# Running Geant4 Functions on a GPU Discussion of Results

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# Brief Project Overview

Take an existing particle simulation toolkit - Geant4 - and have some functions run on a GPU device to improve performance

### What is Geant4?

- Geant4 is a toolkit that is meant to simulate the passage of particles through matter
- It has been developed over the years through collaborative effort of many different institutions and individuals
- Geant4's diverse particle simulation library has a wide variety of applications including:
  - High energy physics simulations
  - Space and radiation simulations
  - Medical physics simulations

### Demonstration

Demonstration #1 – Running Geant4 on the CPU Hadr04 With Visualization

# What is GP-GPU Computing?

- General-purpose graphic-processing-unit computing is a re-purposing of graphics hardware
- Allows GPUs to perform computations that would typically be computed on the CPU
- If a particular problem is well suited to parallelization,
   GP-GPU computing can greatly increase performance

## Scope

- Make current CPU methods available for use on GPU
  - Update build system to support compiling and linking with GPU code
  - Rewrite algorithms in parallel fashion to run on GPU
- Ensure correctness of each GPU-available method by matching results to the corresponding CPU method
- Compare performance of GPU-available methods to CPU methods

## Design Phase – Possible Implementations

There were initially two different implementation approaches:

- Port much of Geant4 to the GPU such that each particle runs in parallel
  - Unreasonable given schedule/resource limitations
- Port all methods in some modules to the GPU, storing all relevant data in GPU memory
  - Easy to switch between CPU & GPU implementations
  - Supports splitting up work by module and by method, and working incrementally

## Purpose

- Determine if target methods are suitable to parallelization
- Increase performance of methods when run on GPU
- Decrease time required to run simulations involving ported methods

Easily Enable/Disable GPU Acceleration
Impl. 1: Existing Module in GPU Memory
Impl. 2: Add New GPU-Accelerated Methods to Interfac
Accuracy / Testing

### **Features**

#### Overview of Main Features:

- GPU acceleration available on an "opt-in" basis
- Easy to enable/disable GPU acceleration
- If GPU acceleration is enabled, some methods will run on GPU
- Same results whether acceleration enabled or disabled

# Easily Enable/Disable GPU Acceleration

- Existing projects can use GPU acceleration without having to change any code
- Flag during build phase enables/disables GPU acceleration
- Interface remains the same<sup>1</sup>, acceleration happens behind the scenes

<sup>&</sup>lt;sup>1</sup>implementation 1 only

Easily Enable/Disable GPU Acceleration
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### Demonstration

Demonstration #2 - Enabling CUDA Acceleration

## Easily Enable/Disable GPU Acceleration

Methods with GPU versions forwarded to GPU-based implementation at compile time

### Example of Forwarding Method Calls

```
inline G4double GetY(G4double x)
{
    #if GEANT4_ENABLE_CUDA
        return cudaVector->GetXsec(x);
    #else
        return GetXsec(x);
    #endif
}
```

## Accelerating Module on GPU

Existing module G4ParticleHPVector ported to GPU using CUDA

#### Definition: CUDA

CUDA is a GP-GPU programming model developed by NVIDIA, for use with NVIDIA graphics cards

### G4ParticleHPVector Overview

Represents empirically-found probabilities of collisions for different particles based on their energy

- Identified as starting point by relevant stakeholders
  - Used heavily in simulations run by stakeholders
- Seems well-suited to parallelization
  - Based on large vector of 2D points
  - Performs calculations over this vector
  - Sorted by x-value (particle energy)

## Two Implementations

- Forward all calls to existing G4ParticleHPVector interface to a GPU-based implementation of the module
  - Store data vector in GPU memory
  - Copy results back to the CPU to return to the caller
- 2 Add new methods to G4ParticleHPVector interface that are well-suited to GPU computing
  - Copy data vector to GPU memory on method call
  - Existing G4ParticleHPVector methods unchanged, continue to run on CPU

Easily Enable/Disable GPU Acceleration
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### Impl. 1: Existing Module in GPU Memory

Calls to G4ParticleHPVector forwarded to new GPU-based class

#### Pros:

- + Do not have to maintain a copy of the vector on the CPU<sup>2</sup>
- + Data rarely copied to GPU memory

