GPU Acceleration of the Generalized Interpolation Material Point Method

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Sponsored in part by NSF awards CSR-0615412 and OCI-0749360 and by hardware donations from NVIDIA Corporation.

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Outline

- What is Material Point Method and Generalized Interpolation Material Point Method?
- Suitability for GPU Acceleration
- Implementation Challenges
  - Inverse mapping from grids to particles (global synchronization)
  - I/O in sequential implementation
- Experimental Results
- Looking to the future:
  - Programming Tools and Auto-tuning

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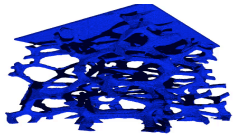
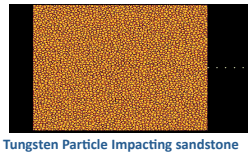
Rigid, Soft Body and Fluid Simulations

- Breadth of applications
  - fluids and smoke in games, astrophysics simulation, oil exploration, and molecular dynamics
- MPM Part of Center for the Simulation of Accidental Fires and Explosions (C-SAFE) software environment



Compaction of a foam microstructure



Tungsten Particle Impacting sandstone

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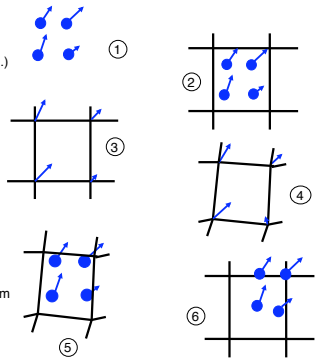
The Material Point Method (MPM)

1. Lagrangian material points carry all state data (position, velocity, stress, etc.)
2. Overlying mesh defined
3. Particle state projected to mesh, e.g.:
   $v_g = \sum_p S_{gp} m_p v_p / \sum_p S_{gp} m_p$
4. Conservation of momentum solved on mesh giving updated mesh velocity and (in principal) position.

   Stress at particles computed based on gradient of the mesh velocity.
5. Particle positions/velocities updated from mesh solution.
6. Discard deformed mesh. Define new mesh and repeat



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Approach

- Start with sequential library implementation of MPM and GIMP
  - And descriptions of parallel OpenMP and MPI implementations
- Profiling pinpointed key computations *(updateContribList and advance, >99%)*
- Two independent implementations (2-3 person teams)
- Some other aspects of mapping
  - Makes heavy use of C++ templates
  - Gnuplot used for visualization

Key Features of MPM and GIMP Computation

- Large amounts of data parallelism
- Particles mapped to discretized grid
  - Compute contribution of particles to grid nodes *(updateContribList)*
  - Compute <force, velocity, acceleration, stress> operations on grid nodes *(advance)*
- Each time step, the particles are moving
  - Compute stresses and recompute mapping
- Periodically, visualize or store results

Overview of Strategy for CUDA Implementation

- Partition particle data structure and mapping to grid across threads
- Build an inverse map from grid nodes to particles
  - Requires global synchronization
- Later phase partitions grid across threads
- Two implementations differ in strategy for this inverse map
  - V1: Sort grid nodes after every time step
  - V2: Replicate inverse map, using extra storage to avoid hotspots in memory (focus)

Global Synchronization for Inverse Map (CUDA Particle Project)

```
__device__ void addParticleToCell(int3 gridPos, uint
    index, uint* gridCounters, uint* gridCells)
{
  // calculate grid hash
  uint gridHash = calcGridHash(gridPos);

  // increment cell counter using atomics
  int counter = atomicAdd(&gridCounters[gridHash], 1);
  counter = min(counter, params.maxParticlesPerCell-1);

  // write particle index into this cell (uncoalesced!)
  gridCells[gridHash*params.maxParticlesPerCell +
    counter] = index;
}
```

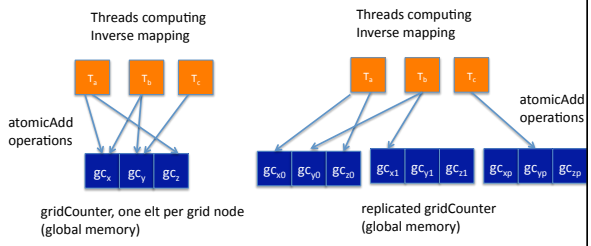
index refers to index of particle

gridPos represents grid cell in 3-d space

gridCells is data structure in global memory for the inverse mapping

What this does:
Builds up gridCells as array limited by max # particles per grid
atomicAdd gives how many particles have already been added to this cell

