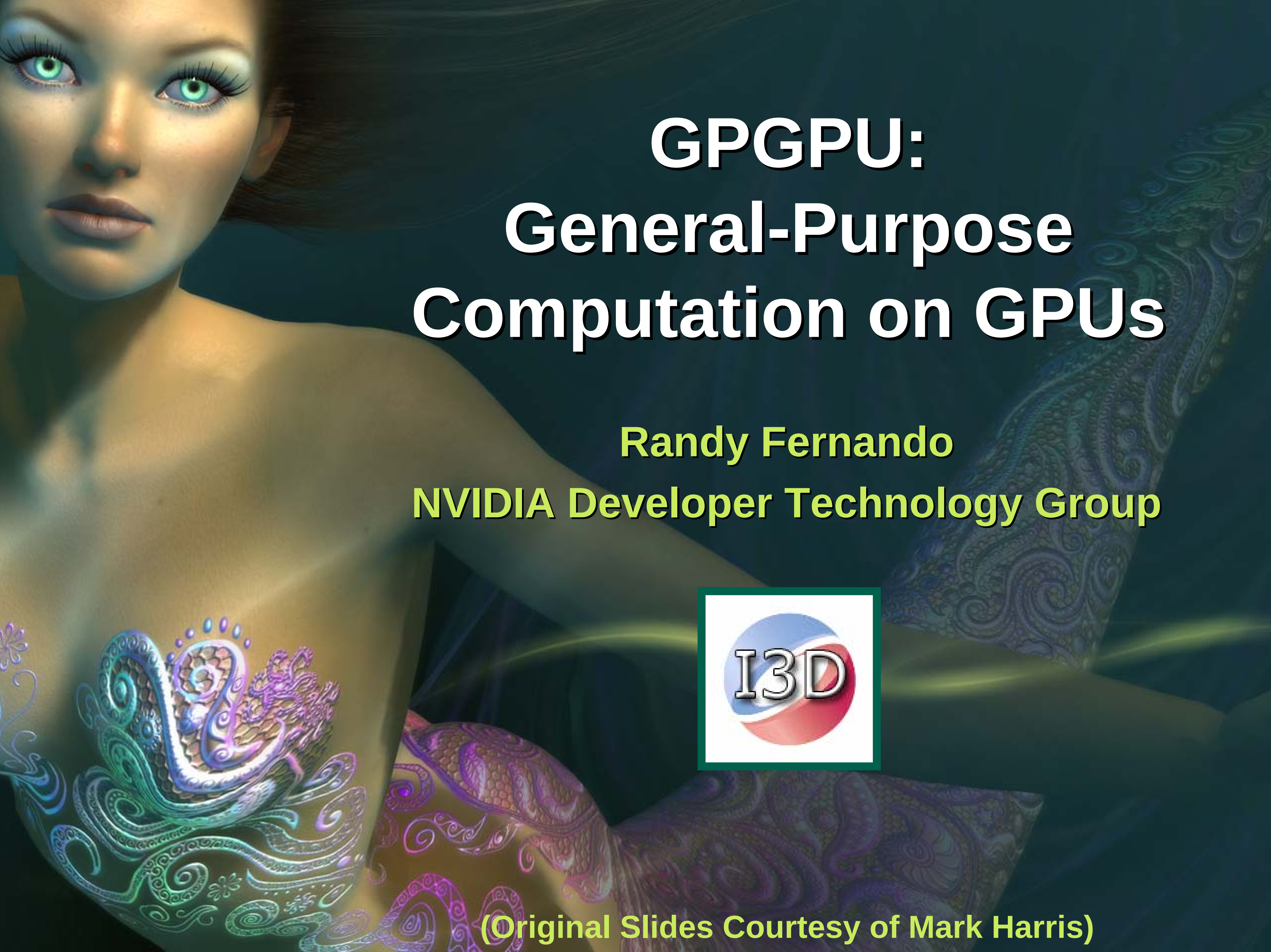


GPGPU: General-Purpose Computation on GPUs

Randy Fernando

NVIDIA Developer Technology Group

(Original Slides Courtesy of Mark Harris)

Why GPGPU?

- The GPU has evolved into an extremely flexible and powerful processor
  - Programmability
  - Precision
  - Performance
- This talk addresses the basics of harnessing the GPU for general-purpose computation

Motivation: Computational Power

- GPUs are fast…
  - 3 GHz Pentium 4 *theoretical*: 6 GFLOPS
    - 5.96 GB/sec peak
  - GeForce FX 5900 *observed*[*]: 20 GFLOPs
    - 25.6 GB/sec peak
  - GeForce 6800 Ultra *observed*[*]: 40 GFLOPs
    - 35.2 GB/sec peak

[*]Observed on a synthetic benchmark:

- A long pixel shader with nothing but MUL instructions

GPU: high performance growth

- CPU
  - Annual growth ~1.5× → decade growth ~ 60×
  - Moore’s law
- GPU
  - Annual growth > 2.0× → decade growth > 1000×
  - Much faster than Moore’s law

Why are GPUs getting faster so fast?