#### Cons:

- All methods are run on the GPU, even if not well-suited to parallelism
- Return values must be copied from GPU memory to CPU memory (slow)

<sup>&</sup>lt;sup>2</sup>CPU cache was implemented later

Easily Enable/Disable GPU Acceleration Impl. 1: Existing Module in GPU Memory Impl. 2: Add New GPU-Accelerated Methods to Interface Accuracy / Testing

### Demonstration

Demonstration #3 – Running Geant4 on the GPU Hadr04 With Visualization

# Caching Data Vector in CPU Memory

To improve data-copying performance, maintain cache of data in CPU memory as well

- Only updated when necessary
- For methods that are not parallelizable, can run on CPU using cached data

### CopyToCpulfDirty

```
if (isDataDirtyHost) {
   cudaMemcpy(h_theData, d_theData, nEntries);
   isDataDirtyHost = false;
}
```

### Impl. 1 - Times

Multiplies each element in data vector by factor

#### Times\_CUDA

```
int tid = blockDim.x * blockIdx.x + threadIdx.x;
if (tid < nEntries)
    theData[tid].xSec = theData[tid].xSec * factor;</pre>
```

## Impl. 1 - GetXSec

Returns y-value of first point with energy at least e parameter

#### GetXSec\_CUDA

```
int start = blockDim.x * blockIdx.x + threadIdx.x;
for (int i = start; i < nEntries; i += numThreads)
  if (theData[i].energy >= e) {
    resultIndex = Min(resultIndex, i);
    return;
}
```

# Impl. 1: Performance Results Summary

- Methods generally slower on GPU until ~10,000 entries in data vector
- Most commonly-used methods significantly slower on GPU, even with large data vector
  - Lots of data copying
- Many problems in vector class not well-suited to parallelism

### Impl. 1: Performance Results - Times

#### Multiplies each point in vector by factor

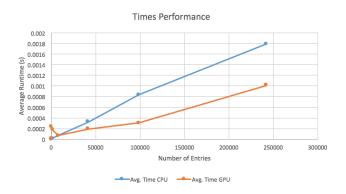


Figure: Runtime vs. Number of Data Points - Times

### Impl. 1: Performance Results - GetXSec

Returns y-value of first point with energy at least 'e'

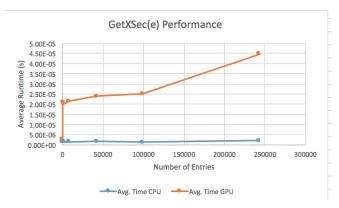


Figure: Runtime vs. Number of Data Points - GetXSec

# Impl. 1: Performance Results - SampleLin

Interpolates between two random, consecutive points and their corresponding integrals

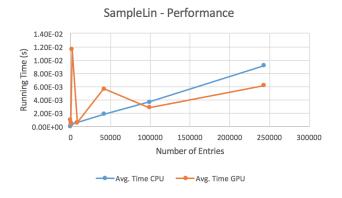


Figure: Runtime vs. Number of Data Points – SampleLin

# Impl. 1: Performance Results – System Tests

System Test #1:

CPU Time	GPU Time	Speedup of GPU
17.07s	22.11s	-1.29×

Table: Performance - Water, 600 events

System Test #2:

CPU Time	GPU Time	Speedup of GPU
54.55s	72.08s	-1.32×

Table: Performance - Water, 2000 events

## Impl. 1: Performance Discussion

- Simple "getters" and "setters" now require copy from GPU to CPU memory
- Current code calling G4ParticleHPVector more data-oriented than computation-oriented
- Low GetXSec performance due to lack of Hash object on GPU to accelerate finding min index
- Although some methods faster, rarely used in practice

### Impl. 2: Add New GPU-Accelerated Methods to Interface

Add new methods to G4ParticleHPVector interface that are well-suited to parallelism

#### **Pros:**

+ Only methods that run faster on the GPU are implemented

#### Cons:

Will need to copy the vector to the GPU whenever method called

### Impl. 2: GetXSecList

#### GetXSecList Overview

- Fill an array of energies for which we want the cross section values for
- Send the array to the GPU to work on
- Each thread works on its own query(s)

