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Parallelizing the Physics Pipeline
: Physics Simulations on the GPU

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Introduction

» Based on my research at the university of Tokyo
  - Not at havok
» The details can be found in my publications
  - Takahiro Harada, "Real-time Rigid Body Simulation on GPUs", GPU Gems 3
  - Takahiro Harada, Issei Masaie, Seiichi Koshizuka, Yoichiro Kawaguchi, Massive Particles: Particle-based Simulations on Multiple GPUs, SIGGRAPH 2008 Talk
  - etc...
  - http://www.iii.u-tokyo.ac.jp/~takahiroharada/

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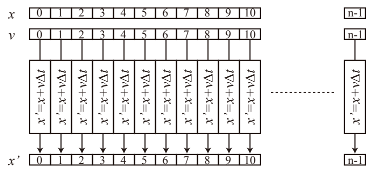
GPU

» GPU is designed for graphics
» GPU is good at
  - Many similar computations
  - Simple computations
  - Not complicated computations
  - All the thread taking the same path is ideal
» Ex. particle simulation without interaction



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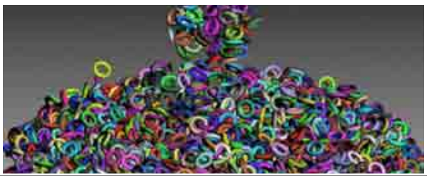
Physics Simulation

» Physics simulation is highly parallel
» Grid-based fluid simulation is well mapped on the GPU
» How about rigid bodies?
  - No general solution yet
  - Simplified approach
    - Takahiro Harada, "Real-time Rigid Body Simulation on GPUs", GPU Gems3



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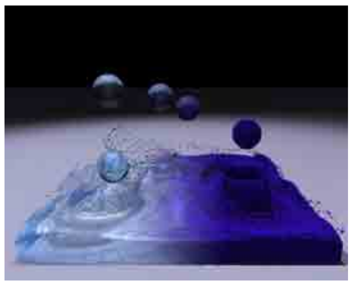
Particle-based Simulation

» Smoothed Particle Hydrodynamics
  - Compressible fluids

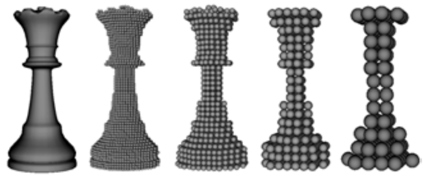


SPH Simulation

- Overview
  - For each particle
    - Look for neighboring particles
  - For each particle
    - Calculate pressure from neighbors
  - For each particle
    - Force on a particle is calculated using values of neighbors
  - For each particle
    - Integrate velocity and position
- Problem is neighbor search
  - Use uniform grid to accomplish this
  - Discuss later

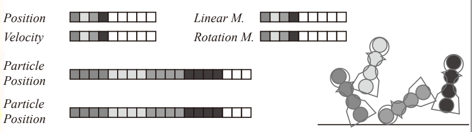
Rigid Body Simulation using Particles

- Extension to particle based simulation
- Use particles to calculate collision
- Rigid body is represented by particles
  - Not accurate shape
  - Trade off between accuracy and computation
  - Simple, uniform computations -> Good for GPUs



Data Structure

- For each rigid body
  - Positions
  - Quaternion
  - Linear momentum
  - Angular momentum
- For each particle
  - Position
  - Velocity
  - Force
- For neighbor search
  - 3D grid

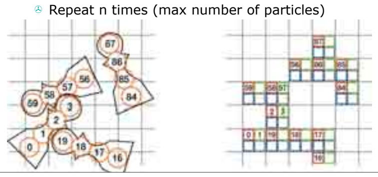


Overview

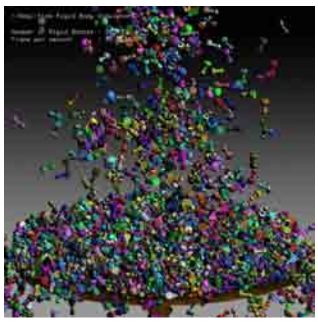
- Computation of particle values
  - For each particle: read values of the rigid body and write the particle values
- Grid generation
  - A little bit tricky, later
- Collision detection and reaction
  - For each particle: read neighbors from the grid, write the calculated force (spring & damper)
- Update momenta
  - For each rigid body: sum up the force of particles and update momenta
- Update position and quaternion
  - For each rigid body: read momenta, update these

Grid Construction

- Storing particle indices to 3D grid
- Can limit the number of particle in a cell if particles does not penetrate
- Each thread read particle position, write the index to the cell location
- But this fails when several particles are in the same cell
  - Divide this into several pass
  - 1 index is written in a pass
  - Repeat n times (max number of particles)

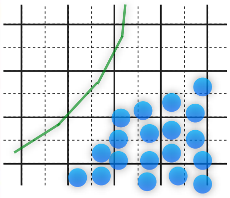


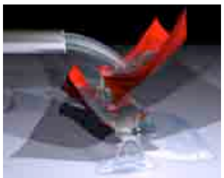
Demo



Extension

- If there are more than particles
  - Particles + Mesh(cloth)
- Can solve using several grids
  - A grid for particle
  - A gird for mesh
- Still not general





Broadphase Collision Detection

- Uniform grid is suited for the GPU
  - But not good for objects of not the same sizes
- Other approaches?
  - Sweep and prune
  - Tree
- Good for objects varying sizes
  - Much complicated than uniform grid
  - Can implement and accelerate on the GPU?