- Computational intensity
  - Specialized nature of GPUs makes it easier to use additional transistors for computation not cache
- Economics
  - Multi-billion dollar video game market is a pressure cooker that drives innovation

Motivation: Flexible and precise

- Modern GPUs are programmable
  - Programmable pixel and vertex engines
  - High-level language support
- Modern GPUs support high precision
  - 32-bit floating point throughout the pipeline
  - High enough for many (not all) applications

Motivation: The Potential of GPGPU

- The performance and flexibility of GPUs makes them an attractive platform for general-purpose computation
- Example applications (from www.GPGPU.org)
  - Advanced Rendering: Global Illumination, Image-based Modeling
  - Computational Geometry
  - Computer Vision
  - Image And Volume Processing
  - Scientific Computing: physically-based simulation, linear system solution, PDEs
  - Stream Processing
  - Database queries
  - Monte Carlo Methods

The Problem: Difficult To Use

- GPUs are designed for and driven by graphics
  - Programming model is unusual & tied to graphics
  - Programming environment is tightly constrained

- Underlying architectures are:
  - Inherently parallel
  - Rapidly evolving (even in basic feature set!)
  - Largely secret

- Can’t simply “port” code written for the CPU!

Mapping Computational Concepts to GPUs

- Remainder of the Talk:

- Data Parallelism and Stream Processing
- Computational Resources Inventory
- CPU-GPU Analogies
- Flow Control Techniques
- Examples and Future Directions

Importance of Data Parallelism

- GPUs are designed for graphics
  - Highly parallel tasks
- GPUs process *independent* vertices & fragments
  - Temporary registers are zeroed
  - No shared or static data
  - No read-modify-write buffers
- Data-parallel processing
  - GPU architecture is ALU-heavy
    - Multiple vertex & pixel pipelines, multiple ALUs per pipe
  - Hide memory latency (with more computation)

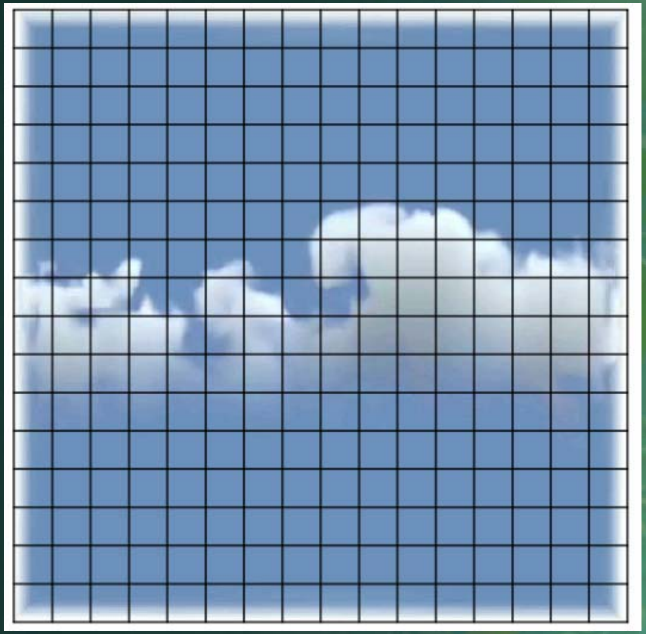
Data Streams & Kernels

- Streams
  - Collection of records requiring similar computation
    - Vertex positions, Voxels, FEM cells, etc.
  - Provide data parallelism
- Kernels
  - Functions applied to each element in stream
    - transforms, PDE, …
  - Few dependencies between stream elements
    - Encourage high Arithmetic Intensity

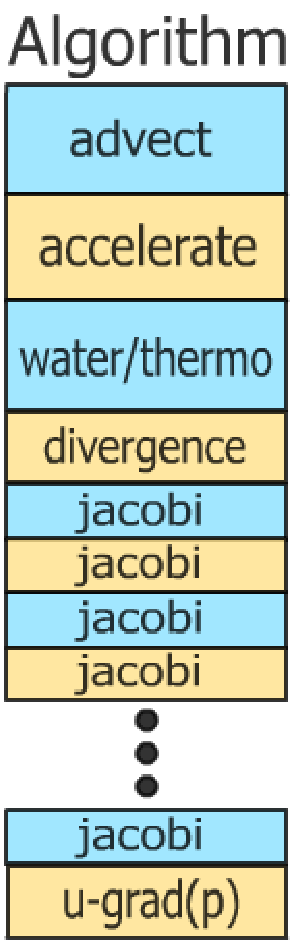
Courtesy of Ian Buck

Example: Simulation Grid

- Common GPGPU computation style
  - Textures represent computational grids = streams
- Many computations map to grids
  - Matrix algebra
  - Image & Volume processing
  - Physical simulation
  - Global Illumination
    - ray tracing, photon mapping, radiosity
- Non-grid streams can be mapped to grids