### Implementation - GetXSecList

#### GetXSecList

```
stepSize = sqrt(nEntries);
e = queryList[threadID];

for (int i = 0; i < nEntries; i += stepSize)
   if (d_theData[i].energy >= e)
        break;
```

## Implementation - GetXSecList Cont.

```
GetXSecList - cont

i = i - (stepSize - 1);

for (; i < nEntries; i++)
   if (d_theData[i].energy >= e)
       break;

d_queryList[threadID] = i;
```

# Impl. 2: Performance Results Summary

Performance of implementation 2 also proved slower than similar CPU-based method

- Performance on GPU linear to number of elements in data array
- Performance on CPU not affected by number of elements after point, due to saved hashes

## Impl. 2: Performance Results - GetXSecList

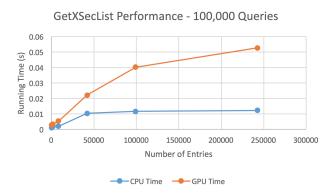


Figure: Runtime vs. Number of Data Points - GetXSecList, 100,000 Queries

## Impl. 2: Performance Discussion

- CPU implementation makes use of Hash to quickly find minimum index
- Finding first element satisfying predicate not well-suited to parallelism
- If one thread finds element, must wait for all other threads (blocking divergence)

Easily Enable/Disable GPU Acceleration Impl. 1: Existing Module in GPU Memory Impl. 2: Add New GPU-Accelerated Methods to Interfac Accuracy / Testing

## Accuracy

- All modified methods except SampleLin and Sample yield results that precisely match original implementations
  - Some methods fell extremely close in accuracy to the original, and were considered to 'pass'
  - For Sample and SampleLin, the average of 1000 tests was compared, with a relative error tolerance of 0.01
- The system test results differ with more than 500 events
  - Sample and SampleLin only called if more than 500 events

# **Accuracy Discussion**

- The deviations in SampleLin and Sample can be attributed to their use of random numbers
  - CUDA random number generator will have different results than rand()
  - Both methods take random point and interpolate it and its neighbour, so values differ significantly based on random number
- The negligible deviations in other ported methods are attributed to small differences in CPU and GPU arithmetic round-off errors (log, exp, etc.)

## **Testing**

- Comparing test results and performance with GPU acceleration enabled and disabled
- Testing framework based on two phases, one program for each phase
  - GenerateTestResults: Run unit tests and save results to file
  - 2 AnalyzeTestResults: Compare results from CPU and GPU
- Run GenerateTestResults once with GPU acceleration enabled, once with it disabled

### GenerateTestResults Details

- Outputs simple results directly to results file
- For arrays, calculates hash for array and output it
- Outputs timing data to separate file

### Example: Snippet of Generated Test Results

```
#void G4ParticleHPVector_CUDA::GetXsecBuffer(
   G4double * queryList, G4int length)_6
@numQueries=10
hash: 16548307878283220284
@numQueries=50
hash: 3204132713354913775
```

## AnalyzeTestResults Details

#### Two main functions:

- Compare results for each test case, printing status to stdout
  - If test failed, output differing values
  - Summarize test results at the end
- 2 Generate .csv file from timing data
  - One row per unique method call comparing CPU and GPU times
  - Can use Excel to analyze performance results

Impl. 1: Existing Module in GPU Memory Impl. 2: Add New GPU-Accelerated Methods to Interface Accuracy / Testing

### Demonstration

Demonstration #4 - Analyzing Test Results

# Summary of Results

- Impl. 1 was about 1.3X slower on average in system tests
- Impl. 2 was about 4X slower in unit tests
- Most commonly-used methods not well-suited to parallelism
- Sample and SampleLin have accuracy issues due to random number generation

#### For further work parallelizing Geant4:

- Use Geant4-GPU project as framework for parallelizing other modules
- Look for modules storing large amounts of structured data
- Methods with nested loops are prime candidates for parallelization
- Probabilistic methods and getter/setter methods won't have considerable benefits
- Methods with extensive conditional branching may cause difficulties in parallelizing

### Conclusion

- All project collaborators have gained a lot of experience
- Lack of speedup disappointing, but lets us know G4ParticleHPVector not perfect candidate
- Parallelization of existing software is hard