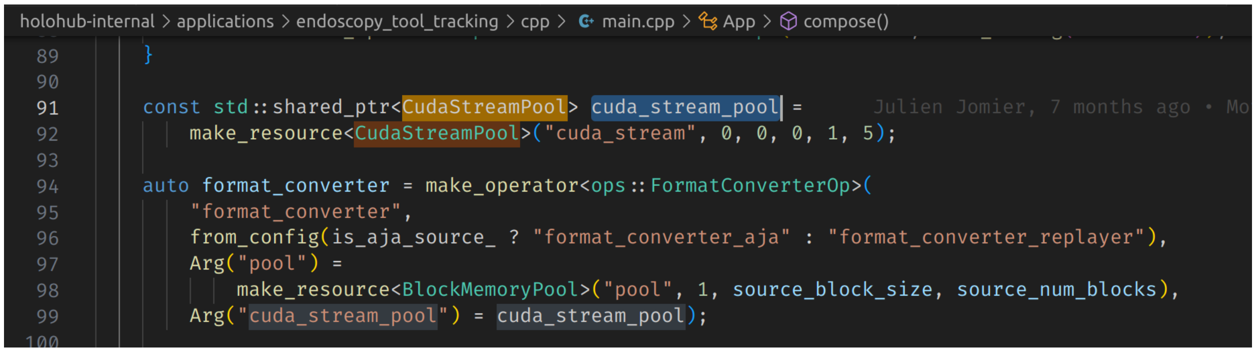


Figure 3



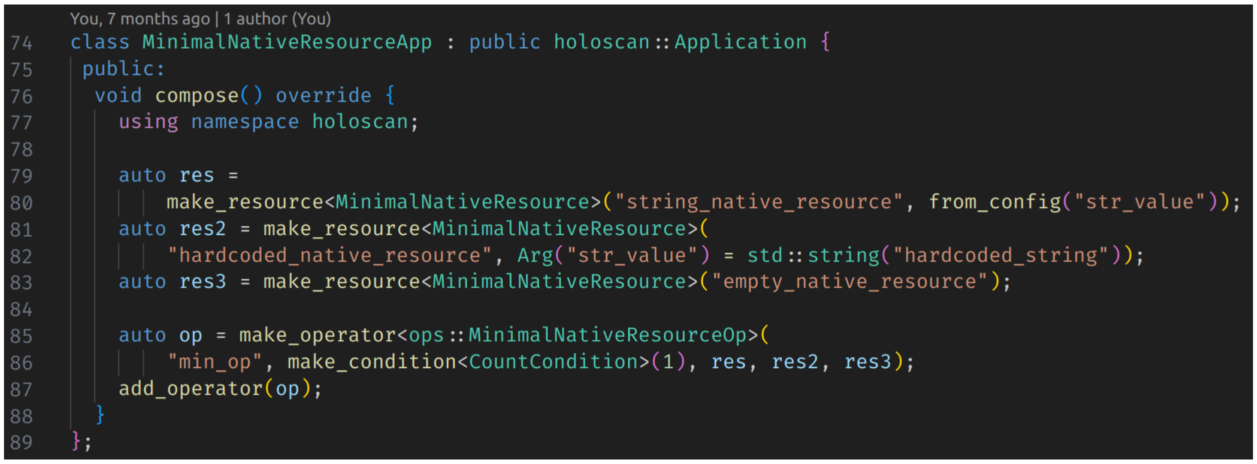
holohub-internal > applications > endoscopy_tool_tracking > cpp > main.cpp > App > compose()

```
    }

    const std::shared_ptr<CudaStreamPool> cuda_stream_pool =      Julien Jomier, 7 months ago • Mo
        make_resource<CudaStreamPool>("cuda_stream", 0, 0, 0, 1, 5);

    auto format_converter = make_operator<ops::FormatConverterOp>(
        "format_converter",
        from_config(is_aja_source_ ? "format_converter_aja" : "format_converter_replayer"),
        Arg("pool") =
            make_resource<BlockMemoryPool>("pool", 1, source_block_size, source_num_blocks),
        Arg("cuda_stream_pool") = cuda_stream_pool);
```