Stream Computation



Algorithm

advect

accelerate

water/thermo

divergence

jacobi

jacobi

jacobi

jacobi

⋮

jacobi

u-grad(p)

- Grid Simulation algorithm
  - Made up of steps
  - Each step updates entire grid
  - Must complete before next step can begin
- Grid is a stream, steps are kernels
  - Kernel applied to each stream element

Scatter vs. Gather

- Grid communication (a necessary evil)
  - Grid cells share information
  - Two ways:
    - Scatter
    - Gather

Computational Resources Inventory

- Programmable parallel processors
  - Vertex & Fragment pipelines
- Rasterizer
  - Mostly useful for interpolating addresses (texture coordinates) and per-vertex constants
- Texture unit
  - Read-only memory interface
- Render to texture
  - Write-only memory interface

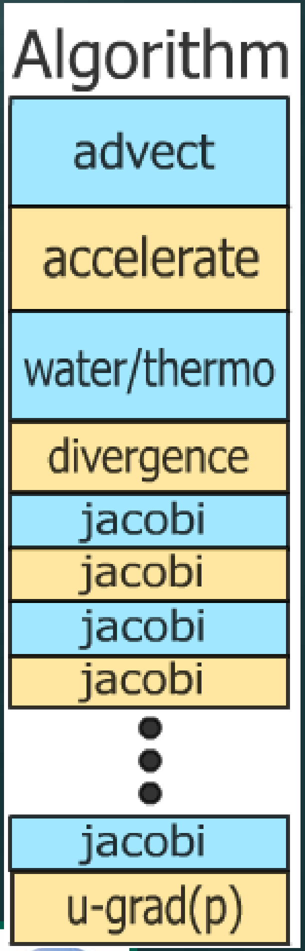
Vertex Processor

- Fully programmable (SIMD / MIMD)
- Processes 4-vectors (RGBA / XYZW)
- Capable of scatter but not gather
    - Can change the location of current vertex (scatter)
    - Cannot read info from other vertices (gather)
    - Small constant memory
- New GeForce 6 Series features:
    - Pseudo-gather: read textures in the vertex program
    - MIMD: independent per-vertex branching, early exit

Fragment Processor

- Fully programmable (SIMD)
- Processes 4-vectors (RGBA / XYZW)
- Capable of gather but not scatter
  - Random access memory read (textures)
  - Output address fixed to a specific pixel
- Typically more useful than vertex processor
  - More fragment pipelines than vertex pipelines
  - Gather / RAM read
  - Direct output
- GeForce 6 Series adds SIMD branching
  - GeForce FX only has conditional writes

GPU Simulation Overview



- Analogies lead to implementation
  - Algorithm steps are fragment programs
    - Computational *kernels*
  - Current state variables stored in textures
    - Data *streams*
  - Feedback via render to texture
- One question:
  - How do we invoke computation?

Invoking Computation

- Must invoke computation at each pixel
  - Just draw geometry!
  - Most common GPGPU invocation is a full-screen quad

Standard “Grid” Computation

- Initialize “view” (so that pixels:texels::1:1)

```
glMatrixMode(GL_MODELVIEW);
glLoadIdentity();
glMatrixMode(GL_PROJECTION);
glLoadIdentity();
glOrtho(0, 1, 0, 1, 0, 1);
glViewport(0, 0, gridResX, gridResY);
```

- For each algorithm step:
  - Activate render-to-texture
  - Setup input textures, fragment program
  - Draw a full-screen quad (1 unit x 1 unit)

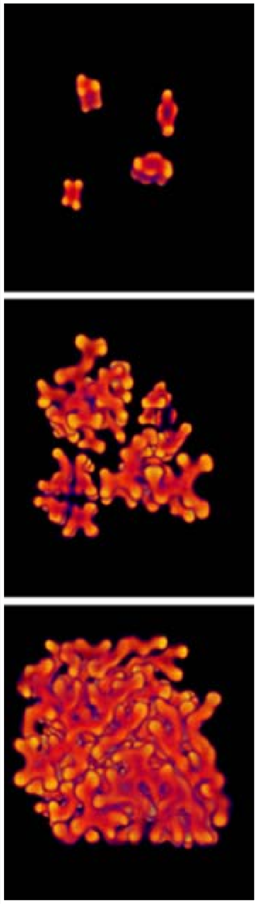
Reaction-Diffusion

- Gray-Scott reaction-diffusion model [Pearson 1993]
- Streams = two scalar chemical concentrations
- Kernel: just Diffusion and Reaction ops

