Performance Optimization Using the NVIDIA Visual Profiler

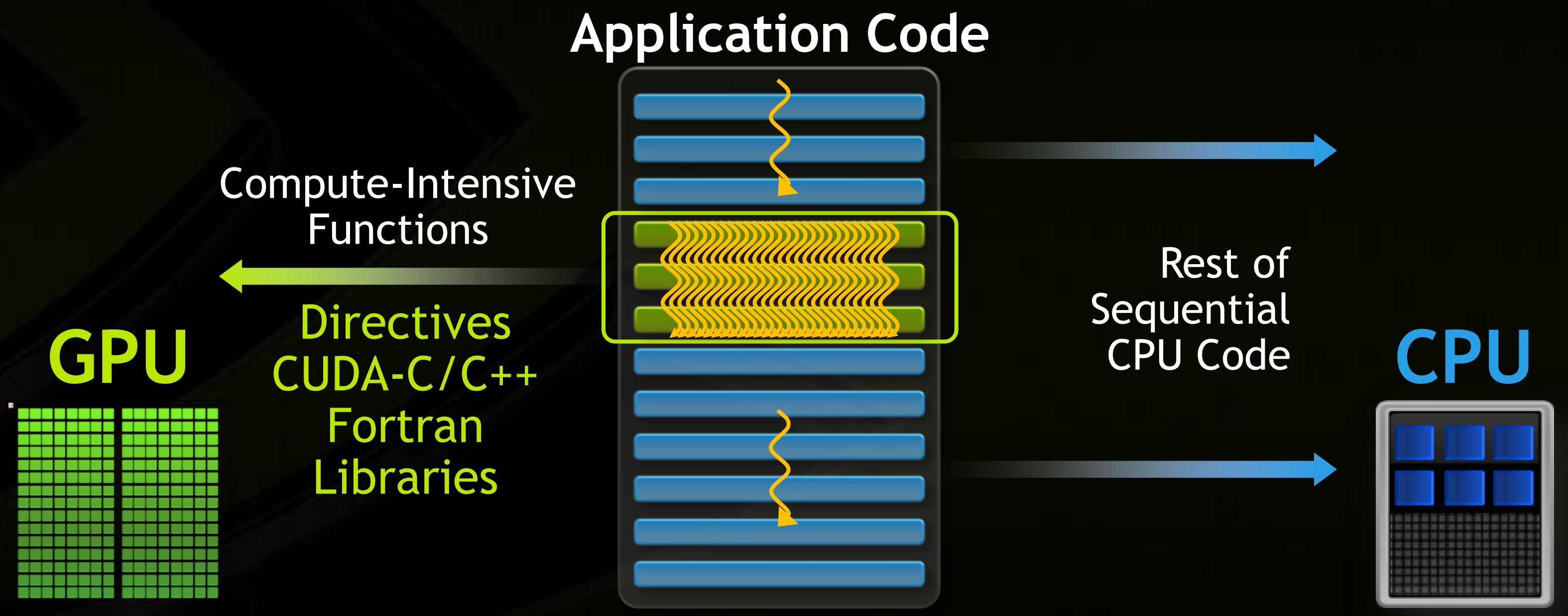
Optimization: CPU and GPU

- A few cores
- Good memory bandwidth
- Best at serial execution

- Hundreds of cores
- Great memory bandwidth
- Best at parallel execution

Optimization: Maximize Performance

- Take advantage of strengths of both CPU and GPU
- Entire application does not need to be ported to GPU

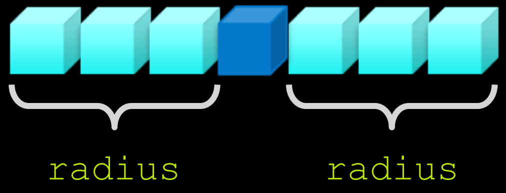


Application Optimization Process and Tools

- Identify Optimization Opportunities
  - gprof
  - Intel VTune
- Parallelize with CUDA, confirm functional correctness
  - cuda-gdb, cuda-memcheck
  - Parallel Nsight Memory Checker, Parallel Nsight Debugger
  - 3rd party: Allinea DDT, TotalView
- Optimize
  - NVIDIA Visual Profiler
  - Parallel Nsight
  - 3rd party: Vampir, Tau, PAPI, …

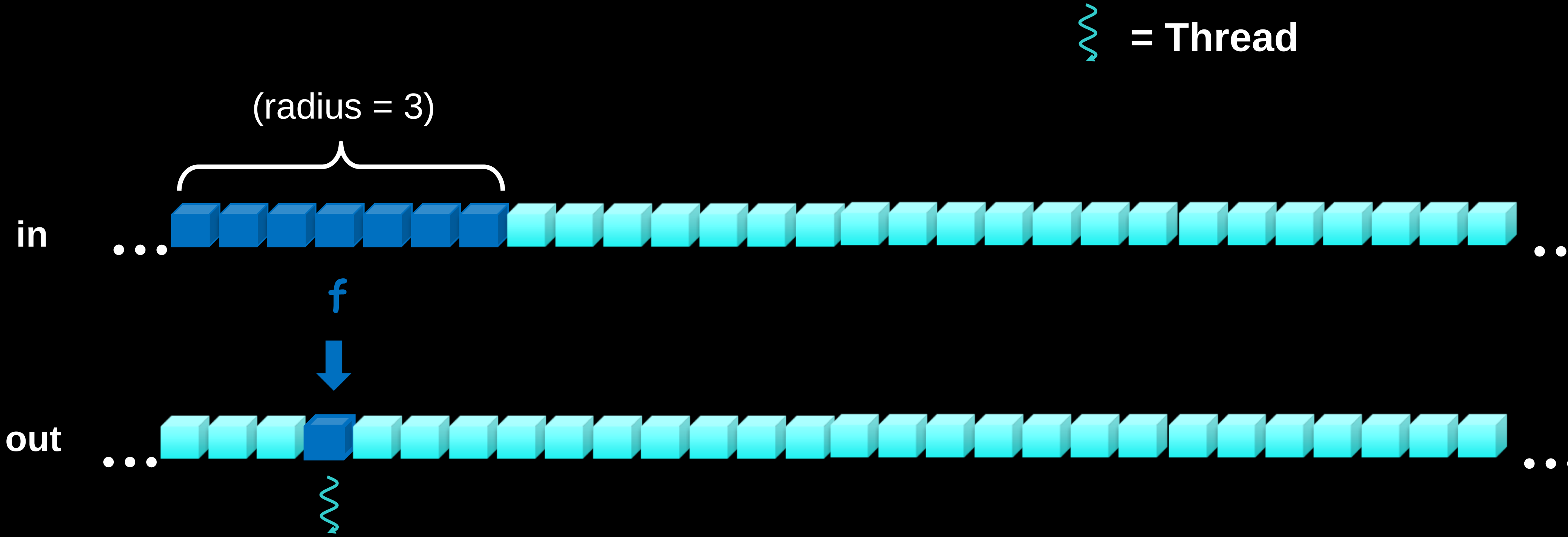
1D Stencil: A Common Algorithmic Pattern

- Applying a 1D stencil to a 1D array of elements
  - Function of input elements within a radius

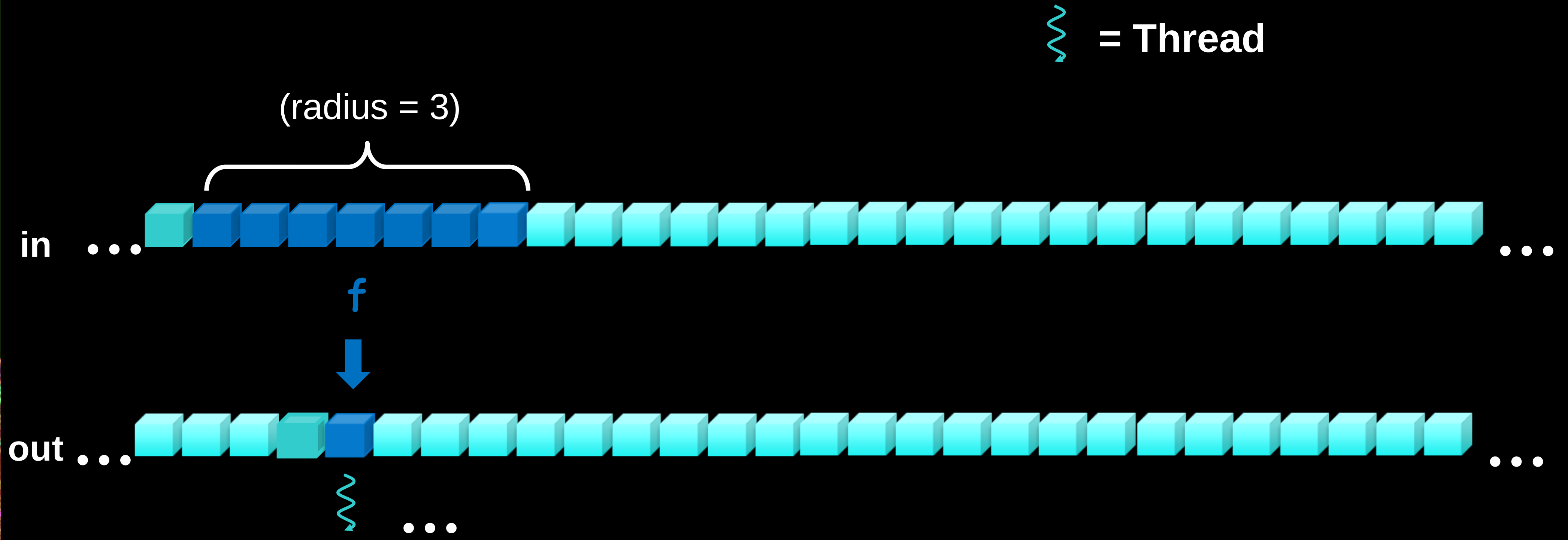


- Fundamental to many algorithms
  - Standard discretization methods, interpolation, convolution, filtering
- Our example will use weighted arithmetic mean