Figure 4



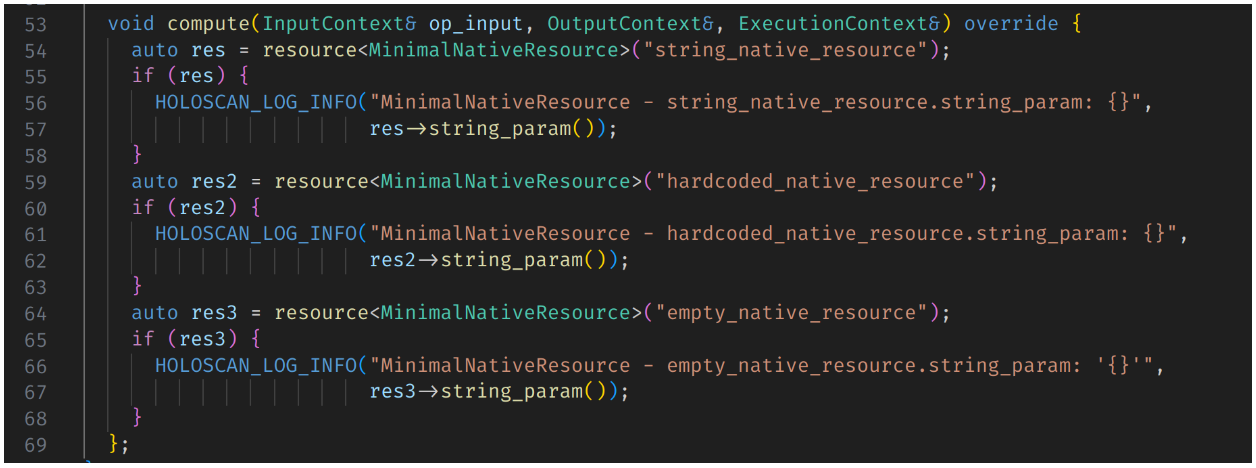
You, 7 months ago | 1 author (You)

```
class MinimalNativeResourceApp : public holoscan::Application {
 public:
  void compose() override {
    using namespace holoscan;

    auto res =
        make_resource<MinimalNativeResource>("string_native_resource", from_config("str_value"));
    auto res2 = make_resource<MinimalNativeResource>(
        "hardcoded_native_resource", Arg("str_value") = std::string("hardcoded_string"));
    auto res3 = make_resource<MinimalNativeResource>("empty_native_resource");

    auto op = make_operator<ops::MinimalNativeResourceOp>(
        "min_op", make_condition<CountCondition>(1), res, res2, res3);
    add_operator(op);
  }
};
```

Figure 5



```
  void compute(InputContext& op_input, OutputContext&, ExecutionContext&) override {
    auto res = resource<MinimalNativeResource>("string_native_resource");
    if (res) {
      HOLOSCAN_LOG_INFO("MinimalNativeResource - string_native_resource.string_param: {}",
                        res->string_param());
    }
    auto res2 = resource<MinimalNativeResource>("hardcoded_native_resource");
    if (res2) {
      HOLOSCAN_LOG_INFO("MinimalNativeResource - hardcoded_native_resource.string_param: {}",
                        res2->string_param());
    }
    auto res3 = resource<MinimalNativeResource>("empty_native_resource");
    if (res3) {
      HOLOSCAN_LOG_INFO("MinimalNativeResource - empty_native_resource.string_param: '{}'",
                        res3->string_param());
    }
  };
```

Figure 6

Q5: I'm encountering difficulties implementing the `PYBIND11_OVERRIDE_PURE` mechanism in pybind11. Specifically, I'm trying to override a pure virtual C++ method with a Python subclass, but it's not working as expected. The Python subclass doesn't seem to be successfully overriding the C++ method. A5:A potential fix is to keep a global reference to the Python object.Please refer to the fix provide here.

This code addresses a potential issue in pybind11's handling of class inheritance and instance management. The problem arises when mocking the C++ `RoceReceiverOp` class with a Python `InstrumentedReceiverOperator` class. Here's a breakdown of the situation:

1. Issue: When the Holoscan app runs, it calls methods from `RoceReceiverOp` instead of the intended `InstrumentedReceiverOperator` methods.
2. Cause: The `InstrumentedReceiverOperator` instance seems to disappear from pybind11's internal registry during app execution. This occurs despite expectations that passing it to C++ should maintain its lifecycle.
3. Debugging attempts: Efforts to track the instance deregistration (via breakpoints in pybind11's `deregister_instance()`) were unsuccessful, leaving the exact cause unclear.
4. Workaround: To prevent the premature destruction of the `InstrumentedReceiverOperator` instance, the code maintains a global reference to it.

This solution ensures the mocked class instance remains available throughout the app's lifecycle, allowing proper method overriding and execution.

38.8 Additional Resources

Q1: Where can I find additional resources and support for the Holoscan SDK?

A1: Additional resources and support can be found on:

- The NVIDIA developer page.For more information, please refer to this link.
- Holoscan SDK GitHub repository.Please refer to this link.
- NVIDIA Developer Forums for community support and discussions. For the Holoscan SDK forum, please refer to this link.

Q2: How can I contribute to the Holoscan SDK?

A2: The Holoscan SDK is open-source. You can contribute by:

- Submitting pull requests for bug fixes or new features. For more detailed information on how to contribute, please refer to this link.
- Participating in community discussions on the Holoscan SDK forum