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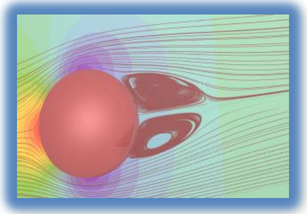

CU++ : An Object Oriented Tool for CFD Applications on GPUs

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2012 GPU Technology Conference,

San Jose, CA

17 May 2012

Motivation - Simplify Numerical Software Development

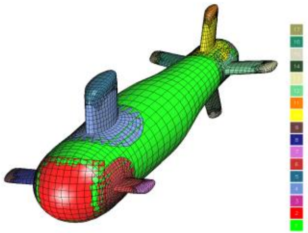
Overture – LLNL
A++P++ Library

Vector addressing – Fortran like statements

```
u(I) = u(I+1) + 0.5*u(I-1)
```

Serial or Parallel mode indices

CG Flow Codes

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PGI insider — The PGI Accelerator Programming Model on N
Recognizing and addressing four key performance issue

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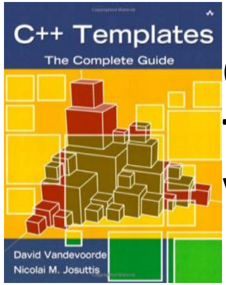
C++ Expression Templates

By Angelika Langer and Klaus Kreft, March 01, 2003

Post a Comment

Do you want high-performance, readable expressions? Expression templates do it all.



C++ Templates : The Complete Guide
Vandevoode and Josuttis

CUDA Based Expression Templates which were developed concurrently

CUDA Expression Templates

Paul Wiemann, Stephan Wenger, Marcus Magnor

Home Team Research Teaching

Paul Wiemann, Stephan Wenger, and Marcus Magnor:
"CUDA Expression Templates",
in *WSCG Communication Papers Proceedings*, pp. 185–192, January 2011.
ISBN 978-80-86943-82-4
[pdf] [bib] [source]

CHAPTER 32

Processing Device Arrays with C++ Metaprogramming

Jonathan M. Cohen

GPU Computing Gems

Indexing is not straightforward as A++P++

Might not have mixed GPU-CPU implementation

Does not work for unstructured data

A Simple Example - 2D Poisson Equation on a Rectangular Domain - $\nabla^2 u = 0$

Discretized form on a Cartesian grid reads :

$$u_{ij} = \frac{1}{4}\left(u_{i,j+1} + u_{i,j-1} + u_{i+1,j} + u_{i-1,j}\right)$$

C/C++ Serial Implementation

```
for ( int idy = 1 ; idy <= n-1 ; idy++ ){
  for ( int idx = 1 ; idx <= n-1 ; idx++ ){
      int id  = idx + n*idy;          // ( I, J )
      int idr = idx+1 + n*idy;        // ( I, J+1)
      int idl = idx-1 + n*idy;        // ( I, J-1)
      int idt = idx + n*(idy+1);      // ( I+1, J)
      int idb = idx + n*(idy-1);      // ( I-1, J)
unp1[id] = 0.25*( un[idr] + un[idl] + un[idt] + un[idb] )
    }}
```

Comparison of C++, CUDA, and CU++

C/C++ Serial Implementation

```
for ( int idy = 1 ; idy <= n-1 ; idy++ ){
  for ( int idx = 1 ; idx <= n-1 ; idx++ ){
      int id  = idx + n*idy;           // ( I, J )
      int idr = idx+1 + n*idy;         // ( I, J+1)
      int idl = idx-1 + n*idy;         // ( I, J-1)
      int idt = idx + n*(idy+1);       // ( I+1, J)
      int idb = idx + n*(idy-1);       // ( I-1, J)
unp1[id] = 0.25*( un[idr] + un[idl] + un[idt] + un[idb] )
    }}
```

CUDA Implementation

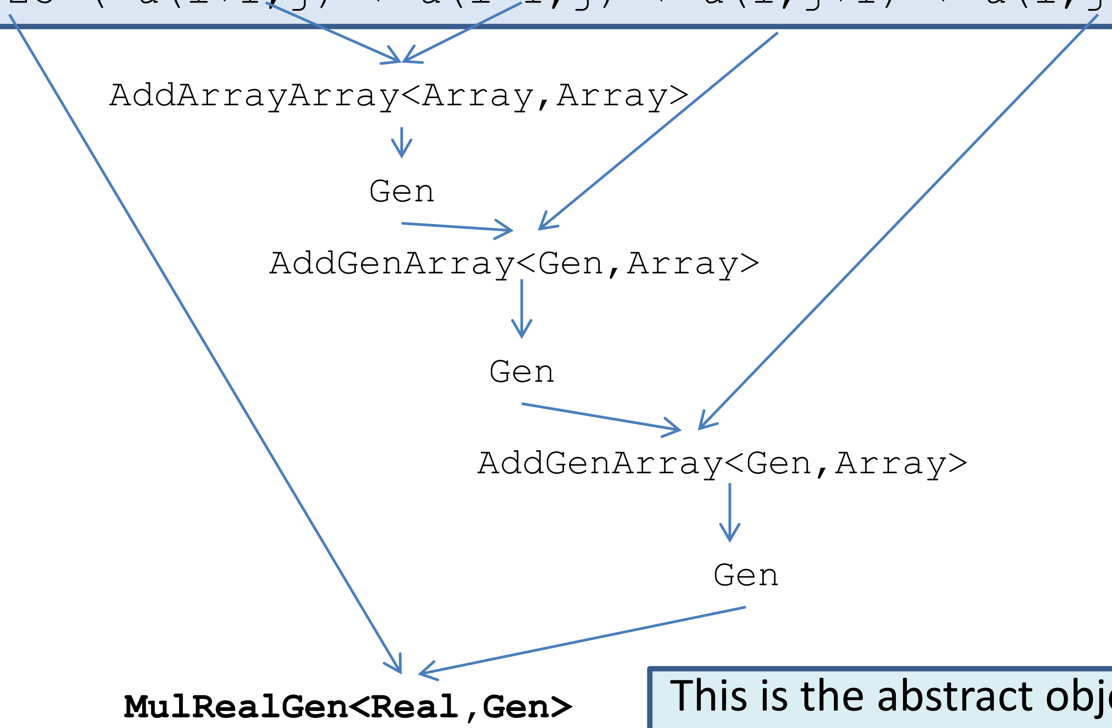
```
  __global__ void point_jacobi( float* unp1, float* un,. . .)
  {
    int idx = threadIdx.x + blockIdx.x*blockDim.x;
    int idy = threadIdy.y + blockIdy.y*blockDim.y;
    int id  = idx + n*idy;          // ( I, J )
    int idr = idx+1 + n*idy;        // ( I, J+1)
    int idl = idx-1 + n*idy;        // ( I, J-1)
    int idt = idx + n*(idy+1);      // ( I+1, J)
    int idb = idx + n*(idy-1);      // ( I-1, J)
    if ( idx >=1 && idx <=n-1 && idy >=1 && idy <= n-1 )
      unp1[id] = 0.25*( un[idr] + un[idl] + un[idt] + un[idb] )
  }
```