Serial Algorithm



Serial Algorithm



Repeat for each element

Serial Implementation

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);

  applyStencil1D(RADIUS,N-RADIUS,weights,in,out);

  //free resources
  free(weights); free(in); free(out);
}
```

```
void applyStencil1D(int sIdx, int eIdx, const
         float *weights, float *in, float *out) {

  for (int i = sIdx; I < eIdx; i++) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Serial Implementation

```c
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);

  applyStencil1D(RADIUS,N-RADIUS,weights,in,out);

  //free resources
  free(weights); free(in); free(out);
}
```

```c
void applyStencil1D(int sIdx, int eIdx, const
        float *weights, float *in, float *out) {

             = sIdx; i < eIdx; i++) {
          [i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Allocate and initialize

Apply stencil

Cleanup

Serial Implementation

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(
  initializeWeights(weights,
  initializeArray(in, N);

  applyStencil1D(RADIUS,N-RADIUS,weights,in,out);

  //free resources
  free(weights); free(in); free(out);
}
```

Weighted mean over radius

```
void applyStencil1D(int sIdx, int
        float *weights, float *i

  for (int i = sIdx; I < eIdx; i++) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

For each element…

Serial Implementation Performance

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);

  applyStencil1D(RADIUS,N-RADIUS

  //free resources
  free(weights); free(in); free(
}
```

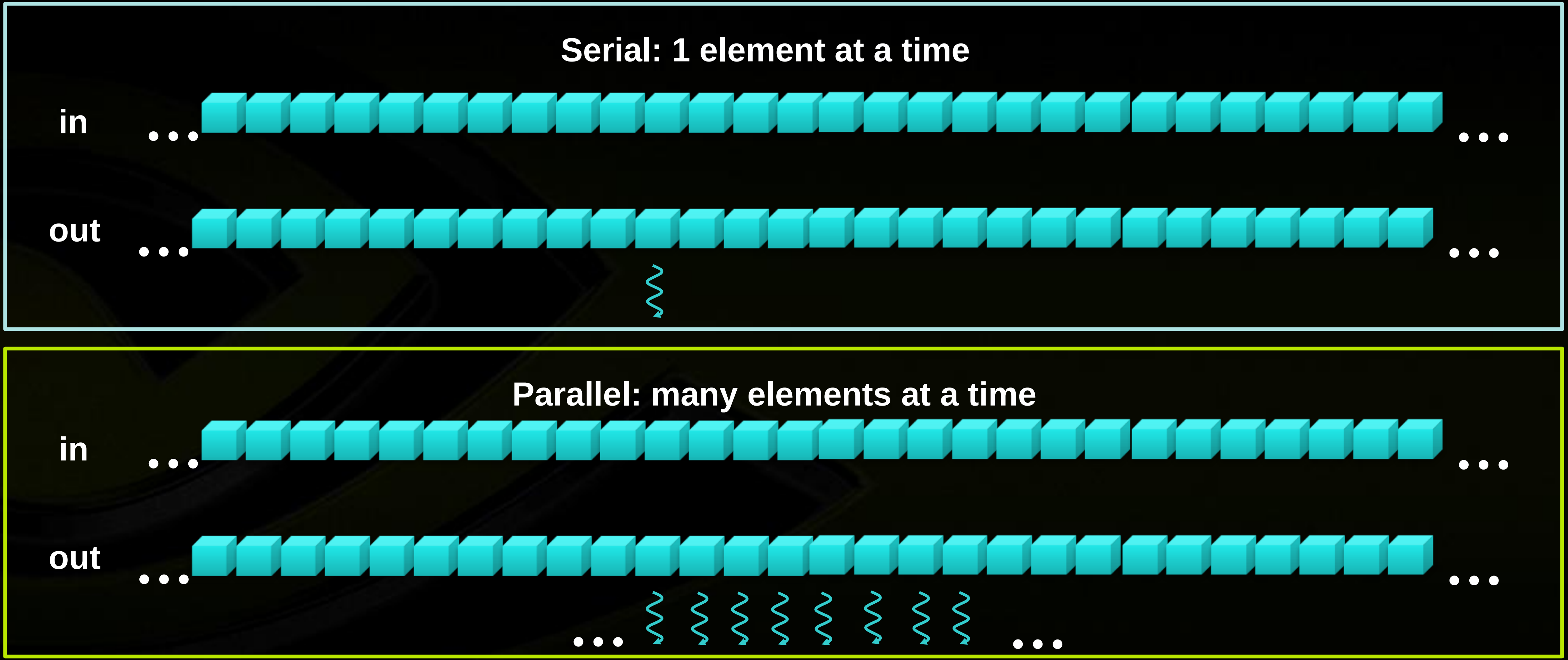
```
void applyStencil1D(int sIdx, int eIdx, const
          float *weights, float *in, float *out) {

  for (int i = sIdx; I < eIdx; i++) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
```

CPU	MElements/s
i7-930	30

Parallel Algorithm

= Thread



Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights,wsize,cudaMemcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
  applyStencil1D<<<N/512, 512>>>
             (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

Indicates GPU kernel

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights,wsize,cudaMemcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
  applyStencil1D<<<N/512, 512>>>
             (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

            Idx + blockIdx.x*blockDim.x + threadIdx.x;
             x) {
             = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Allocate GPU memory

Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights,wsize,cudaMemcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
  applyStencil1D<<<N/512, 512>>>
               (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
          all elements in the stencil
                 DIUS; j <= RADIUS; j++) {
                 ts[j + RADIUS] * in[i + j];

    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Copy inputs to GPU

Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_we
  float *d_in;       cudaMalloc(&d_in,
  float *d_out;      cudaMalloc(&d_out, si

  cudaMemcpy(d_weights,weights,wsize,cu    emcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemc  yHostToDevice);
  applyStencil1D<<<N/512, 512>>>
              (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

Launch a thread for each element

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float
  float *in = (float *)ma
  float *out= (float *)mal
  initializeWeights(weights, RAD
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights,wsize,cudaMemcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
  applyStencil1D<<<N/512, 512>>>
             (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

Get the array index for each thread.

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Each thread executes kernel

Parallel Implementation With CUDA

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights,wsize,cudaMemcpyHostToDevice);
  cudaMemcpy(d_in, in, size, cudaMemcpyHostToDevice);
  applyStencil1D<<<N/512, 512>>>
              (RADIUS, N-RADIUS, d_weights, d_in, d_out);
  cudaMemcpy(out, d_out, size, cudaMemcpyDeviceToHost);

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Copy results from GPU

Parallel Implementation Performance

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights = (float *)malloc(wsize);
  float *in = (float *)malloc(size);
  float *out= (float *)malloc(size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;  cudaMalloc(&d_weights, wsize);
  float *d_in;       cudaMalloc(&d_in, size);
  float *d_out;      cudaMalloc(&d_out, size);

  cudaMemcpy(d_weights,weights
  cudaMemcpy(d_in, in, size, c
  applyStencil1D<<<N/512, 512>
             (RADIUS, N-RADI
  cudaMemcpy(out, d_out, size,

  //free resources
  free(weights); free(in); free(out);
  cudaFree(d_weights);  cudaFree(d_in);  cudaFree(d_out);
}
```