Tree traversal on the GPU

- Well studied in the field of ray tracing
  - Octree
  - Kd tree
- 2 problems when using for a real-time rigid body simulation
  - Dynamic construction of the tree
    - Several studies but few of them can beat the CPU
  - Traversal
    - Packet based for ray tracing -> cannot use this for collision detection
    - What is good for collision detection?

Dynamic Construction of Tree

- Tree construction is recursive subdivision of inputs -> not good for GPUs
- Convert the problem to a sorting problem
  - Calculate morton key of objects
  - Sort them
  - Add child-parent information to the sorted list
    - Lauterbach et al., Fast BVH Construction on GPUs, Eurographics 2009
    - MacCool, M., Creating Coherence-Ray tracing, Spatial Search and irregular Data Structure, Symposium on Interactive Ray Tracing 2008
- Still an open problem

Tree Traversal

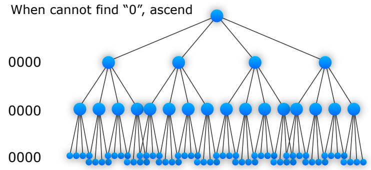
- Using stack is most common
  - Can implement on the GPU
  - **But** the requirement of resources is too much -> kill the performance
- Stackless traversal with additional info
  - Dynamic update?
  - High overhead
- Restart
  - Cannot restart because we want the overlap of bounding boxes (maybe can truncate BB...)

Tree Traversal using History Flags

- Observation
  - Descending a tree does not need any information
    - Start from first element of children
  - Ascending a tree needs where to get back
- Instead of stacking node indices, stores the history of traversal
- Data can be small

Tree Traversal using History Flags

- For each level, store 4 bits
  - Initialize 0000
- After visiting a node, flip the flag
  - 1000
- Descending to the next level
  - Just leave the flag and do the same to the next level
- Visiting the next element
  - Find "0" in the history flag
- Ascending the tree
  - When cannot find "0", ascend



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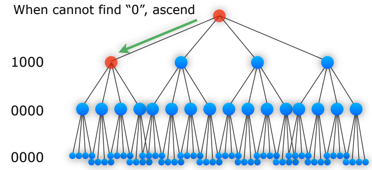

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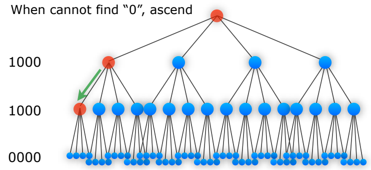

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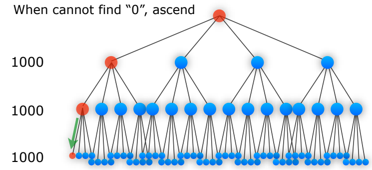

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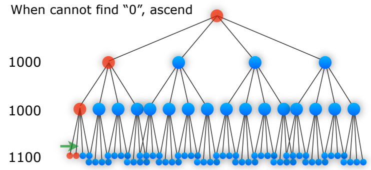

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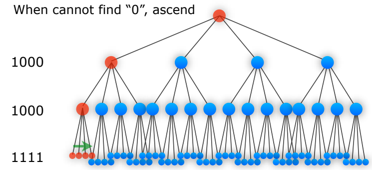

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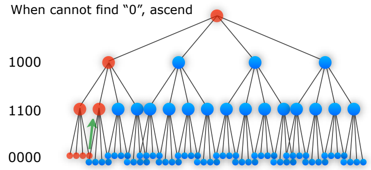

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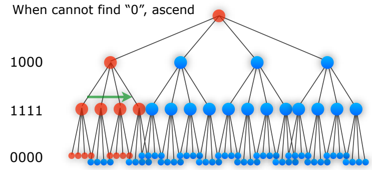

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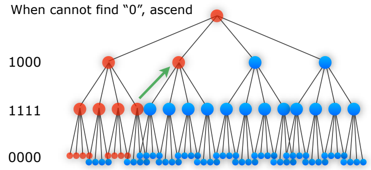