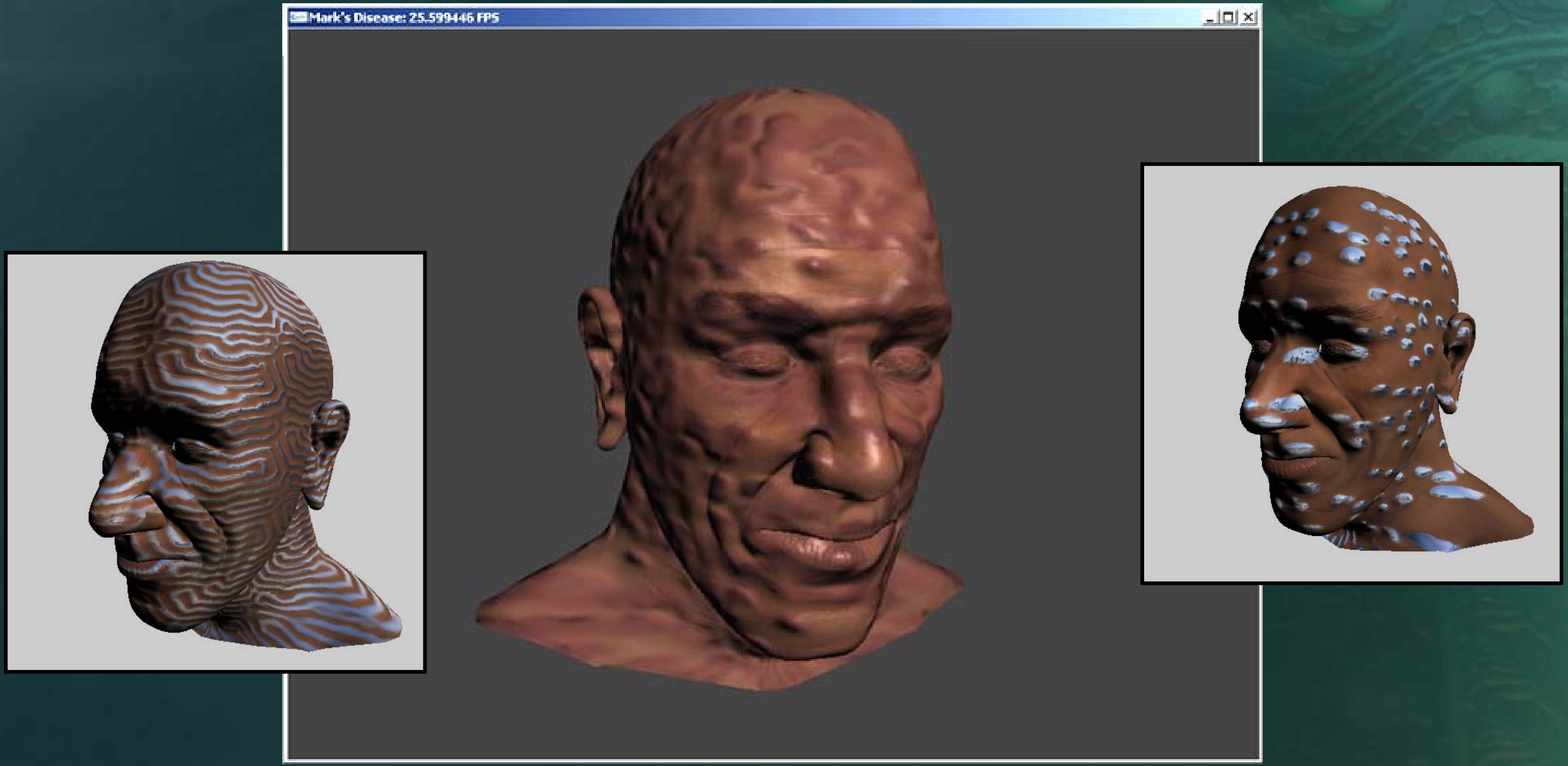
$$\frac{\partial U}{\partial t} = \boxed{D_u \nabla^2 U} \boxed{- UV^2 + F(1-U),}$$

$$\frac{\partial V}{\partial t} = \boxed{D_v \nabla^2 V} \boxed{+ UV^2 - (F+k)V}$$

U, V are chemical concentrations,
F, k, D_u, D_v are constants



Demo: "Disease"



Available in NVIDIA SDK: http://developer.nvidia.com

"Physically-based visual simulation on the GPU",
Harris et al., Graphics Hardware 2002

Per-Fragment Flow Control

- No true branching on GeForce FX
  - Simulated with conditional writes: every instruction is executed, even in branches not taken
- GeForce 6 Series has SIMD branching
  - Lots of deep pixel pipelines → many pixels in flight
  - Coherent branching = likely performance win
  - Incoherent branching = likely performance loss

Fragment Flow Control Techniques

- Try to move decisions up the pipeline
  - Replace with math
  - Occlusion Query
  - Domain decomposition
  - Z-cull
  - Pre-computation