```
__global__ void applyStencil1D(int sIdx, int eIdx,
      const float *weights, float *in, float *out) {

  int i = sIdx + blockIdx.x*blockDim.x + threadIdx.x;
  if (i < eIdx) {
    out[i] = 0;
    //loop over all elements in the stencil
    for (int j = -RADIUS; j <= RADIUS; j++) {
      out[i] += weights[j + RADIUS] * in[i + j];
    }
    out[i] = out[i] / (2 * RADIUS + 1);
  }
}
```

Device	Algorithm	MElements/s	Speedup
i7-930*	Optimized & Parallel	130	1x
Tesla C2075	Simple	285	2.2x

*4 cores + hyperthreading

2x Performance In 2 Hours

- In just a couple of hours we…
  - Used CUDA to parallelize our application
  - Got 2.2x speedup over parallelized and optimized CPU code

- We used CUDA-C/C++, but other options available…
  - Libraries (NVIDIA and 3rd party)
  - Directives
  - Other CUDA languages (Fortran, Java, …)

Application Optimization Process (Revisited)

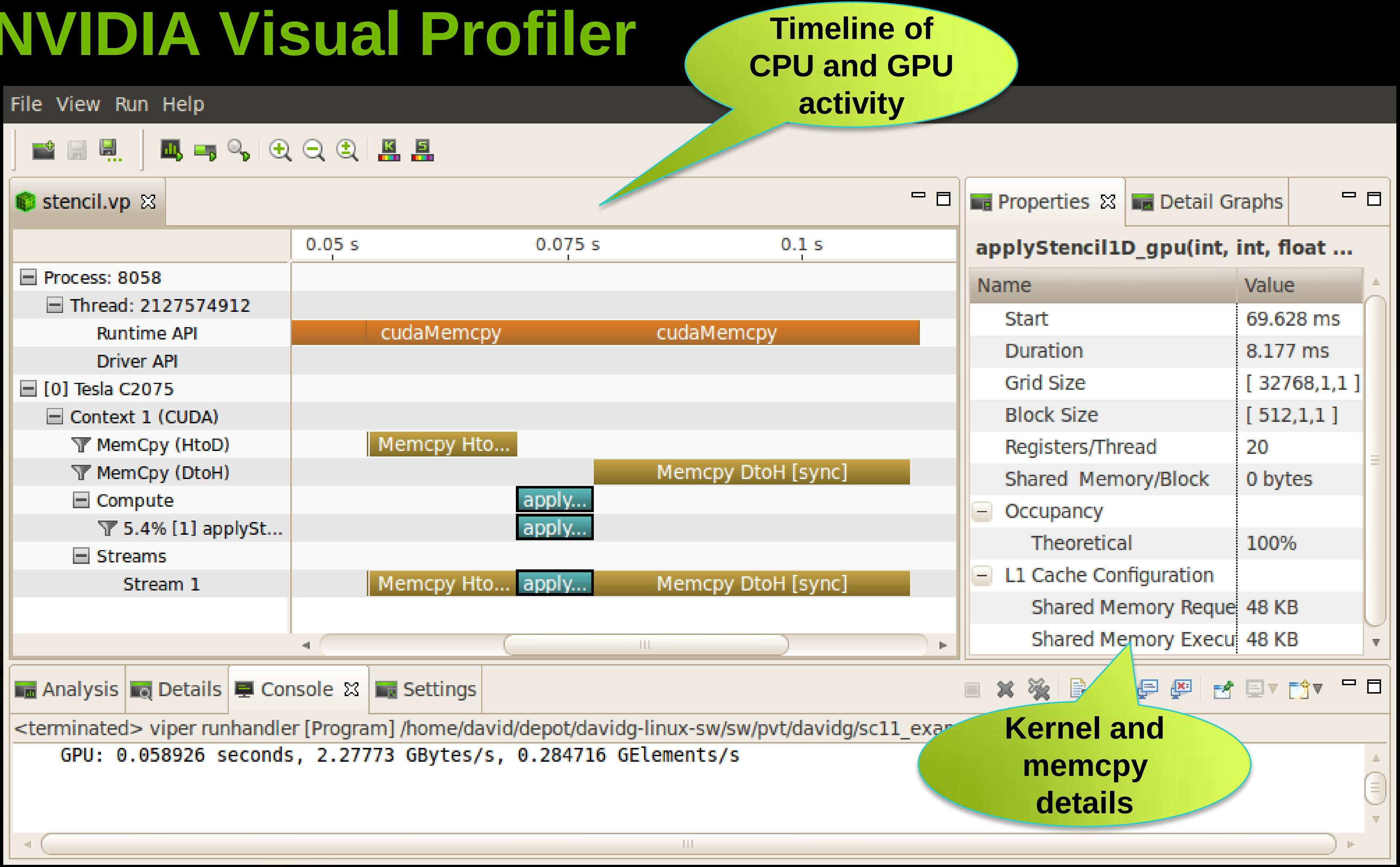
- Identify Optimization Opportunities
  - 1D stencil algorithm
- Parallelize with CUDA, confirm functional correctness
  - cuda-gdb, cuda-memcheck
- Optimize
  - ?

Optimize

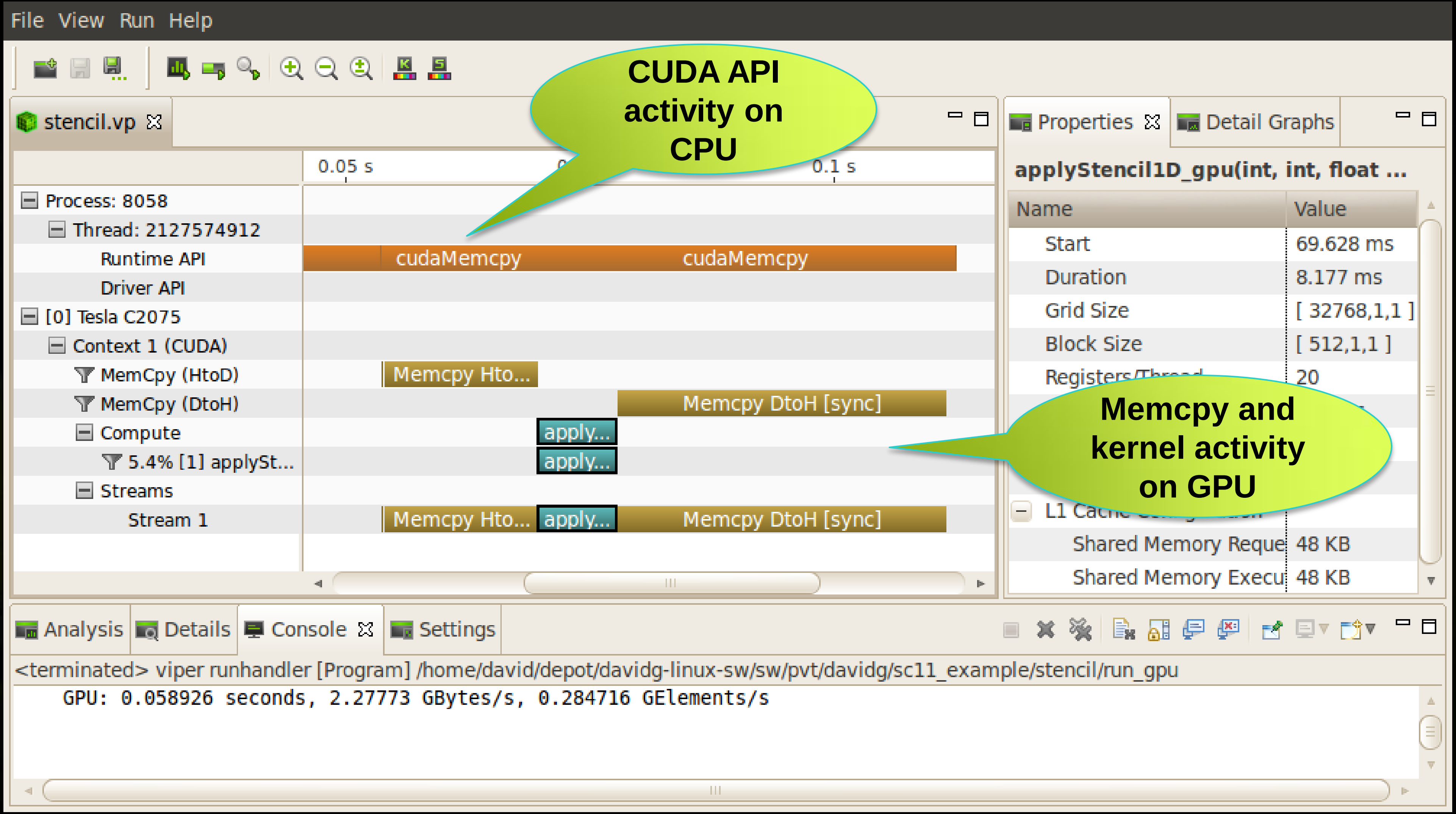
- Can we get more performance?

- Visual Profiler
  - Visualize CPU and GPU activity
  - Identify optimization opportunities
  - Automated analysis

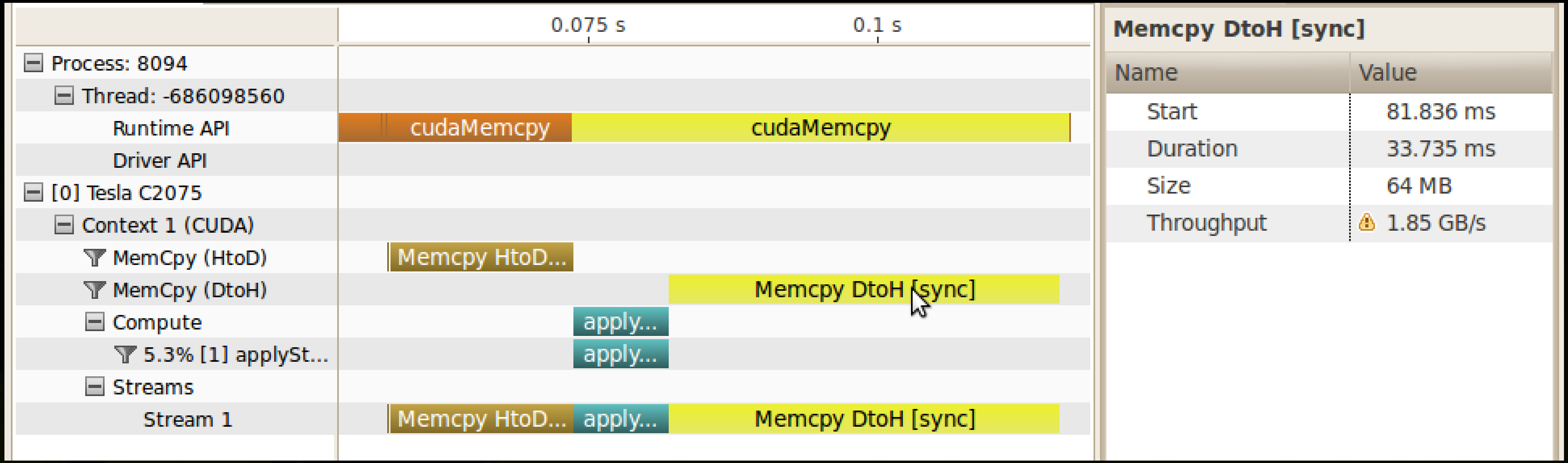
NVIDIA Visual Profiler



NVIDIA Visual Profiler



Detecting Low Memory Throughput

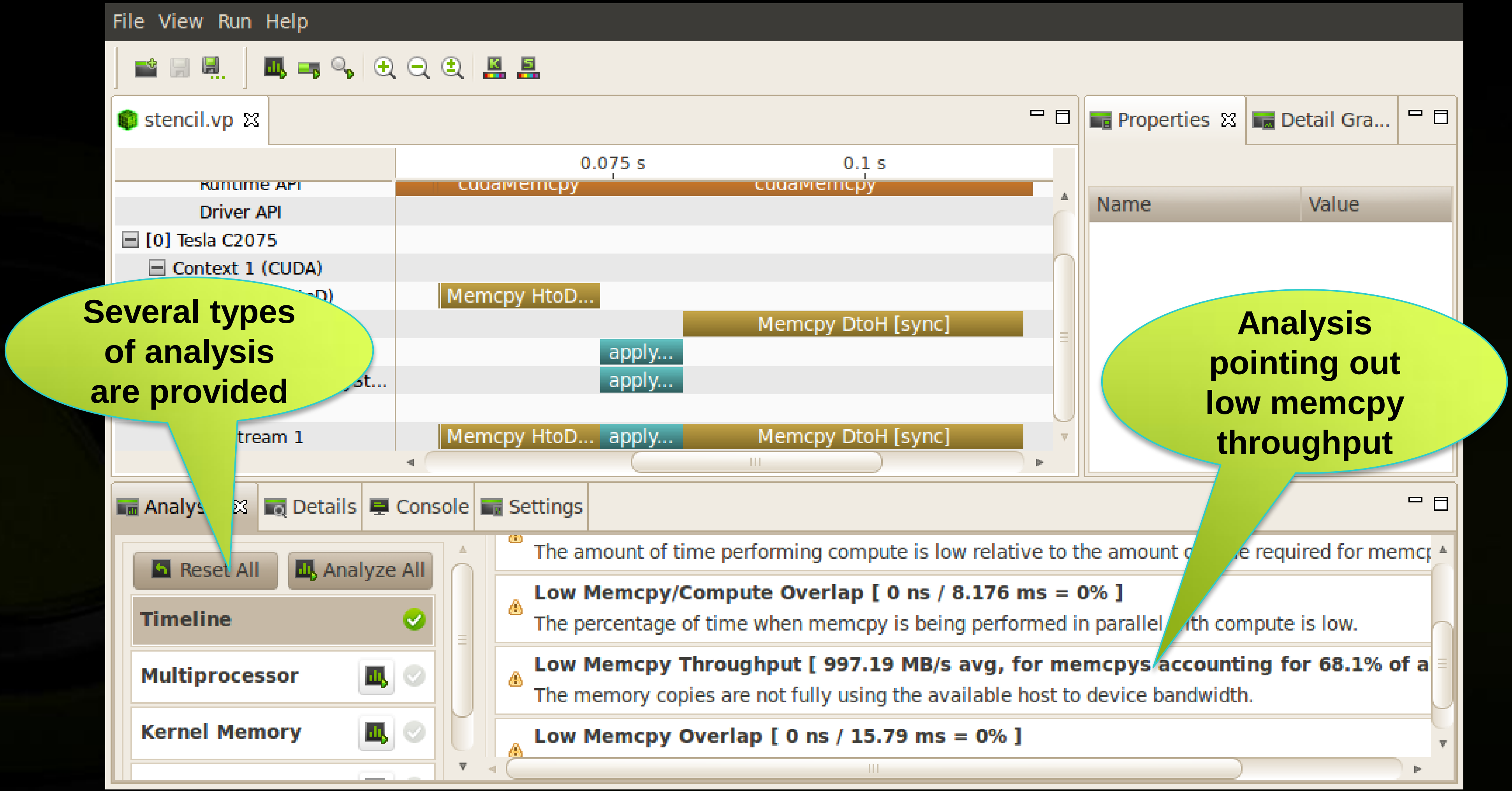


- **Spend majority of time in data transfer**
  - **Often can be overlapped with preceding or following computation**
- **From timeline can see that throughput is low**