CU++ Implementation

```
// Index objects are used to represent the base and bound of the array
Index i(1,N-2), j(1,N-2);
// u is a distributed array object defined as follows:
distArray u(N,N);
   for ( step = 0 ; step < maxNumberofSteps ; step++ )
    {
      u(i,j) = 0.25*( u(i,j+1) + u(i,j-1) + u(i+1,j) + u(i-1,j) ;
    }
```

Encoding The Jacobi Expression – Compile Time

```
u(i,j) = 0.25*( u(i+1,j) + u(i-1,j) + u(i,j+1) + u(i,j-1) )
```



This is the abstract object that the generic kernel will see

Decoding The Jacobi Expression - Runtime

```
Template < typename ComplexType >
__global__ void computeKernel( ComplexType ctype, real* result )
{
  int TID = threadIDx.x + …

  result[TID] = ctype[TID];
}
```

MulRealGen<Real,Gen>

[ ] operators are overloaded

```
__device__ real operator [] ( int i )
{
 return  constant_val * v[i];
}
```

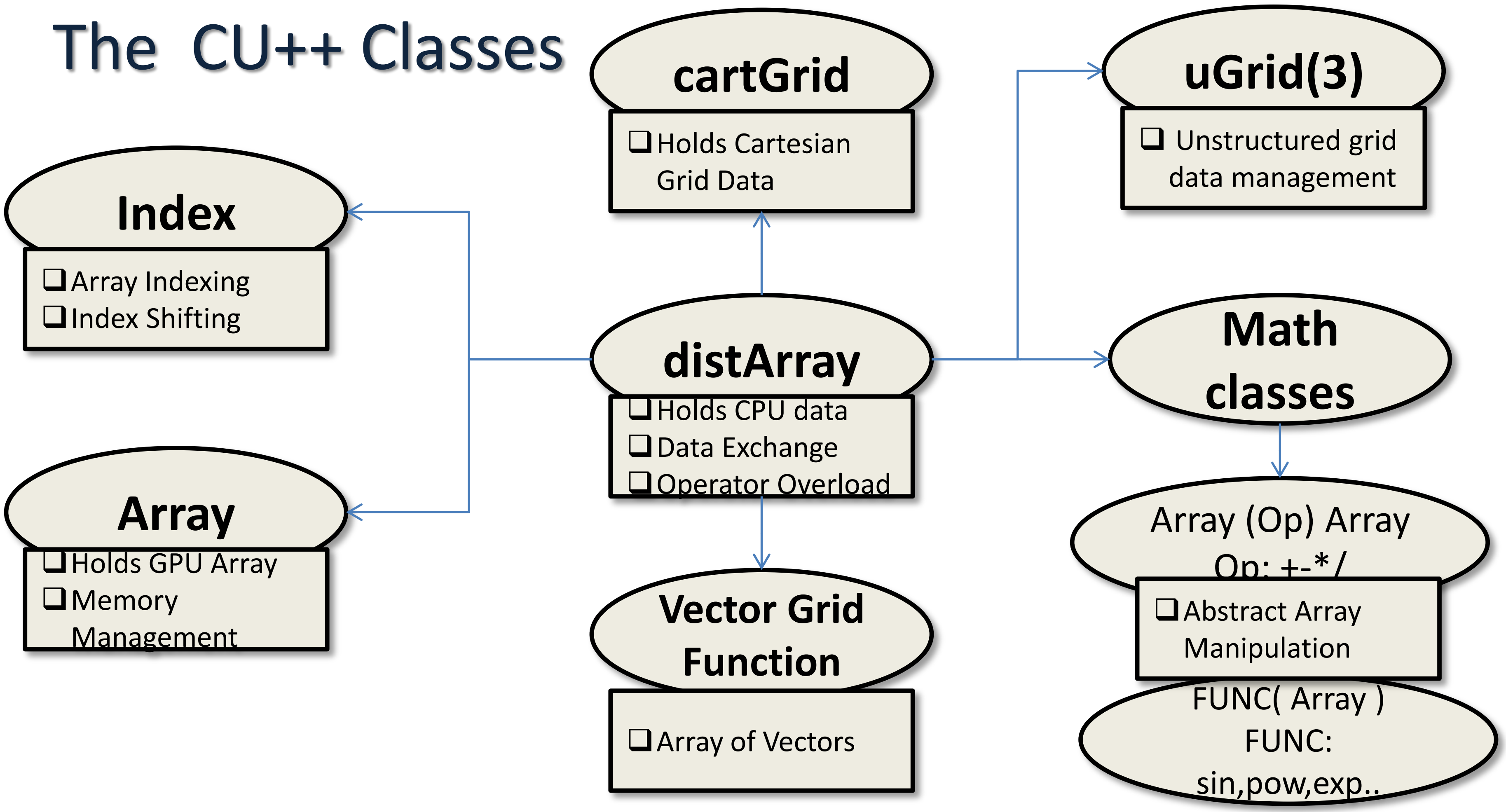
AddGenArray<Gen,Array>

AddGenArray<Gen,Array>

AddArrayArray<Array,Array>

The Tree expands during Run time

The CU++ Classes



The CU++ Classes

cartGrid
- ❑ Holds Cartesian Grid Data

uGrid
- ❑ Holds Unstructured Grid Data

Index
- ❑ Array Indexing
- ❑ Index Shifting

distArray
- ❑ Holds CPU data
- ❑ Data Exchange
- ❑ Operator Overload

Math classes

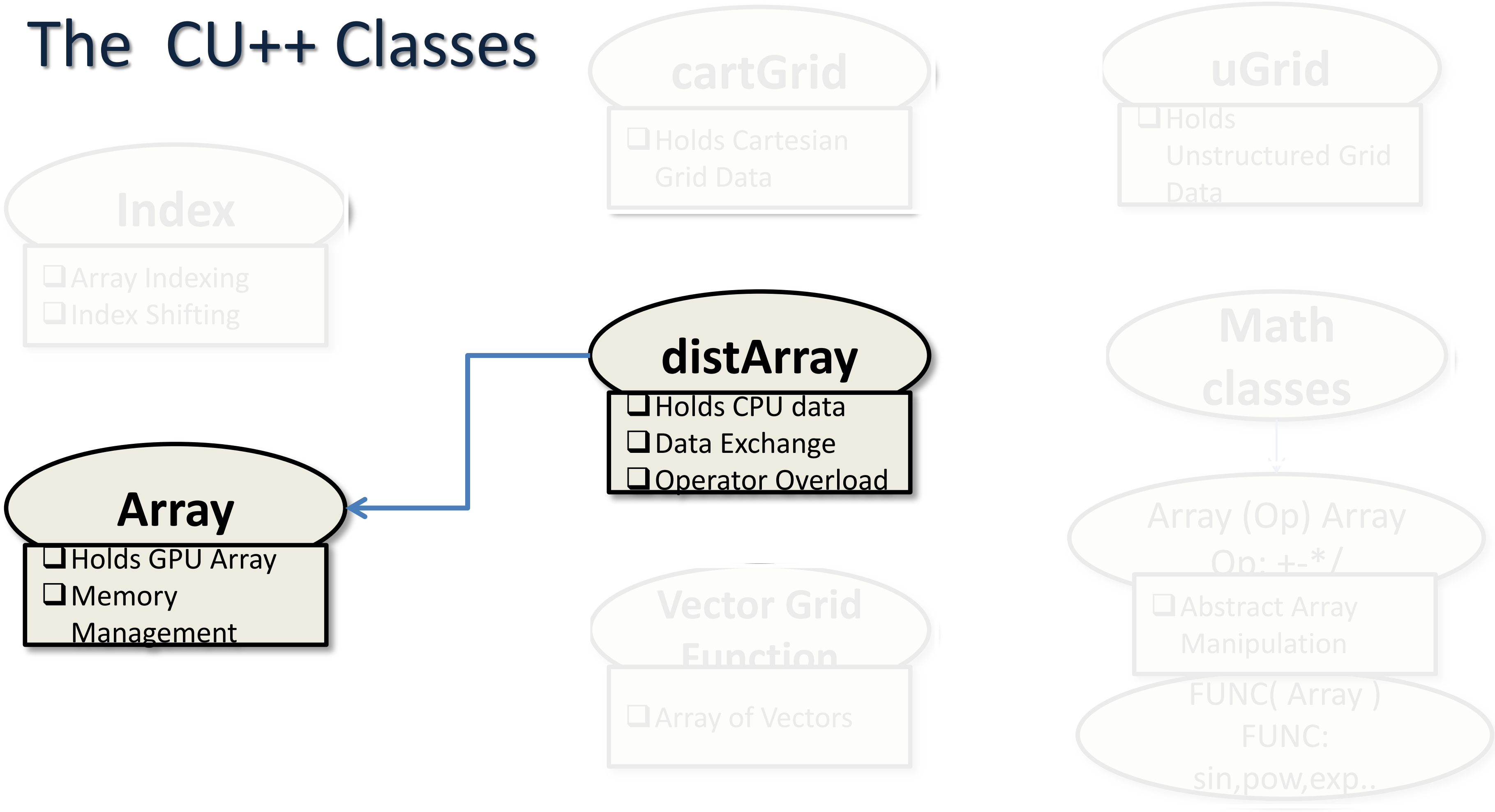
Array (Op) Array
Op: +-*/
- ❑ Abstract Array Manipulation

FUNC(Array)
FUNC: sin,pow,exp..

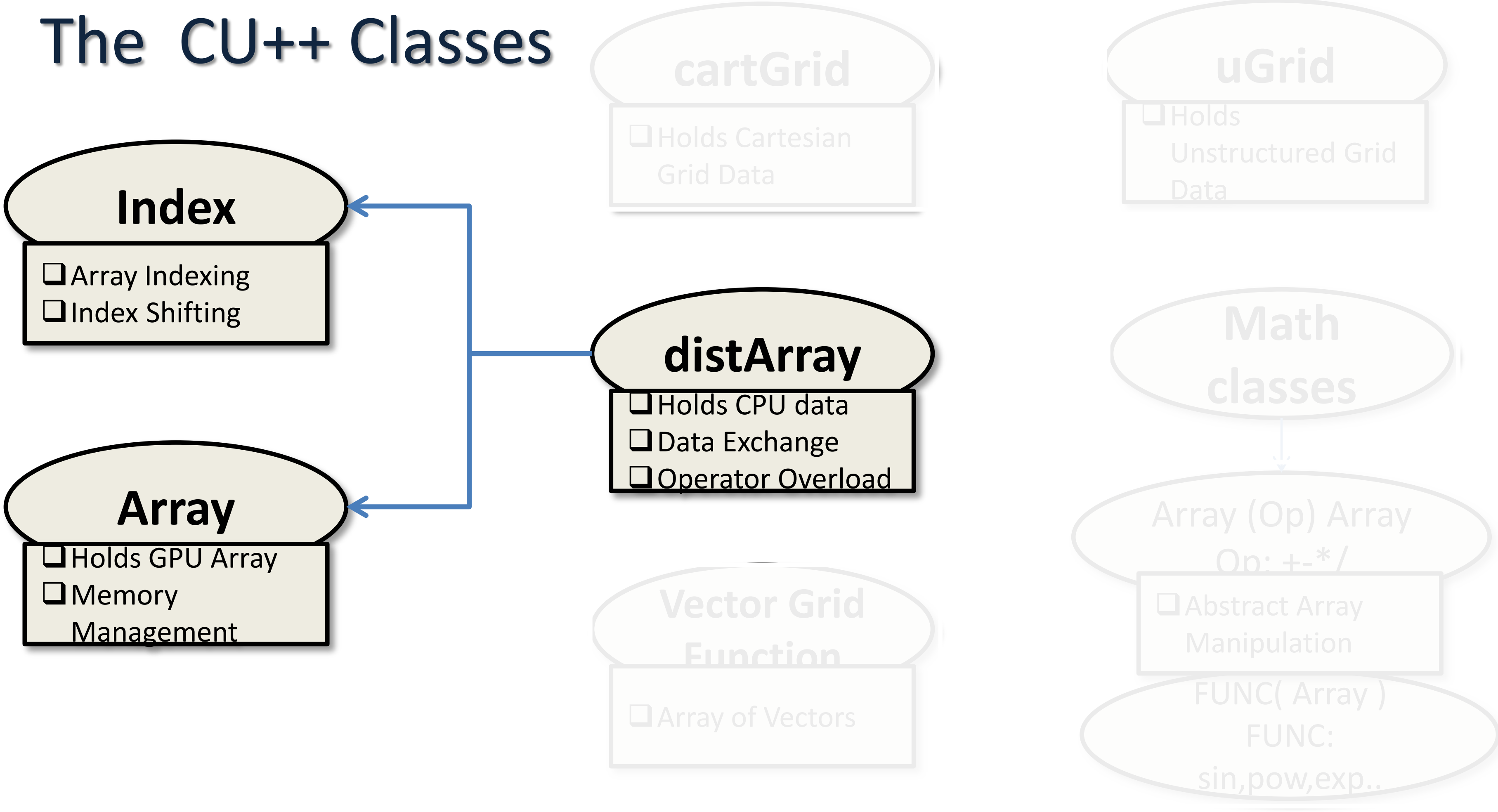
Array
- ❑ Holds GPU Array
- ❑ Memory Management