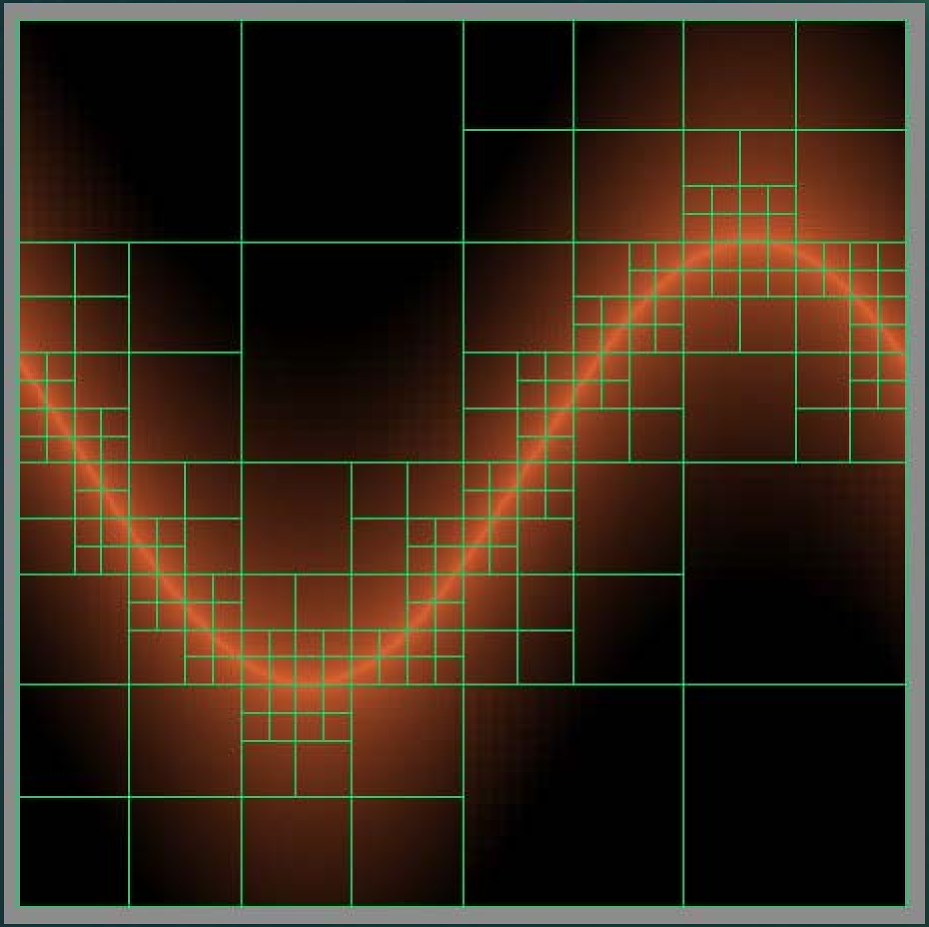
Branching with Occlusion Query

- OQ counts the number of fragments written
  - Use it for iteration termination

```
Do {  // outer loop on CPU
  BeginOcclusionQuery {
      // Render with fragment program
      // that discards fragments that
      // satisfy termination criteria
  } EndQuery
} While query returns > 0
```