  - **PCIe x16 can sustain > 5GB/s**

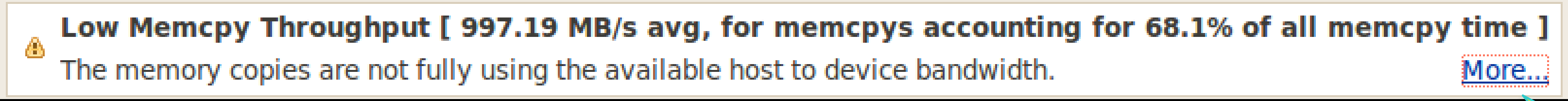
Visual Profiler Analysis

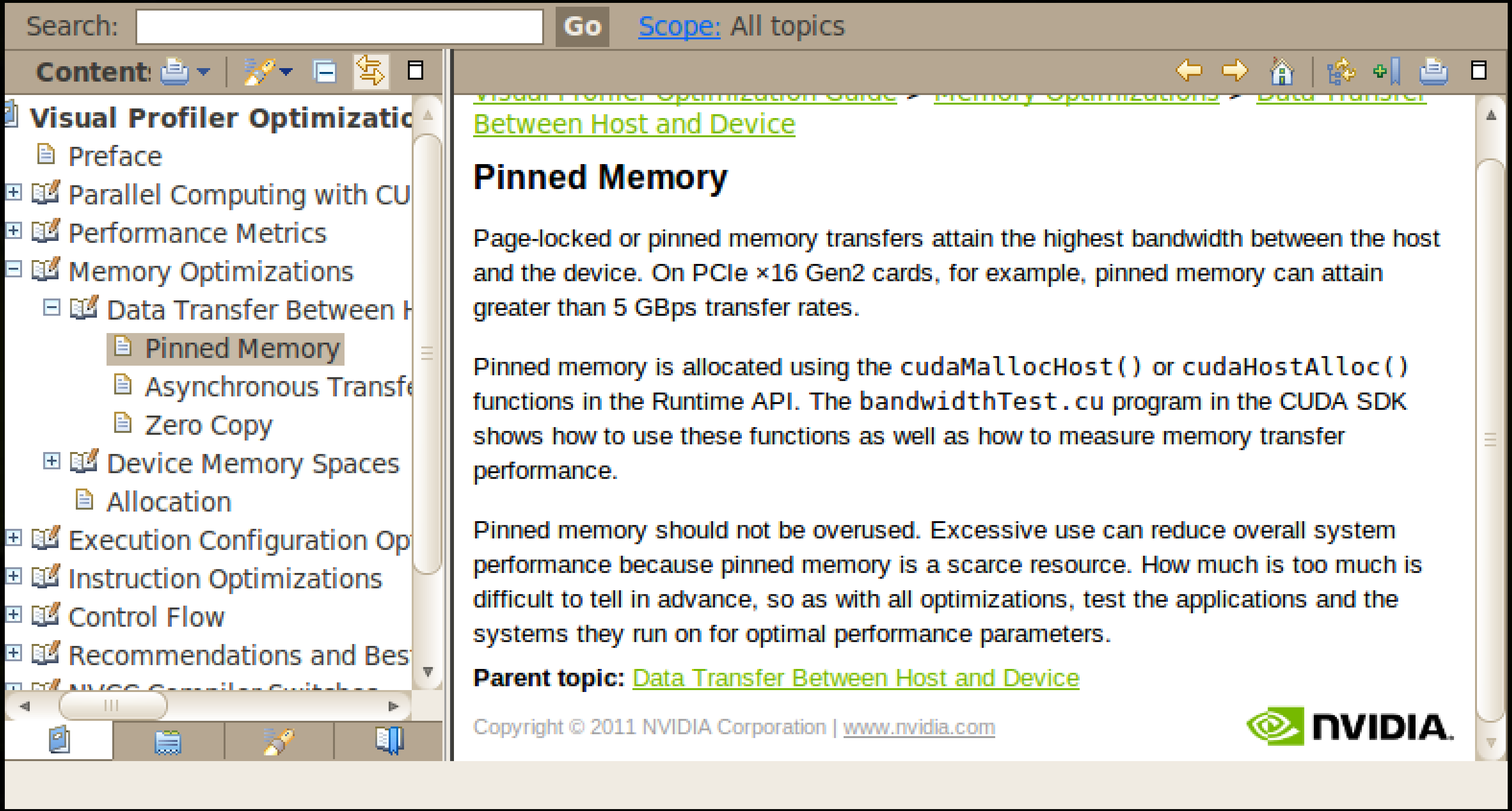
- How do we know when there is an optimization opportunity?
  - Timeline visualization seems to indicate an opportunity
  - Documentation gives guidance and strategies for tuning
    - CUDA Best Practices Guide
    - CUDA Programming Guide
- Visual Profiler analyzes your application
  - Uses timeline and other collected information
  - Highlights specific guidance from Best Practices
  - Like having a customized Best Practices Guide for your application

Visual Profiler Analysis



Online Optimization Help





Each analysis has link to Best Practices documentation

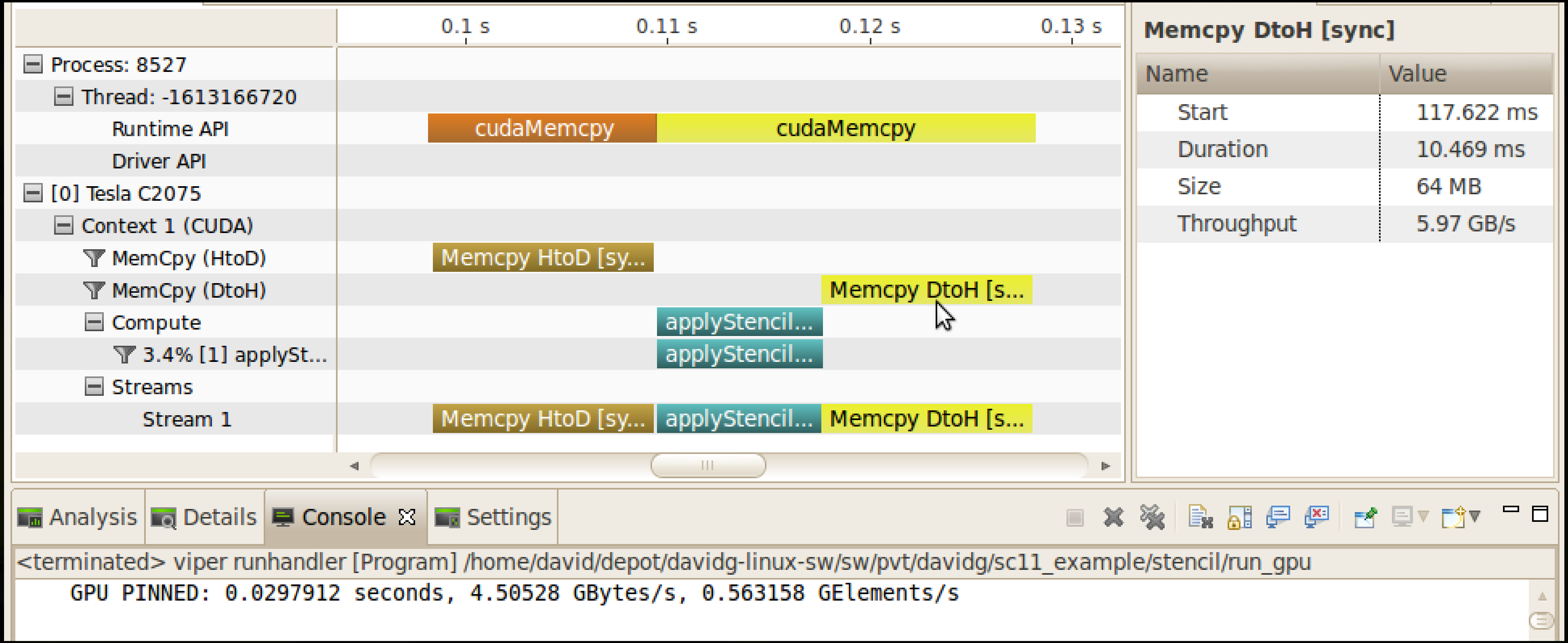
Pinned CPU Memory Implementation

