Accelerating Financial Applications on the GPU

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Sixth Workshop on General Purpose Processing Using GPUs

Outline

1. Introduction
   - QuantLib and Financial Applications
   - Directive-Based Acceleration
2. Experiment Setup
   - Source Code Modifications
   - Compilation
   - Execution Environment
3. Application Results
   - NVIDIA K20 Results
4. Auto-Tuning
   - Framework
   - Results
   - Alternate Architectures
5. Conclusion
   - Future Work
   - Final Notes

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QuantLib

- Open-Source library for Quantitative Finance
- Written in C++
- Contains various financial models and methods
  - Models: yield curves, interest rates, volatility
  - Methods: analytic formulae, finite difference, monte-carlo
- Financial applications optimized are particular code paths in QuantLib

Financial Applications

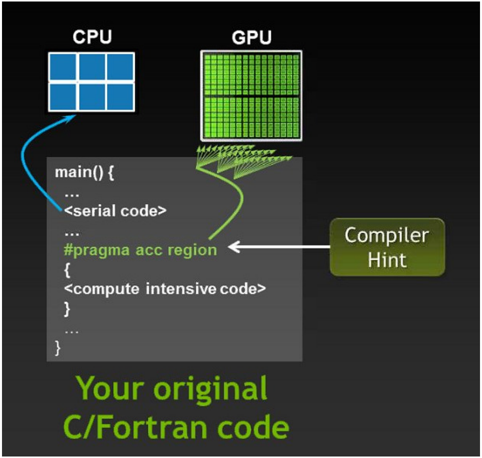
Four financial applications selected for parallelization

Application	**Description**	**Precision**
Black-Scholes	Option pricing using Black-Scholes-Merton pricing	Single
Monte-Carlo	Pricing of a single option using QMB (Sobol) Monte-Carlo method	Single
Bonds	Bond pricing using a fixed-rate bond with a flat forward-curve	Double
Repo	Repurchase agreement pricing of securities which are sold and bought back later	Double

- Each application is data-parallelized
- Algorithm for each application is parallelized where possible

Overview on Directive-Based Acceleration

- Syntax comparable to OpenMP
- Annotates what code should run on an accelerator
- Focuses on highlighting parallelism of code
- Preserves serial implementation of code
- Simplifies interaction between scientists and programmers



```
main() {
  ...
  <serial code>
  ...
  #pragma acc region
  {
  <compute intensive code>
  }
  ...
}
```

Directive-Based Programming Languages

OpenACC

- Joint collaboration between CAPS Entreprise, CRAY, PGI, and NVIDIA
- Directive syntax near identical to OpenMP with added data clauses
- Introduces a kernel directive that drives compiler-assisted parallelization

HMPP

- Originally developed by CAPS Entreprise
- Fundemental execution unit is a codelet
- Provides fine-grain control for optimizations

Outline

Source Code Modifications

- Code flatten QuantLib C++ ⇒ Sequential C code
- Implementations derived from Sequential C code
- Argument passing — Structure of Arrays
- Verification: Compared all results to original QuantLib code paths. All results were within 3 degrees of precision (10^{-3})

Code Flattening

```
// C++ code:
struct C {
  int x;
  void addFour() {
    x += 4;
  }
};
struct B {
  C myObj;
  virtual void foo() = 0;
};
struct A : public B {
  virtual void foo() {
    myObj.addFour();
  }
};
A inst;
inst.foo();
```

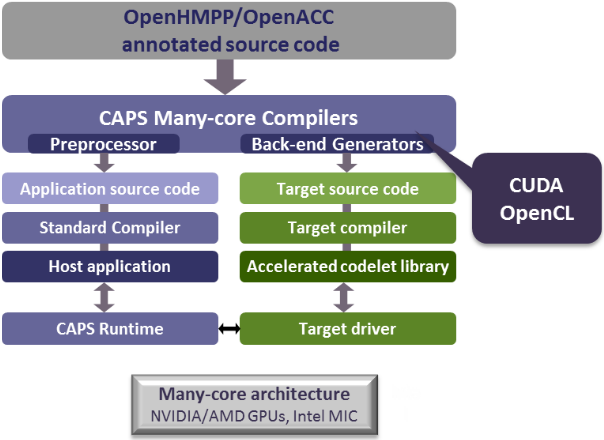
```
// flattened code:
int inst_x;
inst_x += 4;

// Alternative flattening:
int addFour (int x) {
  return x + 4;
}

int inst_x;
inst_x = addFour (inst_x);
```

Compilation

- Host code compiled with GCC 4.7.0
  - `-O2` flag used for serial
  - `-O3 -march=native` flag used for OpenMP
- OpenACC and HMPP compiled with HMPP Workbench 3.2.1
- CUDA compiled with CUDA 5 Toolkit
- OpenCL used NVIDIA driver version 304.54