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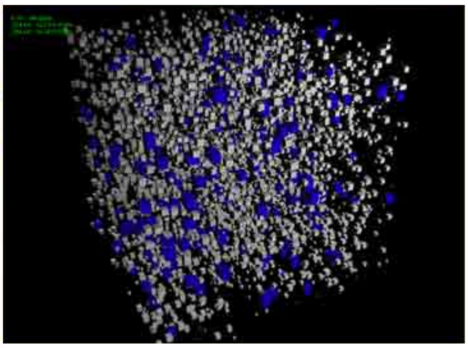
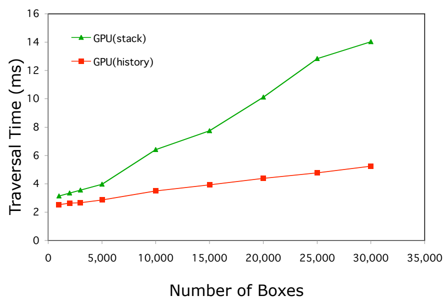
- Ascending the tree
  - When cannot find "0", ascend
- Discarding the flags of the level because they are used when descending to this level again
- 7 level octree traversal only requires 4bit x 7level = 28bit
- Can use shared memory for the storage of history flag -> fast access

Demo



Performance Comparison



Consideration

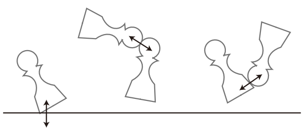
- Can implement tree construction and traversal on the GPU
  - If compare this to best solution on the CPU??
    - Octree is not the best solution on the CPU
- Kd tree on the GPU is also studied
- But the CPU is better
  - Shevtsov et al., "Highly Parallel Fast KD-tree Construction for Interactive Ray Tracing of Dynamic Scenes", EUROGRAPHICS 2007
  - Zhou et al., "Real-Time KD-Tree Construction on Graphics Hardware", SIGGRAPH Asia 2008

Solving Constraint

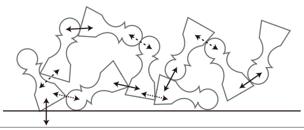
- Usually, constraints are solved for velocity
- Penalty based
  - No problem for parallel computation
  - Input: position, output: force
- Impulse based
  - Problem when parallelizing
  - Input: velocity, output: velocity
  - How to parallelize on the GPU?

Problem of Parallel Update

- If a rigid body is colliding to another rigid body, no problem

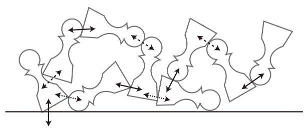


- If a rigid body is colliding to several rigid bodies, cannot update in parallel



Batching

- Not update everything at the same time
- Divide them into several batches
- Update batches in sequential
  - Update collisions in a batch in parallel



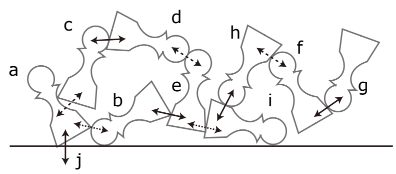
- But how to divide into batches?? GPU??

Batch Creation on GPU

- CPU can do this easily
  - Chen et al., High-Performance Physical Simulation on Next-Generation Architecture with Many Cores, Intel Technology Journal, volume 11 issue 04
- To implement on the GPU, the computation has to be parallel
- Do it by partially serialize the computation
  - Synchronization of several threads, which is available on CUDA, OpenCL

Batch Creation

- A thread is assigned for a constraint

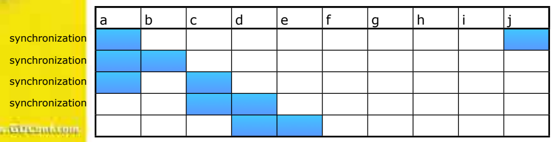


Thread ID	0	1	2	3	4	5	6	7	8	9
Constraint	a, j	a, b	a, c	c, d	d, e	e, i	b, e	h, i	f, h	f, g

Batch Creation

- A thread reads a constraint data
  - Thread0 reads 0, 9
- And write a flag to 0, 9, if they are not flagged
- Can serialize operation in a block
  - syncthreads

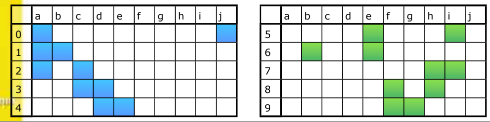
Thread Id	0	1	2	3	4	5	6	7	8	9
Constraint	a, j	a, b	a, c	c, d	d, e	e, i	b, e	h, i	f, h	f, g



Inconsistency

- But it does not solve the conflict among blocks
- Thread 1 and Thread 6 run at the same time
  - Both try to flag 1
- Need another mechanism to solve this situation
  - Need global synchronization

Thread Id	0	1	2	3	4	5	6	7	8	9
Constraint	a, j	a, b	a,c	c, d	d, e	e, i	b, e	h, i	f, h	f, g



