Interacting with Huge Particle Simulations in Maya using the GPU
Introduction

- Particles (as used in VFX).
- Demo.
- GPU implementation.
  - Data organization.
  - Emission.
  - Environmental forces & collisions.
- Designing for a professional workflow.
- Fun with fluids.
- Demo & questions.
Introduction to Particles

- Discrete points with attributes, in space.
- Movement is defined by forces and constraints.
- They have limited state.
  - e.g. Force modifies velocity, and velocity modifies position.
    - Unconstrained by a grid.
      - Computation and storage are only used where needed.

- Already used extensively in VFX...
Particles in Film VFX


2008 - Disney use GPUs to efficiently render particles as sprites.

2009 - ILM use GPU particles for fast rigid-body dynamics in Transformers 2.
Particle Data Structures

- **System-wide attributes**
  - Attributes shared by all particles.
  - Typically constant.
  - e.g. gravity, deltaTime, mass, radius, etc.

- **Per-particle attributes**
  - Specified by the solver-definition / user-defined.
  - Structure of arrays.
  - e.g. position, velocity, color, temperature, etc.
Autodesk Maya - “nParticles”

- **Emitters.**
  - Omni, Volume, Surface, etc.
  - Surfaces can emit particle attributes.
- **Force-fields.**
  - Uniform, Radial, Vortex, Air, Drag, etc.
- **Collision with arbitrary geometry.**
- **Expression language.**
- **Allows integration of different kinds of materials (e.g. cloth, fluid) by using a singular physics representation.**
Motivation for Particles on the GPU

- Particles are simple and elegant.
- Small memory footprint.
- Easy to implement.
- Highly scalable.

= GPU friendly!

- See S. Green’s “particles” example in CUDA SDK.
Demo - nParticles vs. GPU Particles
Implementation Goals

- Integrate with existing Maya workflow.
- Be more interactive than current Maya tools.
  - We don’t want to slow down the Maya user-experience.
- Solution for *any* kind of particle problem.
  - rigid-bodies, DEM, fluid, hair, crowds... (smoke, fire)
The GPU in 1½ slides

- multi-core CPU (4 cores)
- Huge cache
- Lots of cores
- many-core GPU (448 cores)
Latency-hiding vs. Throughput

The CPU hides latency by optimizing memory accesses.

The GPU hides latency by quickly switching between compute threads.

WAIT  GO

Time

Cores

C M C M C M C M C M C M

Stall

M = Memory access time
C = Computation time

= Stall 😞
System Architecture

- **Solver-definition:**
  - Defines attributes & attributeArrays (per-particle attributes)
  - Informs emitters what they *must* provide.

- **Containers are mirrored on device**
  - (Going out-of-core if we need to).
Typical Particle Life-cycle on the Device

- Emit particles
- Sort particles
- Body forces
- Integrate particles
- Handle Collisions

Potentially “kill” particles.
Particle Sort into Uniform Grid

1. Assign particles to cells

2. Sort by cell index

3a. Scan to find first particle index

3b. Sort particle data based on sorting order
Particle Death

- If particle expires, set death flag.
- Cell assignment then puts it into `deadCell` (numCells+1 = 25)
- Sorting will put all dead particles in a contiguous block.
Particle Emission

- Host Container may have “new” particles.
- Upload emitted data using numParticles as offset.
- numParticles += numEmitted

- We use fast host-to-device transfer for emission data.
  - i.e. page-locked & write-combined host memory.
Maya’s Body Forces

- Typically a function of position.

\[ F_{uniform} = \alpha k \mathbf{d} \]
\[ F_{radial} = \alpha k \frac{\mathbf{r}_i}{|\mathbf{r}_i|} \]
\[ F_{vortex} = \alpha k \left( \frac{\mathbf{r}_i}{|\mathbf{r}_i|} \times \mathbf{d} \right) \]

\[ d = \text{axis} \]
\[ k = \text{magnitude} \]
\[ \mathbf{r}_i = \mathbf{x}_i - \mathbf{x}_{\text{origin}} \]
\[ \alpha = \frac{1}{\exp (\beta |\mathbf{r}_i|)} \]

where Beta is the attenuation factor
Primitives

- Multi-purpose geometric primitives.
- Support affine transforms.
- 3 types:
  - Implicit
    - Simple for fast math.
  - Convex-hull
    - Only convex objects.
    - HACD algorithm (K. Mamou et al.)
  - Signed distance fields
    - Handles any topology but with memory cost.
Displacement maps

- Allows more complex objects.
- Effectively a 2-level BVH.
- xNormal for map creation.

Note artifacts
Collision response

1. Transform particle (P) into unit-space and calculate penetration (d)
2. Determine normal (N)
3. Move particle out of collider (along normal)
4. Update velocity based on collider’s friction and restitution coefficients
Getting data back to Maya

- We want to use the particles’ data inside Maya.

- Modern NVIDIA GPUs can overlap compute with copy.
  - Quadro/Tesla have 2 copy engines.