Compile Workflow Using HMPP Workbench

- HMPP Workbench used for HMPP and OpenACC code compilation
- Target CUDA and OpenCL code generation



Execution Environment

CPU — Dual Xeon X5530 (Quad-Core @ 2.40GHz) with 24GB DDR3-1066 ECC RAM

GPU — NVIDIA K20c (2496 CUDA Cores @ 706MHz) with 5GB GDDR5 2.6GHz ECC RAM

NOTE: Also ran all experiments on NVIDIA C2050

Auto-Tuning Targets:

NVIDIA GPU	Architecture	CUDA Cores
NVIDIA C1060	Tesla	240
NVIDIA C2050	Fermi	448
NVIDIA GTX 670	Kepler GK104	1344
NVIDIA K20c	Kepler GK110	2496

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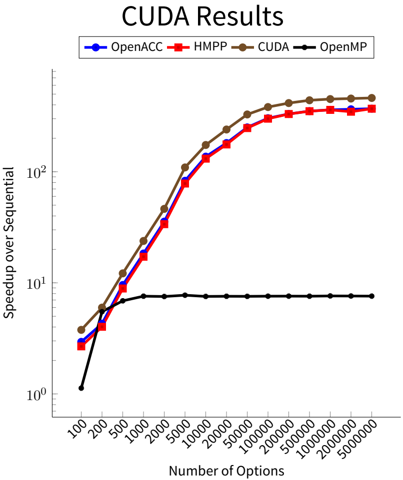
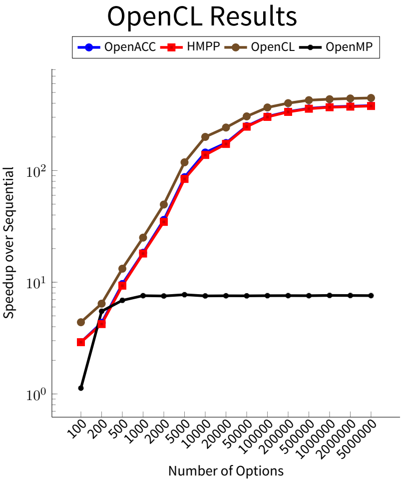
Black-Scholes — K20 Results

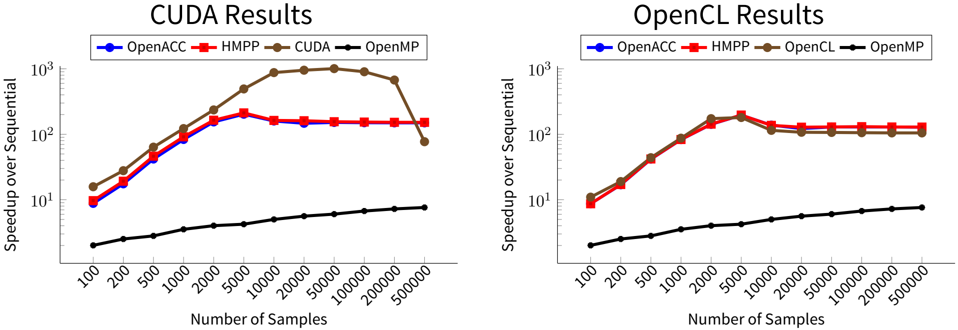




Black-Scholes — K20 Results

- CUDA outperformed OpenCL on NVIDIA K20
    - 461x speedup for CUDA
    - 446x speedup for OpenCL
- HMPP and OpenACC targeting the same language achieved near-identical speedup
- HMPP and OpenACC targeting OpenCL was faster than targeting CUDA
    - 369x speedup for CUDA
    - 380x speedup for OpenCL

Monte-Carlo — K20 Results



Random Number Generation:

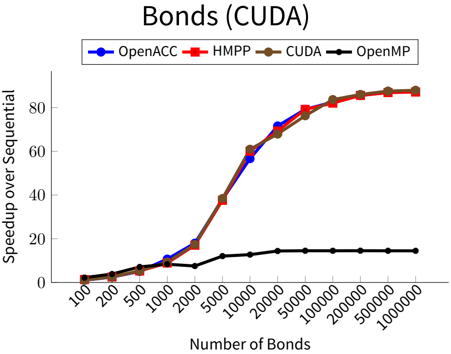
- C/OpenMP — `rand`
- CUDA — `cuRand`
- HMPP/OpenACC/OpenCL — Mersenne Twister