Vector Grid Function
- ❑ Array of Vectors

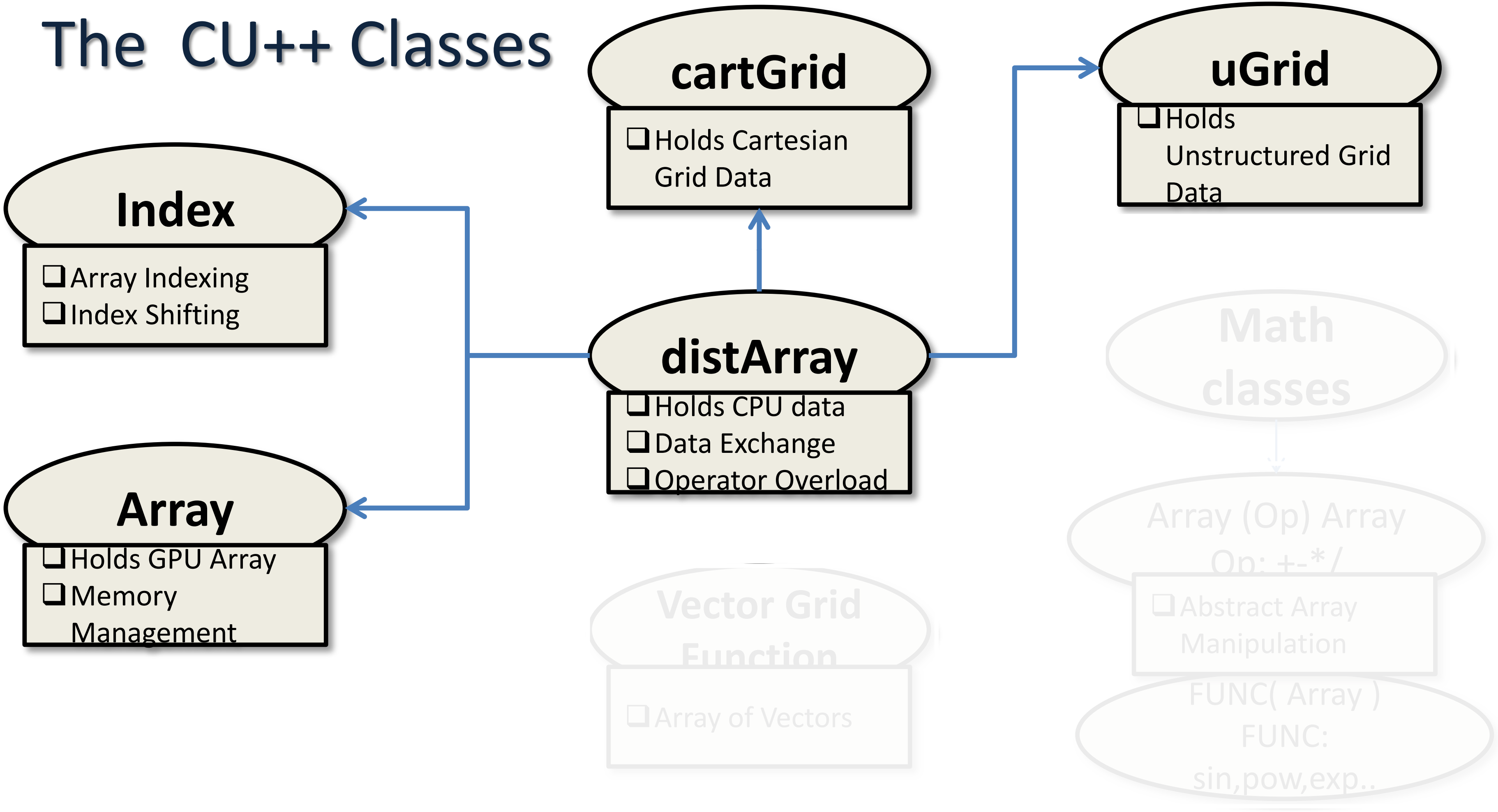
The CU++ Classes



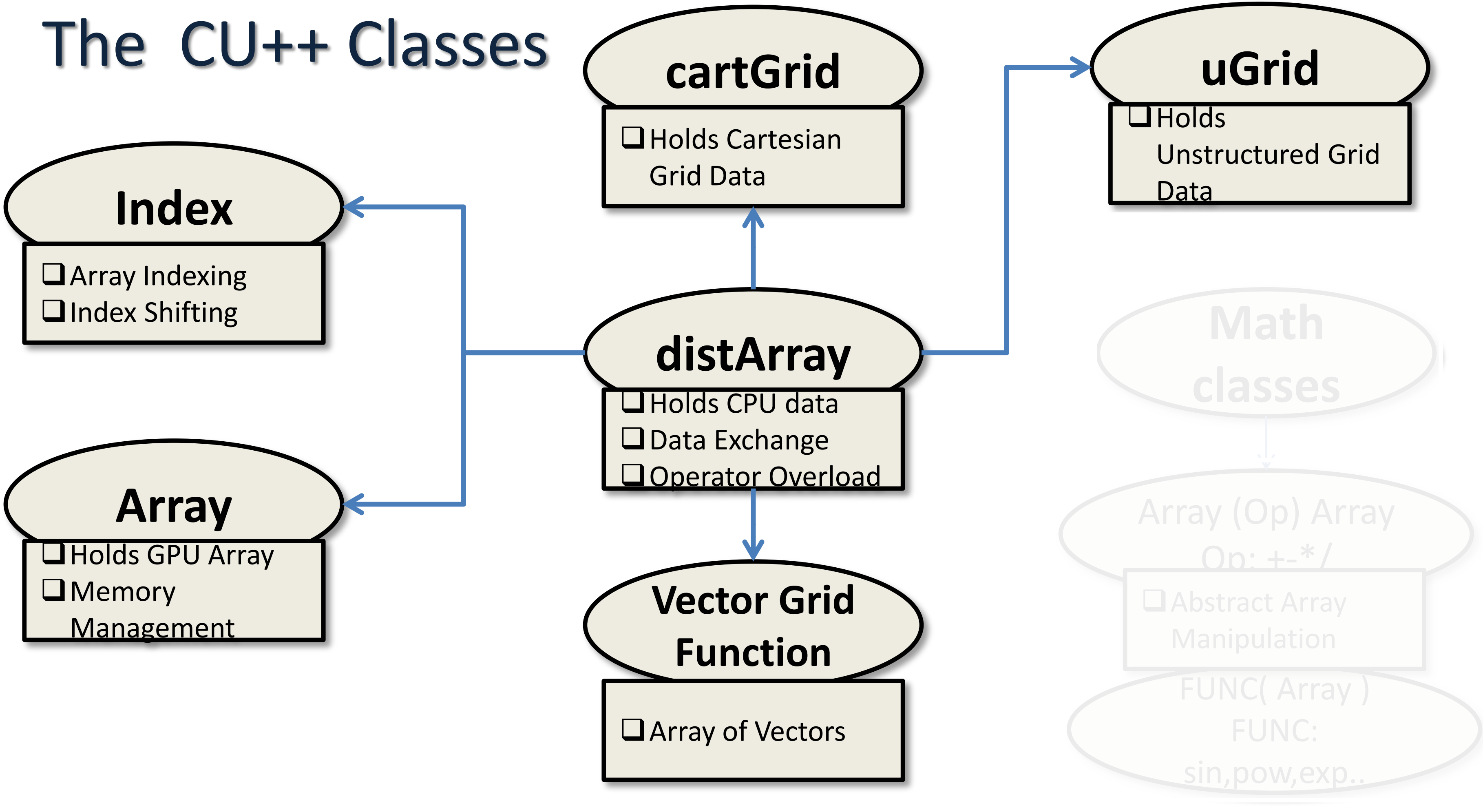
The CU++ Classes



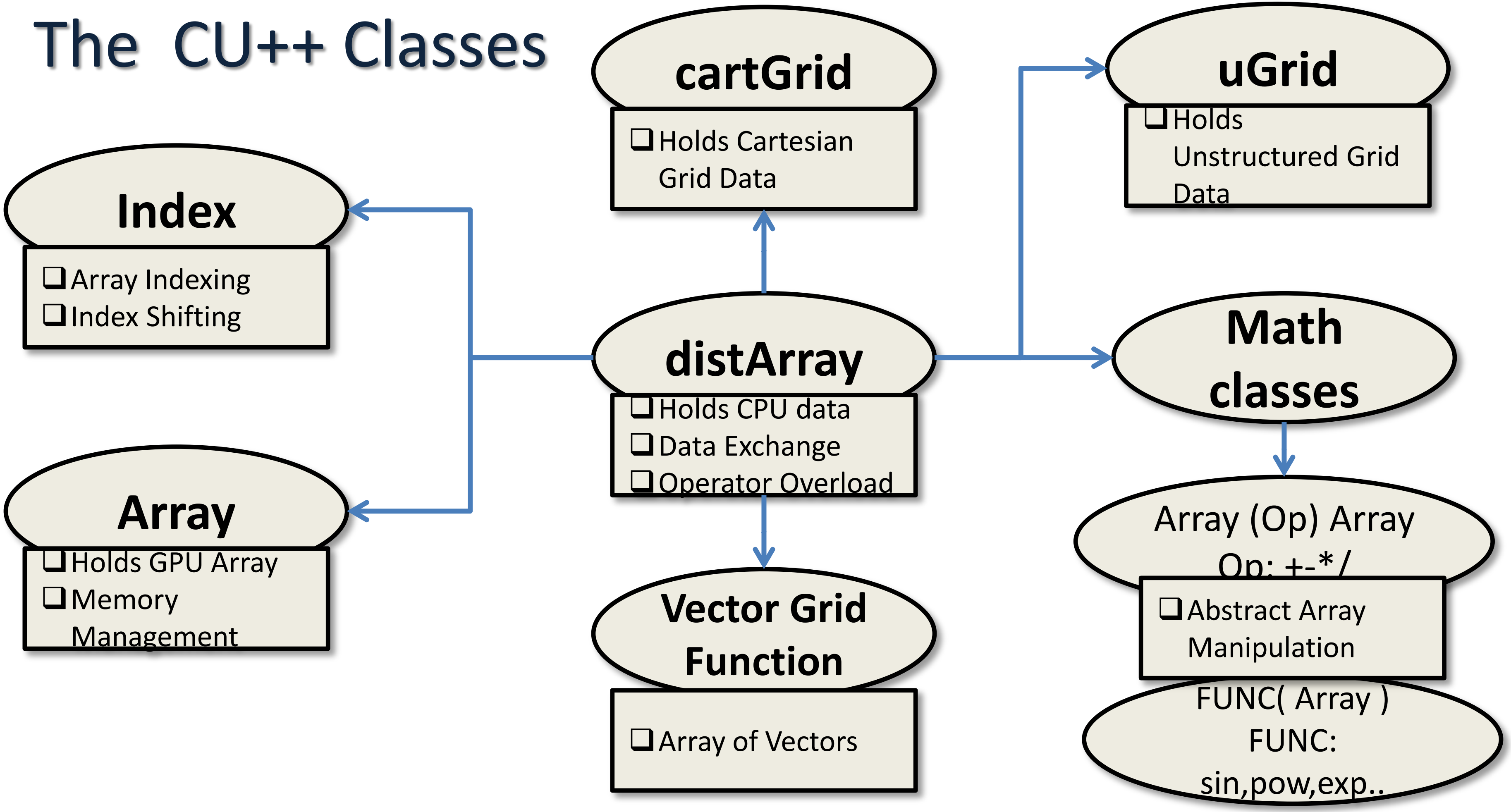
The CU++ Classes



The CU++ Classes



The CU++ Classes



CU++ Features : Array Assignment

We have a structured grid of size $Nx * Ny$, and we would like to fill the internal nodes with a constant value

C++ serial version

```
real *U = new real [Nx*Ny]   ;

for ( int i = 1; i < Ny-1 ; i++)
  for ( int j = 1 ; j < Nx-1 ; j++)
     U[i+j*Nx]=10.0;
```

CU++ET v on

```
distArray U(Nx,Ny);
Index I1(1,Nx-2), I2(1,Ny-2);
U(I1,I2)=10.0;
```

Parallel assignment

CU++ Features : Handling Unstructured Data

```
// Declare an array to hold the solution
distArray Q( number_of_nodes );

// Declare an array to hold the boundary node indices