Optimized Version: Replicate gridCounters to avoid Contention



- Results of this optimization:
  - 2x speedup on *updateContribList*

Summary of Other Optimizations

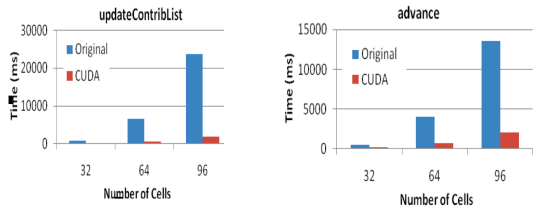
- Global memory coalescing
  - gridHash and gridCounters organization
  - Use of float2 and float4 data types
  - CUDA Visual Profiler pinpointed these!
- Maintain data on GPU across time steps
- Fuse multiple functions from sequential code into single, coarser grained GPU kernel
- Replace divides by multiples of inverse and cache

Experiment Details

- Architectures
  - Original = Intel Core2 Duo E8400 (3.00 GHz)
  - CUDA = nVIDIA GeForce 9600 GT (8 SMs)
- Input data set

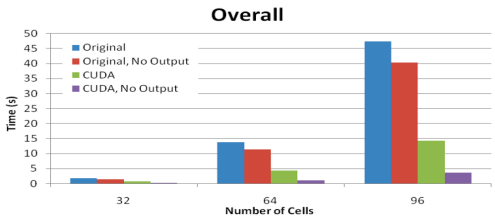
Cell	Grid Nodes	Particles
32	1,352	2,553
64	5,356	9,177
96	12,012	19,897

Results on Key Computations



- All results use 128 threads
- Speedups of 12.5x and 6.6x, respectively, over sequential implementation

Overall Speedup Results



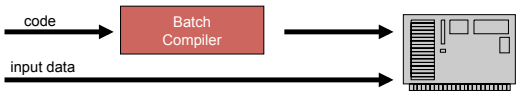
- No output, speedup of 10.7x
- With output, speedup only 3.3x
- Obvious future work: Open GL for visualization

Shifting Gears: Programmability and Auto-tuning

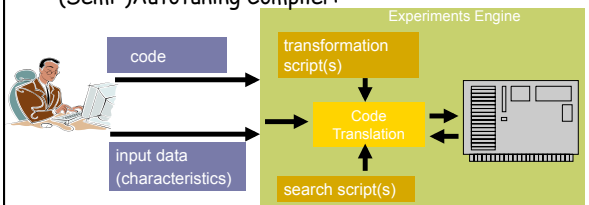
- Midterm extra credit question:
  - "If you could invest in tool research for GPUs, in what areas would you like to see progress?"
- Tools
  - Assistance with partitioning across threads/ blocks
  - Assistance with selecting numbers of threads/ blocks
  - Assistance with calculating indexing relative to thread/block partitioning

Auto-Tuning "Compiler"

Traditional view:



(Semi-)Autotuning Compiler:



Current Research Activity

- Automatically generate CUDA from sequential code and transformation script, with CUDAize(loop,TI,TJ,kernnm)
- Advantages of auto-tuning
  - Tradeoffs between large number of threads to hide latency and smaller number to increase reuse of data in registers
  - Detect ordering sensitivities that impact coalescing, bank conflicts, etc.
  - Evaluate alternative memory hierarchy optimizations
- Addresses challenges from earlier slide
  - Correct code generation, including indexing
  - Auto-tuning to select best thread/block partitioning
  - Memory hierarchy optimizations and data movement

Summary

- Three areas of improvement for MPM/GIMP
  - Used single precision, which may not always be sufficiently precise
  - Wanted more threads but constrained by register limits
  - OpenGL visualization of results
- Newer GPUs and straightforward extensions ameliorate these challenges
- Future work on programmability and auto-tuning

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