- We can remove the cost of the data transfer if we allow some latency...
NVIDIA Maximus (Quadro & Tesla)

- 6GB & 448 cores each.
- DCC apps like Maya already use many GPU resources.
- Option of multi-GPU scaling.
- GL-interop
  - No CPU involved.
  - Tesla-CUDA to Quadro-GL.
  - Driver always looks to optimize.

GL driver

2x faster

CUDA driver

Quadro

Tesla

Display
The Host Application - (Autodesk Maya)

- **Maya plug-in callbacks:**
  - **Update** (called during data computation)
    - Upload & Simulate the particles.
    - Download the particles for export.
  - **Render** (called during Maya’s scene-graph traversal)
    - Render particles.
Example 1: Synchronous CUDA thread

- Create “GPU worker” thread for CUDA context.
  - Protection for both app & plug-in.
- Blit computed buffers to app’s OpenGL context
  - Use the CUDA GL-interop
Example 1: Synchronous CUDA thread

- Advantages:
  - Simple to implement.
  - Multi-threading protects our plug-in / host app.
  - Uses GL-interop for efficient data movement to the Quadro GPU

- Disadvantages:
  - We are relying on Maya calling our update at the start, and our render at the end!
Example 2: Double-buffered CUDA thread

- Use latency to overlap update with host app.
Double-buffered CUDA thread: Conclusions

- **Advantages**
  - Simple to implement.
  - Multi-threaded.
    - protects our plug-in / app.
    - Allows overlap of our computation and app.

- **Disadvantages**
  - One frame of latency.
  - No overlapping of compute with upload/download.
  - No frame-accurate access to particle data.
Example 3: Asynchronous CUDA streams

- One CUDA stream per batch
Asynchronous CUDA streams: Conclusions

- Batching the data means...
  - We hide the cost of data transfer between device and host.
  - Extension to Multi-GPU is now trivial.
- NB. Not all algorithms can batch data.
- Each batch’s stream requires resource allocation.
  - Be sure to do this up-front, before OpenGL gets it all!
  - Number of batches can be chosen based on available resources.
Example 4: Multi-GPU CUDA

- One GPU per batch

![Diagram showing multi-GPU CUDA process](image-url)
We already have the framework for this:

- If particle is beyond partition then kill it and emit on other device.
- If within threshold then emit as a “ghost” (i.e. it lives for only one update).
Fluid dynamics (in 1 slide)

- More interesting than boring particles.
- Works well on GPUs; it requires many data elements.
- Existing techniques:
  - Eulerian (grid-based)
  - Heightfield (2D / 2.5D grid)
  - Lagrangian (particle-based)

\[
\rho \frac{d\mathbf{v}}{dt} = -\nabla P + \nabla \cdot \mathbf{S} + \mathbf{F}
\]

Momentum equation

\[
\frac{d\rho}{dt} + \rho (\nabla \cdot \mathbf{v}) = 0
\]

Continuity equation
### SPH (in 1 slide)

- **Continuity equation:**
  \[
  \rho_a = \sum_b m_b W_{ab}
  \]

- **Momentum equation:**
  \[
  \frac{d\vec{v}_a}{dt} = -\sum_b m_b \left( \frac{P_a}{\rho_a^2} + \frac{P_b}{\rho_b^2} \right) \nabla W_{ab}
  \]
  \[
  P = c_s^2 (\rho - \rho_0)
  \]

- **Motion equation:**
  \[
  \vec{x}_i = \vec{x}_{i-1} + \vec{v}_{i-1/2} \Delta t
  \]
  \[
  \vec{v}_{i+1/2} = \vec{v}_{i-1/2} + \frac{d\vec{v}}{dt} \Delta t
  \]
The life-cycle of particles (with SPH)
Rendering Particles as a fluid

- Polygonize density field
  - e.g. Marching cubes, etc.

- Screen-space rendering

Final Shaded Translucent Surface
Rendering Particles in Screen-space

1. **Render points**
2. Extract the depth
3. Additive blending
4. Final composite
5. Normals from depth

Steps:
- **Render points**
- **Extract the depth**
- **Additive blending**
- **Final composite**
- **Normals from depth**
Future enhancements

- More solvers:
  - Crowds, rigid-bodies, non-newtonian materials, etc.
- More rendering styles:
  - OptiX, Volumes, Sprites, Instanced geometry, etc.
- Better fluid meshing using anisotropic kernels.
- Scriptable particle expressions using a virtual-machine.
- Maya 2013 & Viewport 2.0 integration.
Conclusions

- Building CUDA-accelerated particles in Maya is easy.
  - Leverages some of Maya’s existing framework.

- Using techniques like overlapping and multi-GPU can provide even more performance.

- By using Maximus and simulating on the Tesla card, Maya remains interactive.
Acknowledgments


- W. J Van Der Laan, S. Green, Miguel Sainz: “Screen space fluid rendering with curvature flow” - Proceedings of the 2009 symposium on Interactive 3D graphics and games


- S. Green, “Particles” demo, NVIDIA CUDA SDK.