- Can be used for subdivision techniques

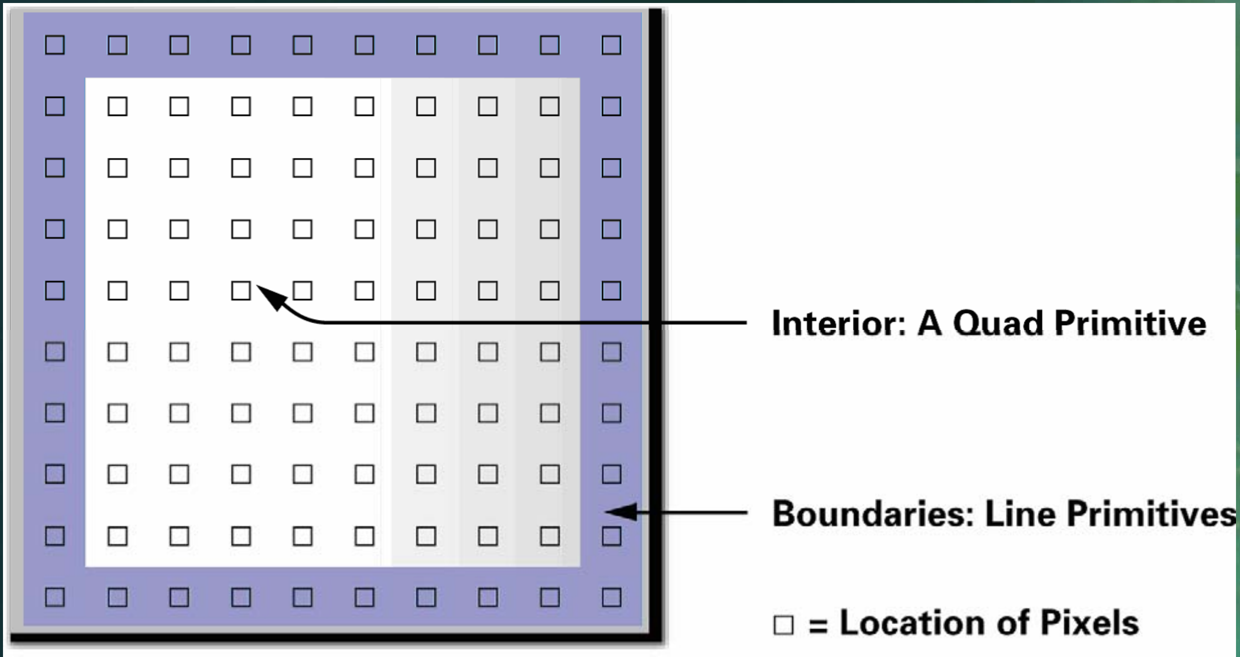
Example: OQ-based Subdivision



Used in Coombe et al., “Radiosity on Graphics Hardware”

Static Branch Resolution

- Avoid branches where outcome is fixed
  - One region is always true, another false
  - Separate FP for each region, no branches
- Example: boundaries



Z-Cull

- In early pass, modify depth buffer
  - Clear Z to 1, enable depth test
  - Draw quad at Z=0
  - Discard pixels that should be modified in later passes
- Subsequent passes
  - Enable depth test (GL_LESS), disable depth write
  - Draw full-screen quad at z=0.5
  - Only pixels with previous depth=1 will be processed

- Can also use early stencil test on GeForce 6

Pre-computation

- Pre-compute anything that will not change every iteration!
- Example: arbitrary boundaries
  - When user draws boundaries, compute texture containing boundary info for cells
    - e.g. Offsets for applying PDE boundary conditions
  - Reuse that texture until boundaries modified
  - GeForce 6 Series: combine with Z-cull for higher performance!

GeForce 6 Series Branching

- True, SIMD branching
  - Lots of incoherent branching can hurt performance
  - Should have coherent regions of > 1000 pixels
    - That is only about 30x30 pixels, so still very useable!
- Don’t ignore overhead of branch instructions
  - Branching over only a few instructions not worth it
- Use branching for early exit from loops
  - Save a lot of computation
- GeForce 6 vertex branching is fully MIMD
  - very small overhead and no penalty for divergent branching

Current GPGPU Limitations

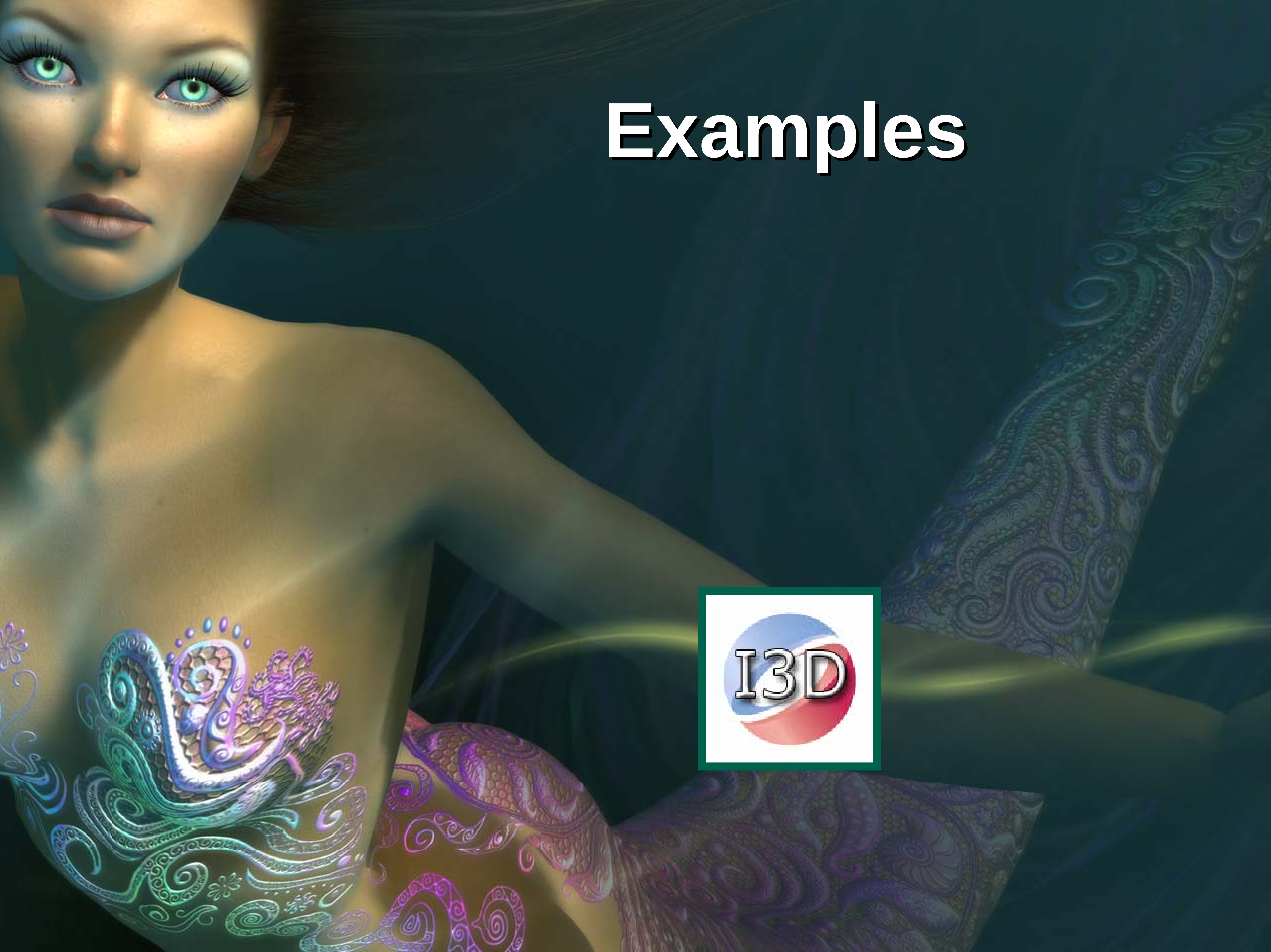
- Programming is difficult
  - Limited memory interface
  - Usually “invert” algorithms (Scatter → Gather)
  - Not to mention that you have to use a graphics API…