distArray bNodeIndex( number_of_boundary_nodes) ;
Index I(0, number_of_boundary_nodes-1);

// Short Notation
#define BI bNodeIndex(I)

//Get the boundary  node indices
getBoundaryNodeIndex ( bNodeIndex )

// Do a small computation on the boundary nodes
Q(BI) = Q(BI) + SIN(x(BI))*COS(Y(BI));
```

```
                 0  1   2   3   4  5 . . . .
bNodeIndex = [ 2  8  23  24  15 19 . . . .          ]
```

CU++ Features : Misc. Features

```
cartGrid cg(0,1,Nx,0,1,Ny,0,1,Nz
```

Creates a Cartesian Grid in Parallel

```
vectorGridFunction u(cg,2)
```

Array of vectors (2 components), each vector has dimension Nx*Ny*Nz

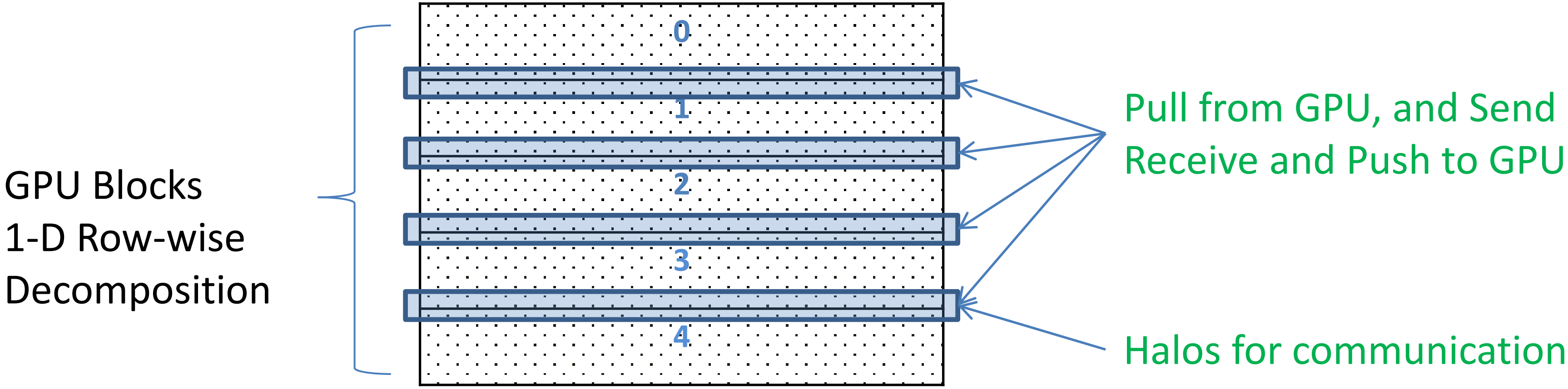
```
u[0](I1,I2,I3) = func()
```

Assigns an arbitrary function to the *first* component of *u*

```
u[1](I1+1,I2,I3) = POW(u[0](I1,I2,I3),2.1)
```