```
int main() {
  int size = N * sizeof(float);
  int wsize = (2 * RADIUS + 1) * sizeof(float);
  //allocate resources
  float *weights; cudaMallocHost(&weights, wsize);
  float *in;      cudaMallocHost(&in, size);
  float *out;     cudaMallocHost(&out, size);
  initializeWeights(weights, RADIUS);
  initializeArray(in, N);
  float *d_weights;   cudaMalloc(&d_weights);
  float *d_in; cudaMalloc(&d_in);
  float *d_out; cudaMalloc(&d_out);
  …
```

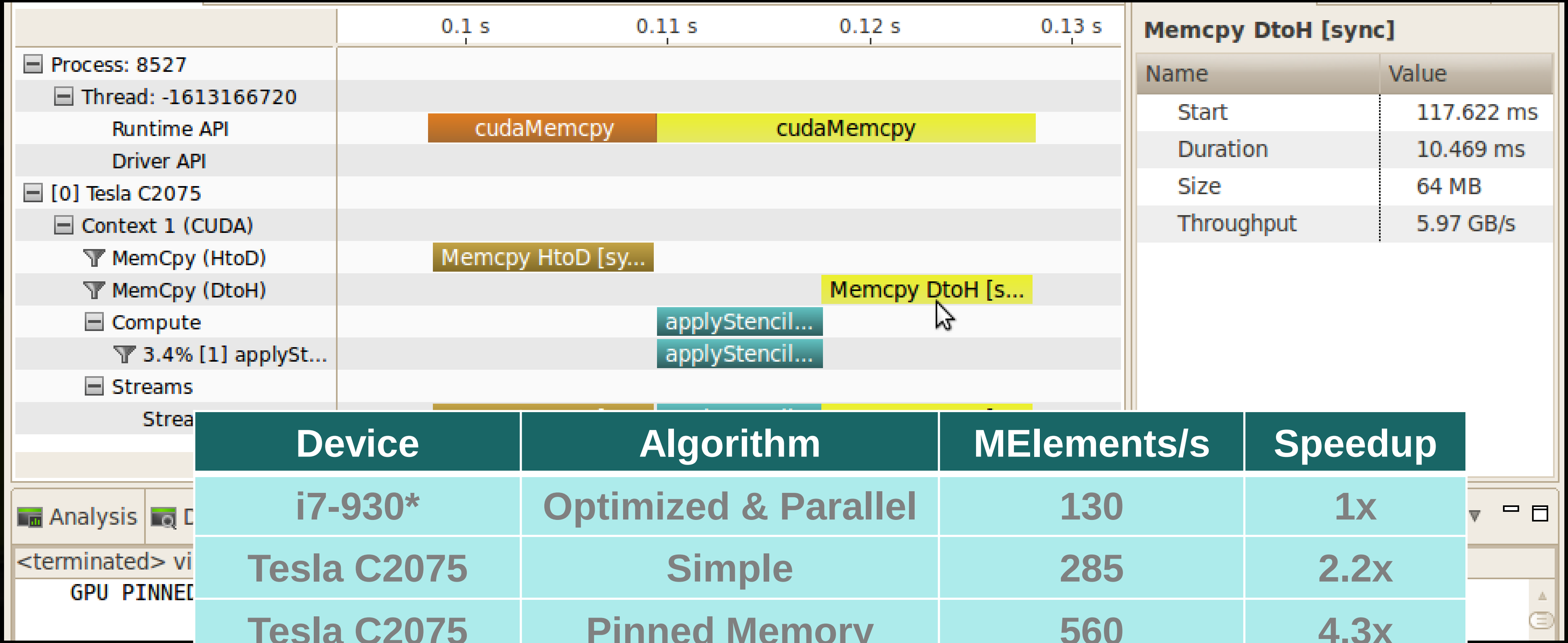
CPU allocations use pinned memory to enable fast memcpy

No other changes

Pinned CPU Memory Result



Pinned CPU Memory Result



Device	Algorithm	MElements/s	Speedup
i7-930*	Optimized & Parallel	130	1x
Tesla C2075	Simple	285	2.2x
Tesla C2075	Pinned Memory	560	4.3x

*4 cores + hyperthreading

Application Optimization Process (Revisited)

- Identify Optimization Opportunities
  - 1D stencil algorithm
- Parallelize with CUDA, confirm functional correctness
  - Debugger
  - Memory Checker
- Optimize
  - Profiler (pinned memory)

Application Optimization Process (Revisited)

- **Identify Optimization Opportunities**
  - **1D stencil algorithm**
- **Parallelize with CUDA, confirm functional correctness**
  - **Debugger**
  - **Memory Checker**

- **Optimize**
  - **Profiler (pinned memory)**

GPU TECHNOLOGY CONFERENCE

Low Memcpy/Compute Overlap [0 ns / 8.176 ms = 0%]
The percentage of time when memcpy is being performed in parallel with compute is low. More...

- Advanced optimization
  - Larger time investment
  - Potential for larger speedup

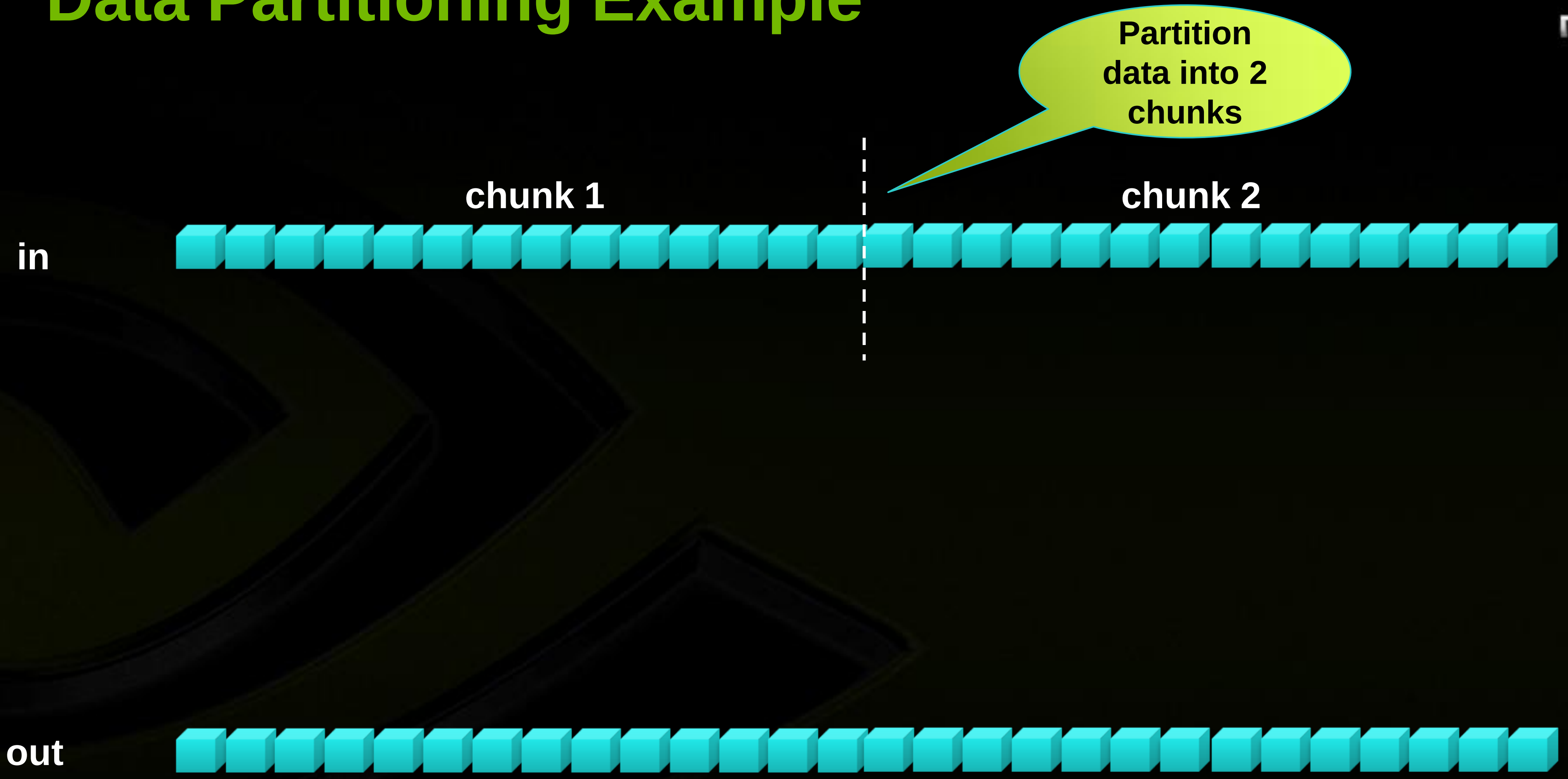
Visual Profiler Optimization Guide > Memory Optimizations > Data Transfer Between Host and Device

Asynchronous Transfers and Overlapping Transfers with Computation

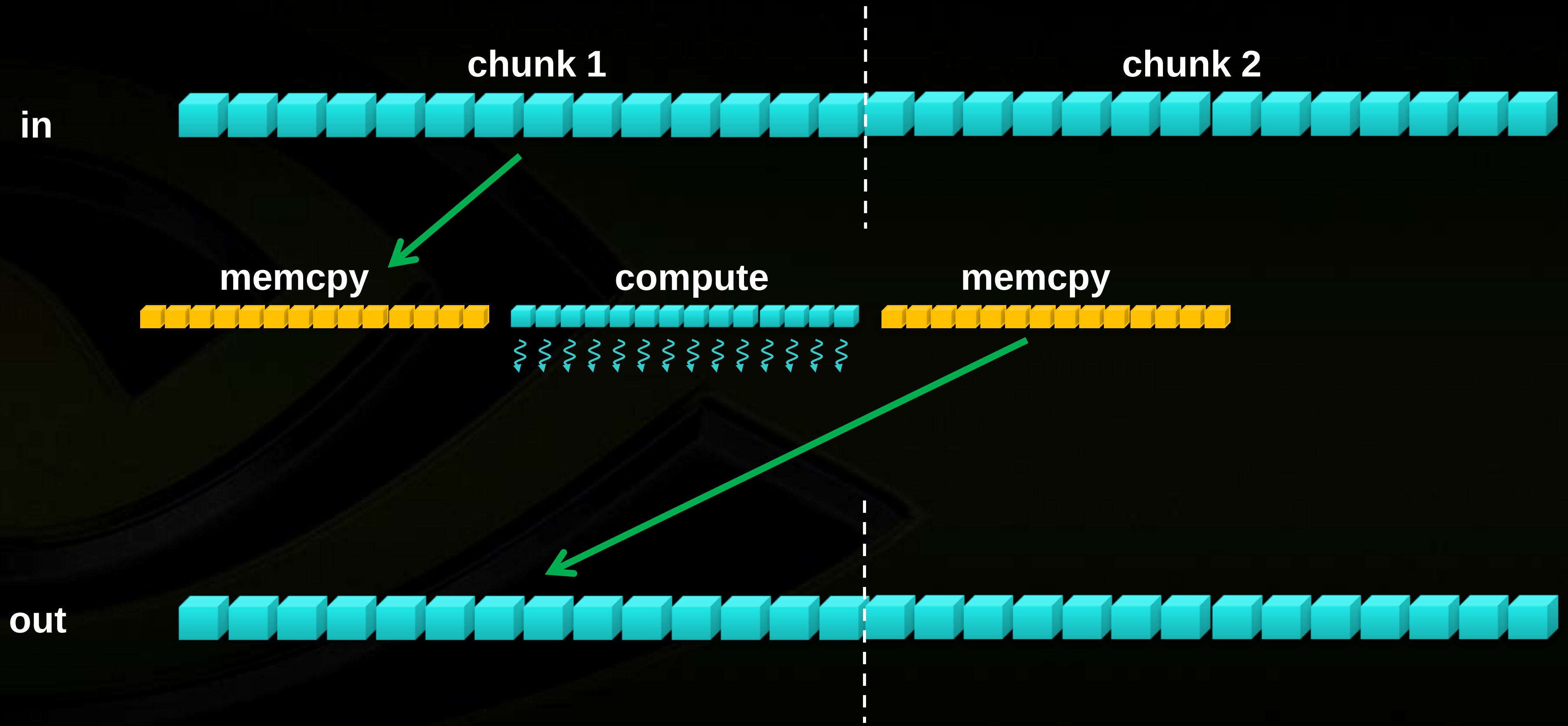