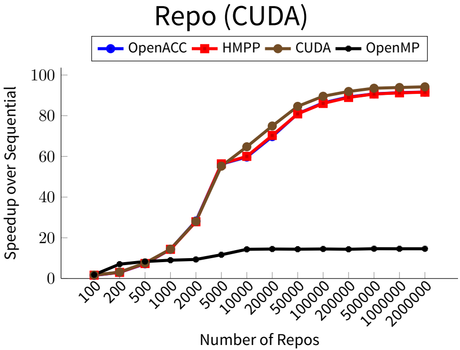
Dropoff in speedup for CUDA ⇒ cache misses

Monte-Carlo — K20 Results

- Manual CUDA outperformed manual OpenCL
  - Up to 1006x vs 180x
- HMPP and OpenACC performed similarly
- Targeting CUDA was faster than targeting OpenCL
  - Up to 162x vs up to 130x

Bonds and Repo — K20 Results





Problem: Generating OpenCL code from HMPP and OpenACC

Bonds and Repo — K20 Results

- Bonds: Up to 87.9x speedup
- Repo: Up to 94x speedup
- HMPP and OpenACC versions produced near-identical execution time
- HMPP and OpenACC versions ran within 2% execution time as manually-written CUDA
- Speedup flattened as problem size increased beyond 100,000 Bonds and 2,000,000 Repos

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Auto-Tuning Framework

- Goal: achieve maximum speedup by applying a set optimizations (while preserving accuracy)
- Collection of python scripts initially provided by CAPS Entreprise
- Injects code optimizations into annotated source code
  - `blocksize` — thread block dimensions on GPU
  - `unroll` — loop unroll factor; can be used with contiguous or split
  - `tile` — loop tiling factor
  - `remainder/guarded` — used for unrolling to specify remainder loop or conditional check, respectively
- Framework generates a set of new HMPP source files

Annotated Source Code Sample

```
%(blocksizePragma)
%(unrollTilePragma_iLoop)
%(parallelNoParallelPragma_iLoop)
for (i = 0; i < NI; ++i) {
 %(unrollTilePragma_jLoop)
 %(parallelNoParallelPragma_jLoop)
 for (j = 0; j < NJ; ++j) {
  c[i][j] *= p_beta;
  %(unrollTilePragma_kLoop)
  %(parallelNoParallelPragma_kLoop)
  for (k = 0; k < NK; ++k) {
   temp = p_alpha * a[i][k] * b[k][j];
   c[i][j] += temp;
  }
 }
}
```

- `unrollTilePragma` — specify loop unroll/tile factor with options
- `parallelNoParallelPragma` — specify whether to parallelize or not
- `blockSizePragma` — use determined block size

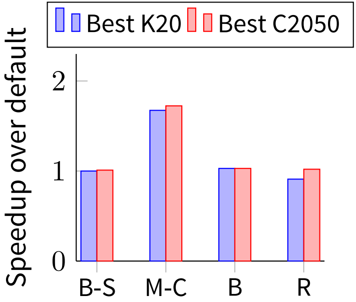
Auto-Tuning Results

Application	Thread Block	Loop Optimizations	Speedup (Default)
Black-Scholes 5,000,000 Options	32 X 4	No tiling / loop unrolling	369x (369x)
Monte-Carlo 400,000 Samples	32 X 2	Tile ‘main’ loop w/ factor 3 and ‘path’ loop w/ factor 4, both with ‘contiguous’ and ‘guarded’ options	265x (152x)
Bonds 1,000,000 Bonds	32 X 2	No tiling / loop unrolling	89.7x (87.1x)
Repo 1,000,000 Repos	32 X 2	Unroll inner ‘cash flows’ loop w/ factor 2 using ‘split’ and ‘guarded’ options	97.6x (91.2x)

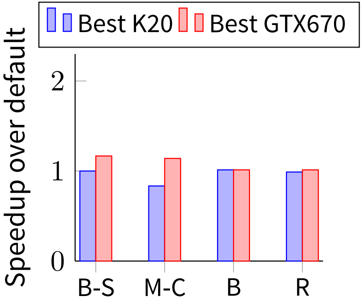
Running Optimized Code on Alternate Architectures

- Run the auto-tuned code on various architectures
- Compare speedup of best auto-tuned code of one architecture on other architecture
- All code paths executed on C1060, C2050, and GTX670

Run on C2050



Run on GTX 670



Outline

Future Work

- Target different architectures
    - AMD GPUs
    - Intel Xeon Phi
    - Heterogeneous systems
- Parallelize more code paths in QuantLib
- Parallelize additional financial applications outside of QuantLib

Final Notes

- Successful parallelization of four QuantLib code paths
- Achieve up to a 1000x speedup by targeting CUDA manually
- Achieve up to a 370x speedup by using HMPP and OpenACC
- Achieve up to a 74% speedup when auto-tuning
- Source code for codes in this presentation will be available at `www.sourceforge.net/projects/quantlib-gpu/`

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