Assigns a function of the *first* component to the *second* component of *u* (shifted by 1)

CU++ Features : MPI Support



Each GPU mapped by one CPU core

CU++ Features : Example Code, Poisson Solver

```
#include "CU++Runtime.h"
int main(int argc, char* argv[])
{
  // Problem size
  int Nx = 1000, Ny=1000, niter = 1e6;
  distArray::Init(argc,argv,Nx,Ny);

  // Create the partition type and declare the array 'u'
  ArrayPartition apobject(1,2,1);
  distArray u(Nx,Ny,apobject);

  // Indices of internal points
  Index i,j;
  u.getIndexOfInternalPoints(i,j);

  // Initialize
  u(i,j)=0.0;
```

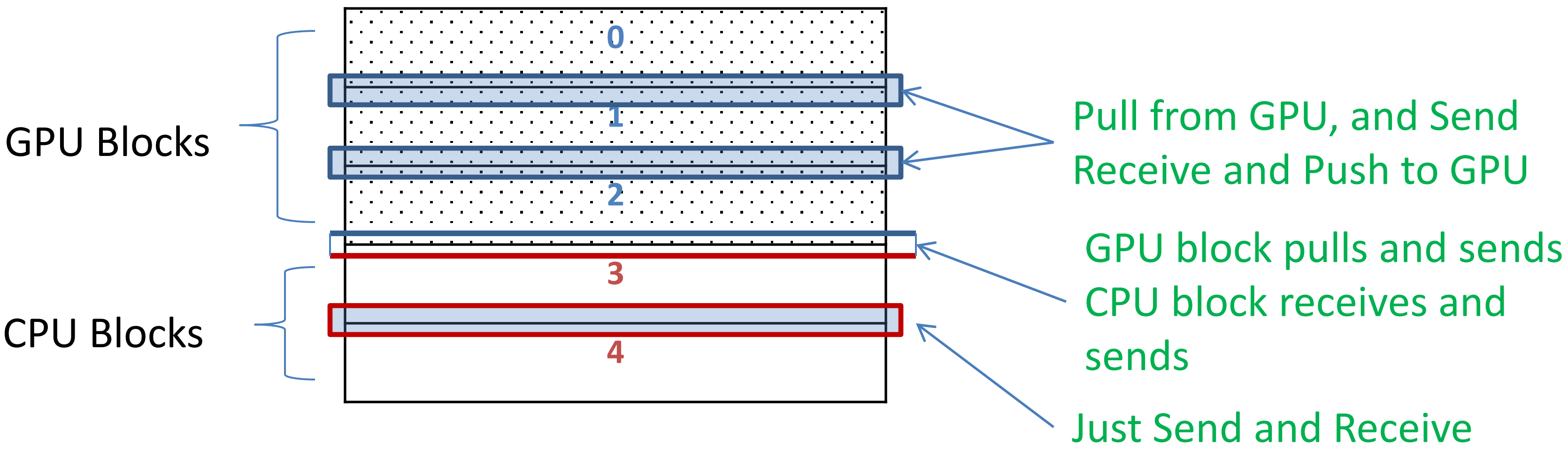
CU++ Features : Example Code, Poisson Solver

```
// Some constants
real dx = 1.0/(Nx+1);
real dy = 1.0/(Ny+1);
real lm = pow( (dx/dy),2.0);
real cont = 0.5/(1+lm);
real F = -2.0;

//  The main loop
for ( int step = 0 ; step < niter ; step++ )
   {
      u(i,j) = cont*( u(i+1,j) + u(i-1,j) +
                 lm*( u(i,j+1) + u(i,j-1)) -F*dx*dx );
      apobject.FixFringePoints(u);
   }

distArray::cleanUp();
}
```

Idle CPUs, Make Them Work !

Each partitioned block knows whether it is a GPU block or a CPU block –

```
bool distArray::iamAGPUBlock = true/ false
```



Needs to be load balanced for achieving speed-up

Load Balancing math – GPU + CPU cores

Assume the following variables:

T: *Total Problem size*

s: *1 GPU/1CPU speed up*

n_g: *Number of GPUs*

n_c: *Number of CPUs*

N_1: *Problem size on GPU*

N_2: *Problem size on a CPU core*

The total problem size can be computed as:

$$T = n_g N_1 + n_c N_2$$

For the load to be balanced between a CPU core and GPU:

$$N_1 = sN_2$$

Using the above relations, we obtain

$$N_1 = \frac{sT}{n_g s + n_c} \quad , N_2 = \frac{T}{n_g s + n_c}$$

If only GPUs are used, then the time spent by **each GPU is**

$$t_{GPU1} \sim \frac{T}{n_g}$$

If the load is shared between GPUs and CPUs, the time spent by **each GPU** is

$$t_{GPU2} \sim N_1$$

Thus Speed-up of the GPU gained by sharing the load with the CPU is

$$\frac{t_{GPU1}}{t_{GPU2}} \sim \frac{T}{n_g N_1} \sim 1 + \left(\frac{n_c}{n_g}\right)\frac{1}{s}$$

Load Balancing math – GPU + CPU cores

$$\text{So Speed-up} \sim 1 + \left(\frac{n_c}{n_g}\right)\frac{1}{s}$$

- Let us assume $s \sim 10$ (common for unstructured grid solvers on GPU), and you have a 16 core CPU, with 4 GPUs.
- You can push for an additional 40% speed-up if you use the CPU cores also.