- Limitations of communication from GPU to CPU
  - PCI-Express helps
    - GeForce 6 Quadro GPUs: 1.2 GB/s observed
    - Will improve in the near future
  - Frame buffer read can cause pipeline flush
    - Avoid frequent communication to CPU

Brook for GPUs

- A step in the right direction
  - Moving away from graphics APIs
- Stream programming model
  - enforce data parallel computing: streams
  - encourage arithmetic intensity: kernels
- C with stream extensions
  - Cross compiler compiles to HLSL and Cg
  - GPU becomes a streaming coprocessor
- See SIGGRAPH 2004 Paper and
  - http://graphics.stanford.edu/projects/brook
  - http://www.sourceforge.net/projects/brook

Examples



Example: Fluid Simulation

- Navier-Stokes fluid simulation on the GPU
  - Based on Stam's "Stable Fluids"
  - Vorticity Confinement step
    - [Fedkiw et al., 2001]
- Interior obstacles
  - Without branching
- Fast on latest GPUs
  - ~120 fps at 256x256 on GeForce 6800 Ultra
- Available in NVIDIA SDK 8.0

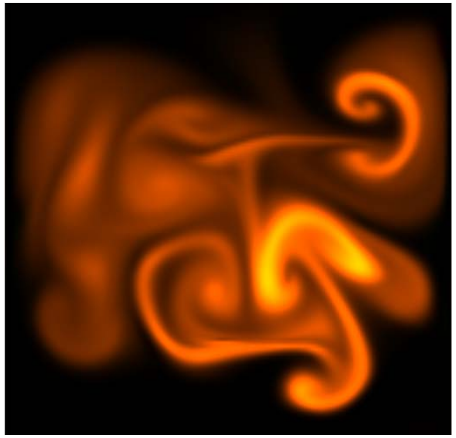
"Fast Fluid Dynamics Simulation on the GPU", Mark Harris. In *GPU Gems*.

Fluid Dynamics

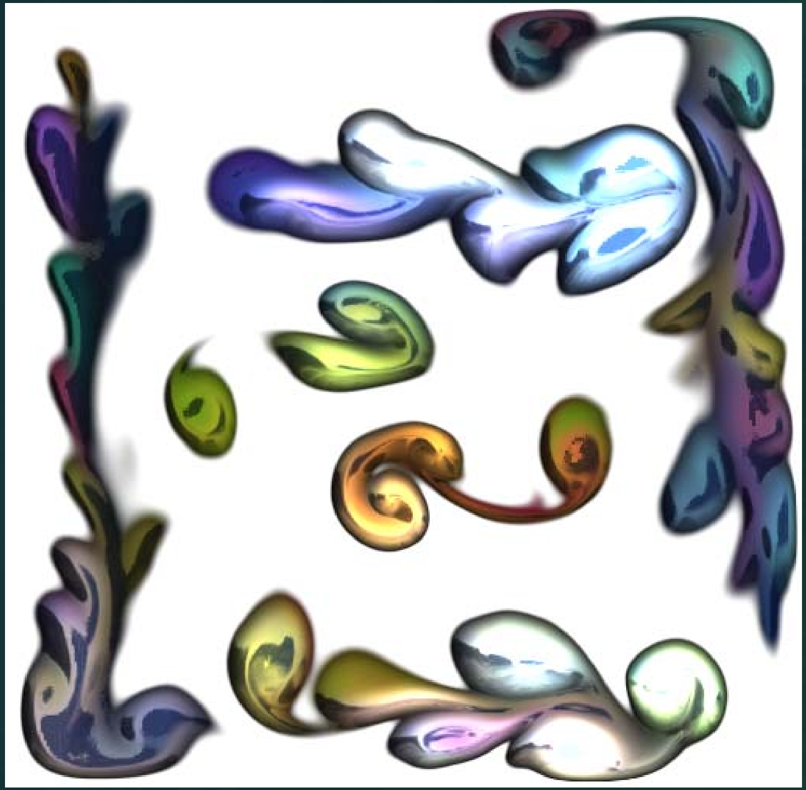
- Solution of Navier-Stokes flow equations
  - Stable for arbitrary time steps
  - [Stam 1999], [Fedkiw et al. 2001]