Data transfers between the host and the device using `cudaMemcpy()` are blocking transfers; that is, control is returned to the host thread only after the data transfer is complete. The `cudaMemcpyAsync()` function is a non-blocking variant of `cudaMemcpy()` in which control is returned immediately to the host thread. In contrast with `cudaMemcpy()`, the asynchronous transfer version *requires* pinned host memory (see Pinned Memory), and it contains an additional argument, a stream ID. A *stream* is simply a sequence of operations that are performed in order on the device. Operations in different streams can be interleaved and in some cases overlapped—a property that can be used to hide data transfers between the host and the device.

Asynchronous transfers enable overlap of data transfers with computation in two different ways. On all CUDA-enabled devices, it is possible to overlap host computation with asynchronous data transfers and with device computations. For example, Overlapping computation and data transfers demonstrates how host computation in the

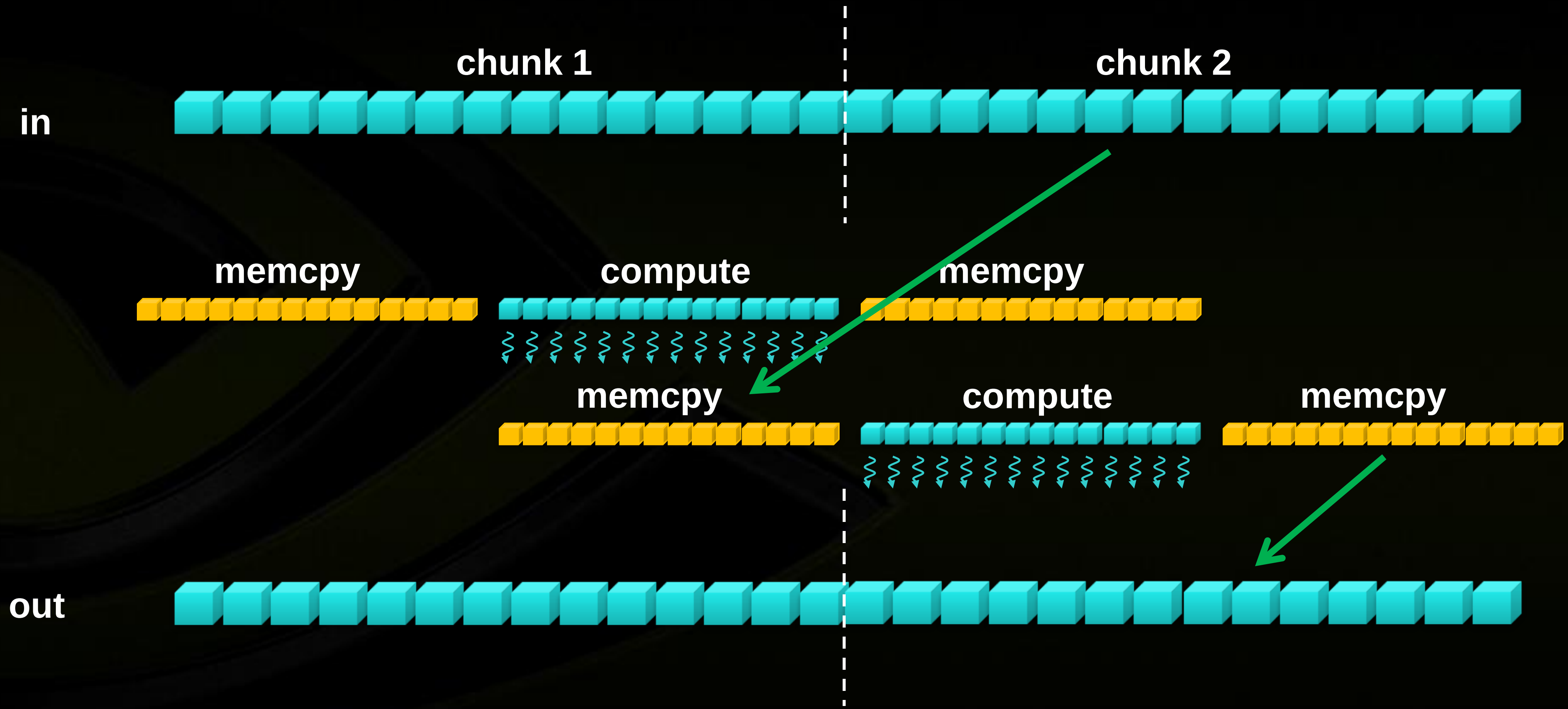
Data Partitioning Example



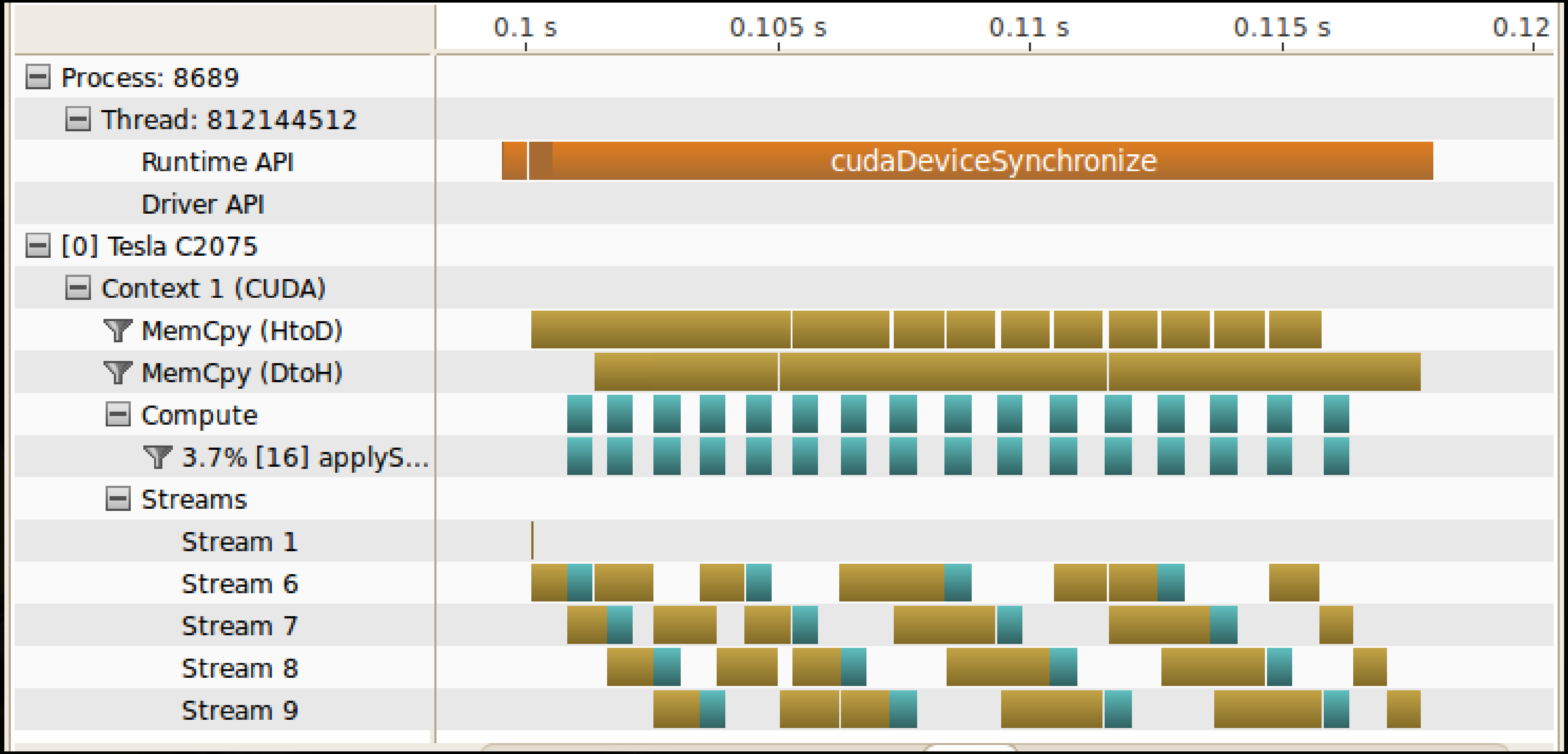
Data Partitioning Example



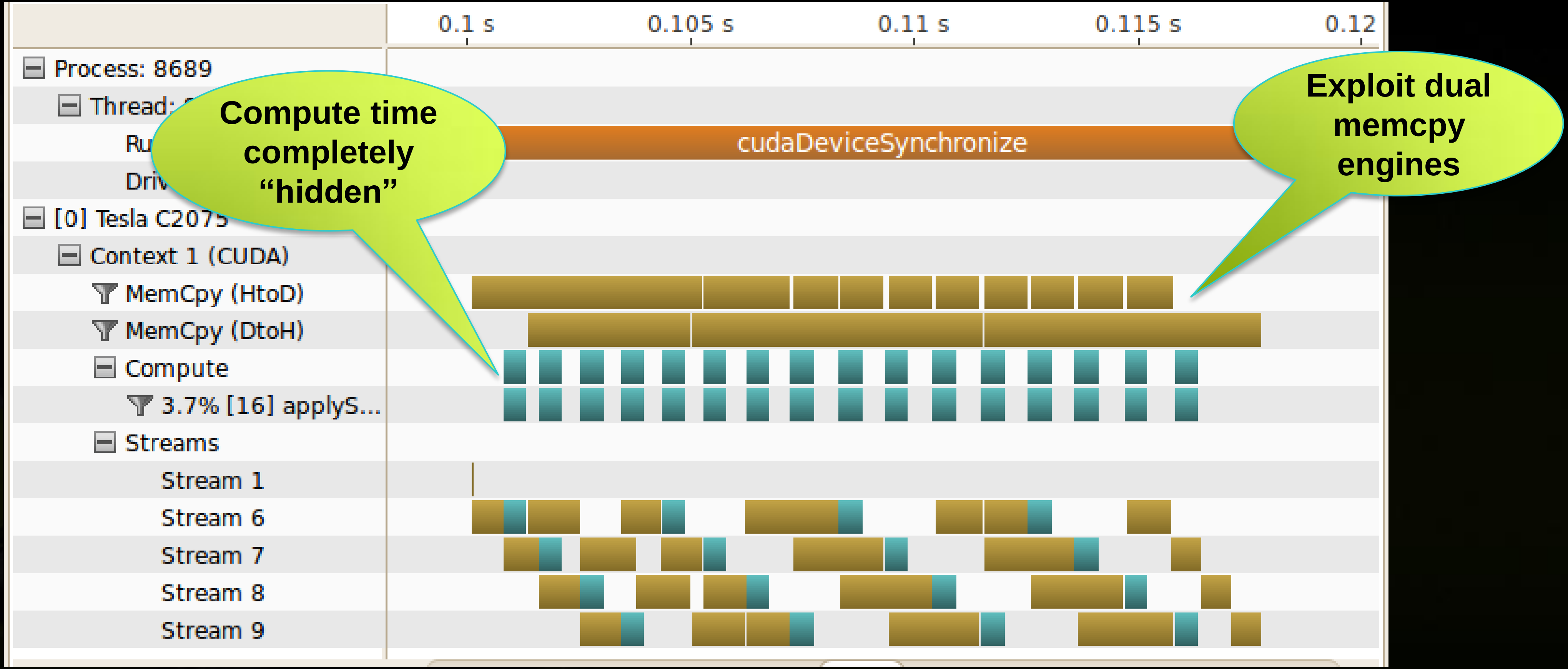
Data Partitioning Example



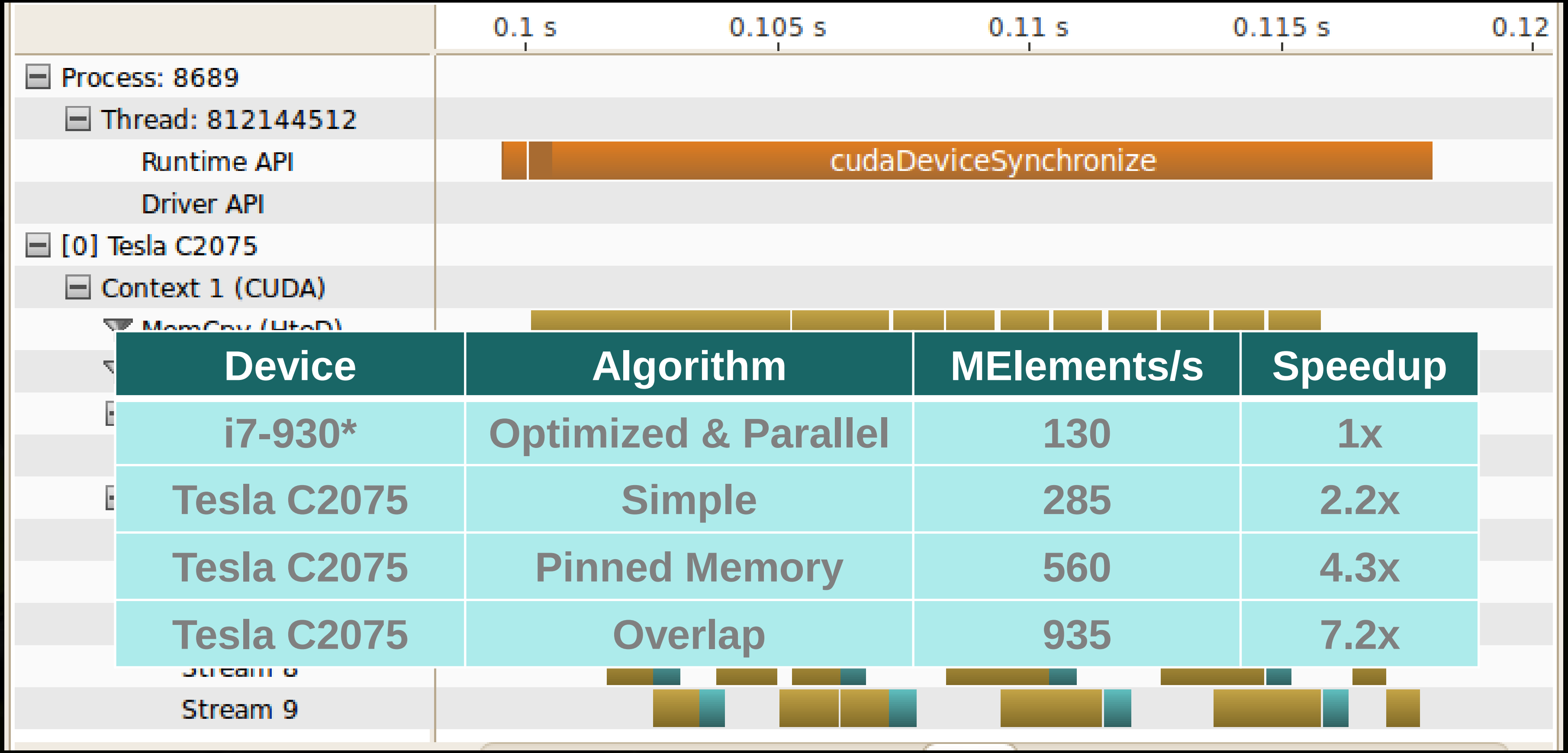
Overlapped Compute/Memcpy



Overlapped Compute/Memcpy



Overlapped Compute/Memcpy Result



Device	Algorithm	MElements/s	Speedup
i7-930*	Optimized & Parallel	130	1x
Tesla C2075	Simple	285	2.2x
Tesla C2075	Pinned Memory	560	4.3x
Tesla C2075	Overlap	935	7.2x

*4 cores + hyperthreading

Application Optimization Process (Revisited)

- Identify Optimization Opportunities
  - 1D stencil algorithm
- Parallelize with CUDA, confirm functional correctness
  - Debugger
  - Memory Checker
- Optimize
  - Profiler (pinned memory)