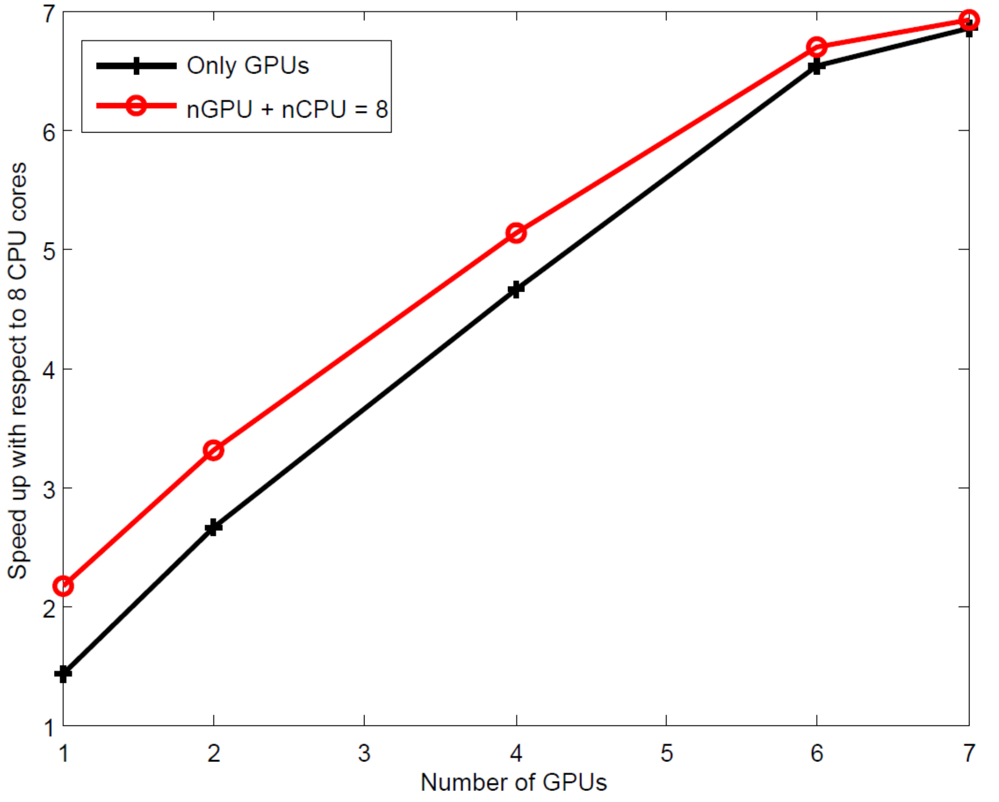
Speed-up figures for the Jacobi Problem, 8 core CPU, with 7 GPUs

GPU Kernel purposely slowed down to achieve 10x speed-up wr.t a single core (s=10)

nGPUs	N Cores	Theoretical	Actual
1	7	1.7	1.51
2	6	1.3	1.25
4	4	1.1	1.1
6	2	1.03	1.02
7	1	1.01	1.02

Load Balancing math – The Overall Picture

Speed-up figures with respect to the parallel performance (no GPUs) on 8 CPU cores



CUDA-C (Hand-coded Kernel) *Vs.* CU++

Poisson equation on a 12288 x 12288 grid, run for 1000 iterations

Order of Disc.	CUDA-C	CU++
2	79.1 s	83.8 s
6	106.5 s	112.2 s

Only
5% slower

CUDA-C (Hand-coded Kernel) *Vs.* CU++

Poisson equation on a 12288 x 12288 grid, run for 1000 iterations

Order of Disc.	CUDA-C	CU++
2	79.1 s	83.8 s
6	106.5 s	112.2 s

Only 5% slower

But ...

Number of Lines Coded

CUDA-C	CU++
33	7

Compiling and Executing CU++ Codes – mpiugc compiler tool

Compile for GPU compute capability 2.0

```
$ mpiugc -arch=sm_20 <program.cu> -o exe
```

Run just on 1 CPU (serial) – Same source code, no gpus

```
$ mpirun -np 1 <exe> -ngpu 0
```

Run on 1 GPU using 1 CPU core: 1 CPU core manages the GPU

```
$ mpirun -np 1 <exe> -ngpu 1
```

Compiling and Executing CU++ Codes – mpiugc compiler tool

Run on 6 GPUs using 6 CPU processes : 6 CPUS Just manage the GPUs

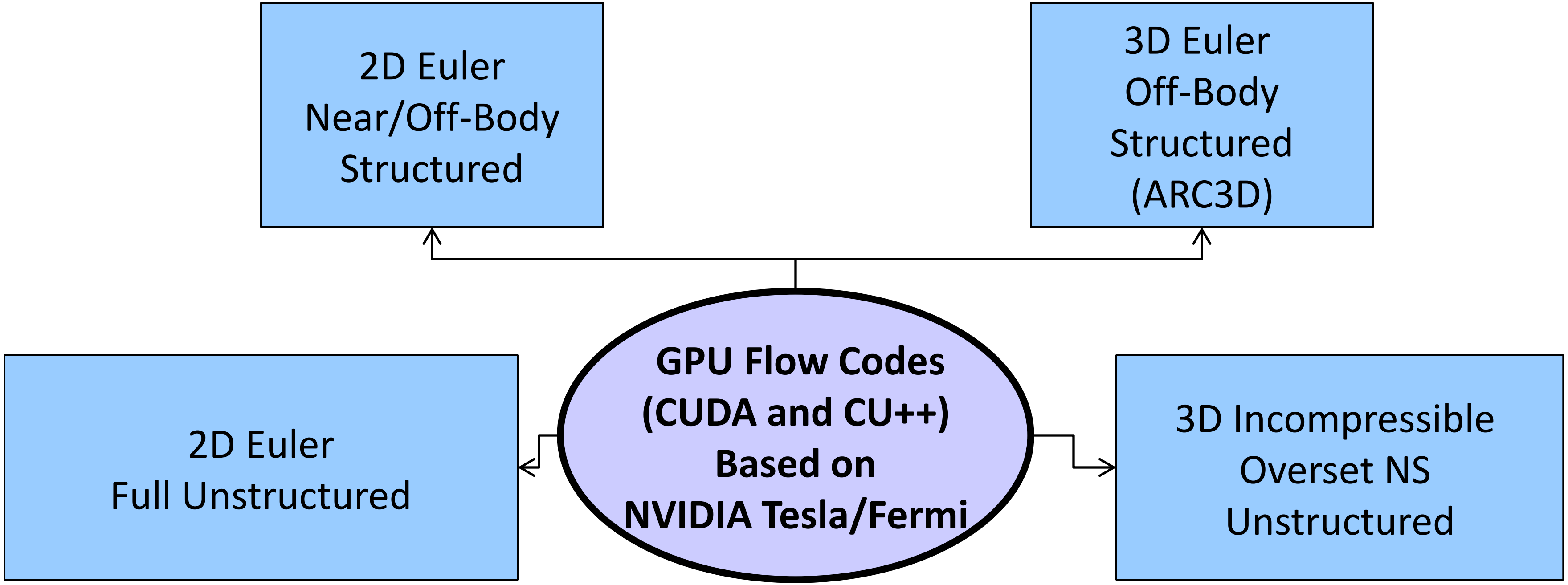
```
$ mpirun –np 6 <exe> -ngpu 6
```

What if you have a 16 core CPU and 4 GPUs and you want to
Use all cores and all GPUs (except the cores that are managing the GPU ?)

```
$ mpirun –np 16 <exe> -ngpu 4
```

- ❑ Processes 0-3 runs on the GPU
- ❑ Processes 4-15 run on the CPU

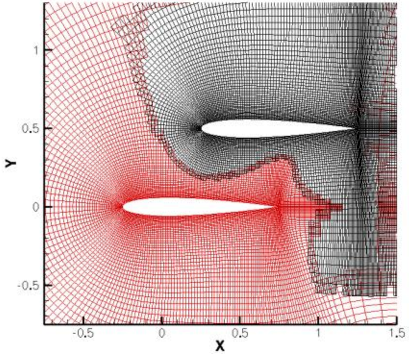
CU++ Applications



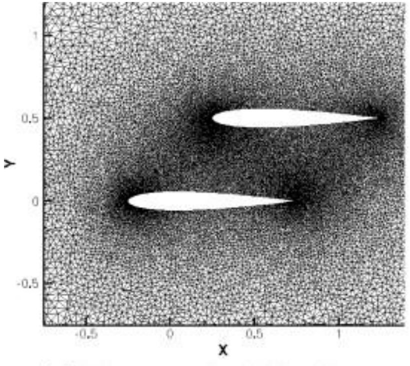
Unstructured Codes use both Kernel and CU++ Implementations – no MPI