Solving Inconsistency

- Thread 1 -> (0, 1)
- Thread 6 -> (1, 4)

- What we get is
  - Thread 1 succeed, Thread 6 failed
  - Thread 1 failed, Thread 1 succeed
- If a thread failed to flag a rigid body, it is not completed
- Instead of flagging, write constraint index to rigid bodies in the constraint
  - Thread 1 writes 1 to 0, 1
  - Thread 6 writes 1 to 1, 4

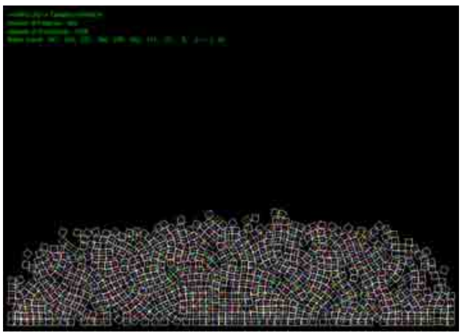
Solving Inconsistency

- [0, 1, 4] -> [1, 1, 6] or [1, 6, 6]
- Run another kernel to check the write
- A thread reads the number in rigid bodies in the constraint
- If both number is identical to the index of the constraint, it succeeded -> keep this
  - otherwise, it is not valid. Delete and do in the next pass

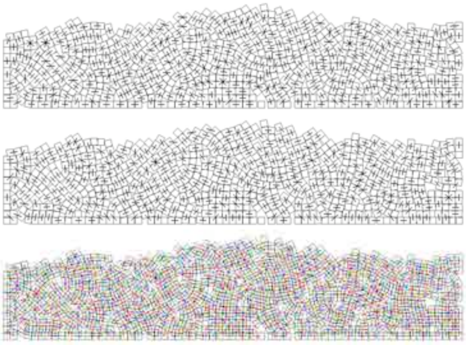
Procedure

- Batch 0
  - Clear the buffer
  - Write indices sequentially in a warp
  - Check if the write was succeed
- Batch 1
  - Clear the buffer
  - Write indices sequentially in a warp
  - Check if the write was succeed
- Batch 2
  - Clear the buffer
  - Write indices sequentially in a warp
  - Check if the write was succeed

Demo

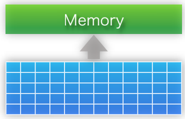


Batch

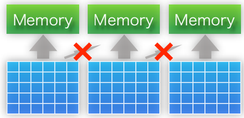


Using Multiple GPUs

- Cannot run applications developed for a GPU
- Need two levels of parallelization
- 1GPU

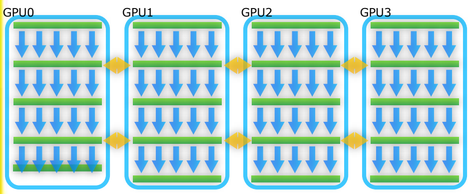


- Multiple GPUs



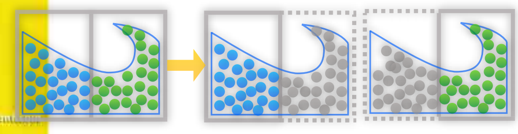
How to Design?

- Each GPU manages its own data
- No sequential process, completely parallel



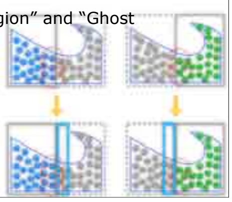
Particle Simulation on Multiple GPUs

- Grid-based
  - Domain decomposition is a natural choice, because elements in a subdomain does not change
- Particle-based
  - Have to assign particles to GPUs dynamically, because they move
  - How??
  - Overhead can be big without careful design



Decomposition of Computation

- Computation of particle values requires values of neighbors
  - Inside of subdomain: all the data is in the memory of its own
  - Boundary of subdomain: some data is in the memory of others
- Have to read data from other GPUs
  - Communicating when required makes the granularity of transfer smaller and inefficient
- Transfer only "Ghost Region" and "Ghost Particles"
  - Ghosts are not updated
  - Just refer the data



Environment

- 4GPUs(Simulation) + 1GPU(Rendering)
  - S870 + 8800GTS

- 6GPU(Simulation) + 1GPU(Rendering) @GDC2008
  - QuadroPlex x 2 + Tesla D870 + 8800GTS

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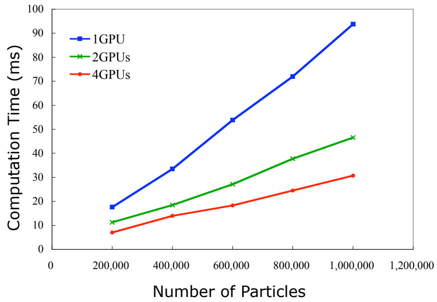
Results



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