  - Profiler (overlap memcpy and compute)

Iterative Optimization

- **Identify Optimization Opportunities**
- **Parallelize with CUDA**
- **Optimize**

Optimization Summary

- Initial CUDA parallelization and functional correctness
  - 1-2 hours
  - 2.2x speedup
- Optimize memory throughput
  - 1-2 hours
  - 4.3x speedup
- Overlap compute and data movement
  - 1-2 days
  - 7.2x speedup

Visual Profiler Demo

Summary

- CUDA accelerates compute-intensive parts of your application
- Visual profiler helps in performance analysis and optimization
- Get Started
  - Download free CUDA Toolkit: www.nvidia.com/getcuda
  - Join the community: developer.nvidia.com/join

Questions?

Performance optimization strategies

- Maximize parallel execution to achieve maximum utilization
- Optimize memory usage to achieve maximum memory throughput
- Optimize instruction usage to achieve maximum instruction throughput

Performance Optimization Process

- Use appropriate performance metric for each kernel
- Determine what limits kernel performance
  - Memory throughput
  - Instruction throughput
  - Latency
  - Combination of the above
- Address the limiters in the order of importance
  - Determine how close to the HW limits the resource is being used
  - Analyze for possible inefficiencies
  - Apply optimizations

3 Ways to Assess Performance Limiters

- Algorithmic
  - Based on algorithm's memory and arithmetic requirements
  - Least accurate: undercounts instructions and potentially memory accesses
- Profiler
  - Based on profiler-collected memory and instruction counters
  - More accurate, but doesn't account well for overlapped memory and arithmetic
- Code modification
  - Based on source modified to measure memory-only and arithmetic-only times
  - Most accurate, however cannot be applied to all codes