Compressible Solver on Overset Grids

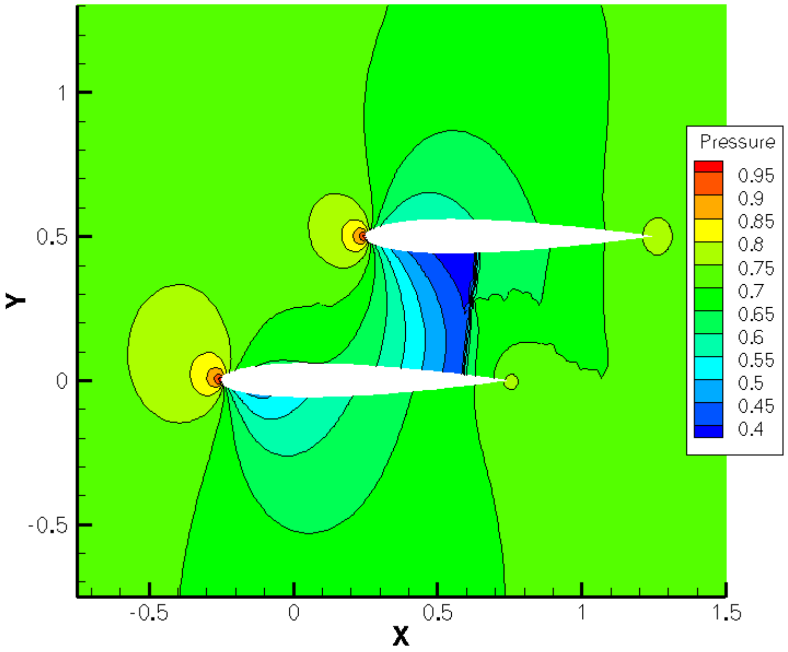
Computers and Fluids (2012)



Overset Structured
27x compared to a single core



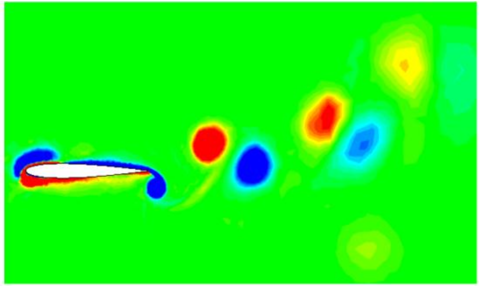
Full Unstructured
12x compared to a single core

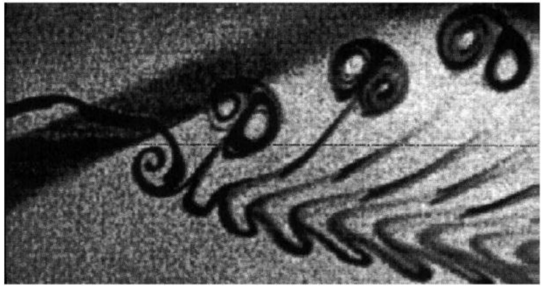


Incompressible Solver

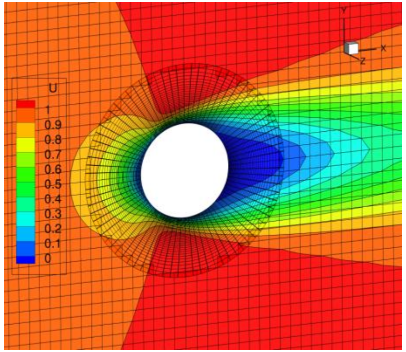
AIAA-2012-723

Flapping Airfoil

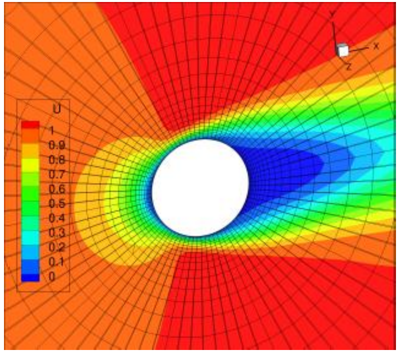




Flow past a sphere



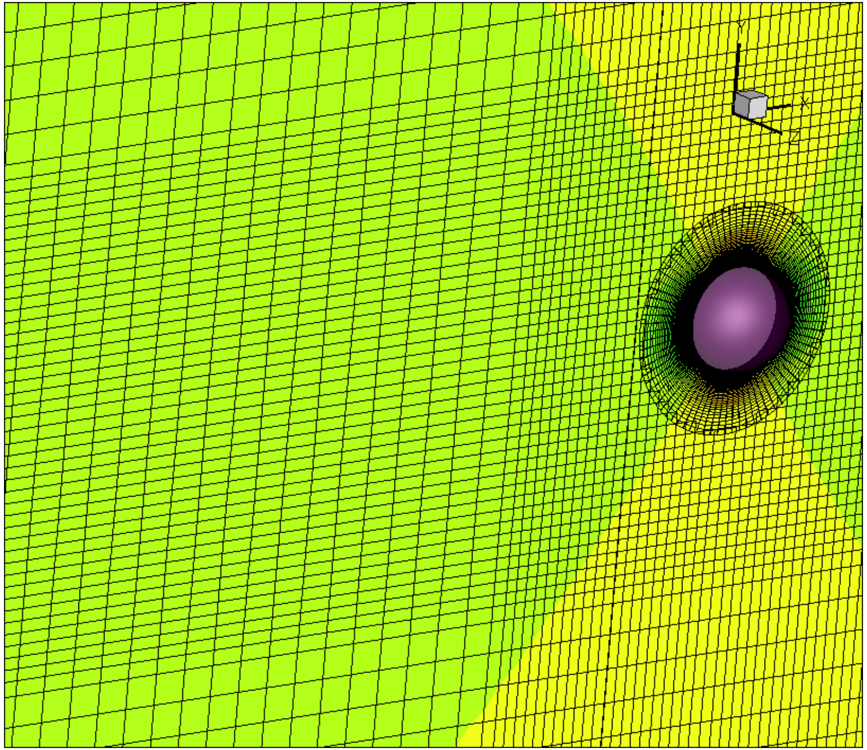
Overset Grid



Single Grid

Incompressible Solver

Moving Sphere



Current Work

- ❑ Partitioning with MPI for unstructured and overset grid cases (3D)
- ❑ Mixed MPI+CPU core implementations for unstructured cases
- ❑ Addition of turbulence models to the incompressible solver
- ❑ Incorporate structural dynamics module to analyze fluid-structure interaction problems - Involves mesh deformation

Acknowledgments

- *Support from the office of Naval Research under ONR grant N00014-09-1-1060 is gratefully acknowledged.*
- *NVIDIA for providing hardware*