- Fast on latest GPUs
  - 100+ fps at 256x256 on GeForce 6800 Ultra

- See “Fast Fluid Dynamics Simulation on the GPU”
  - Harris, *GPU Gems*, 2004

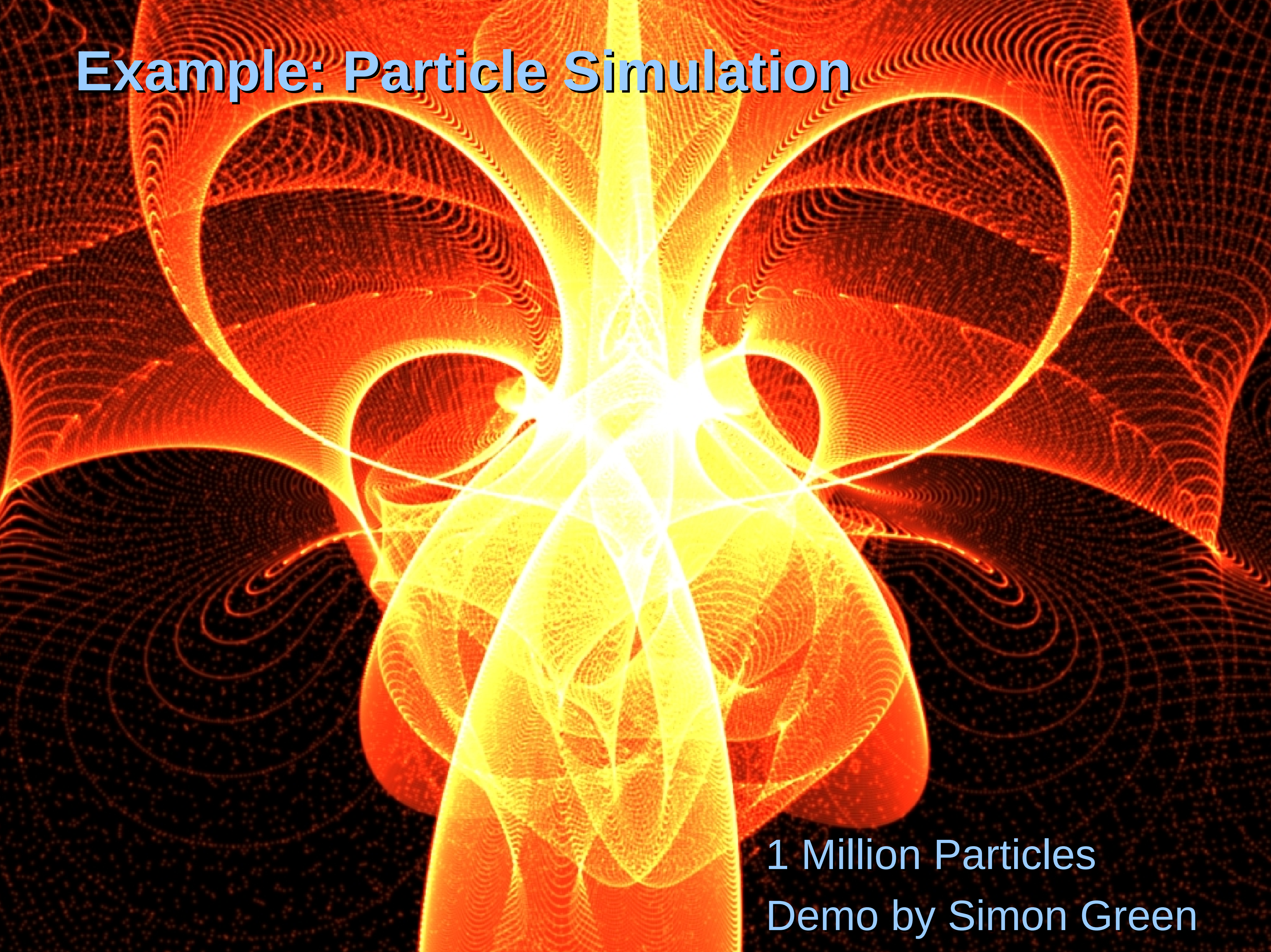


Fluid Simulator Demo



Available in NVIDIA SDK: http://developer.nvidia.com

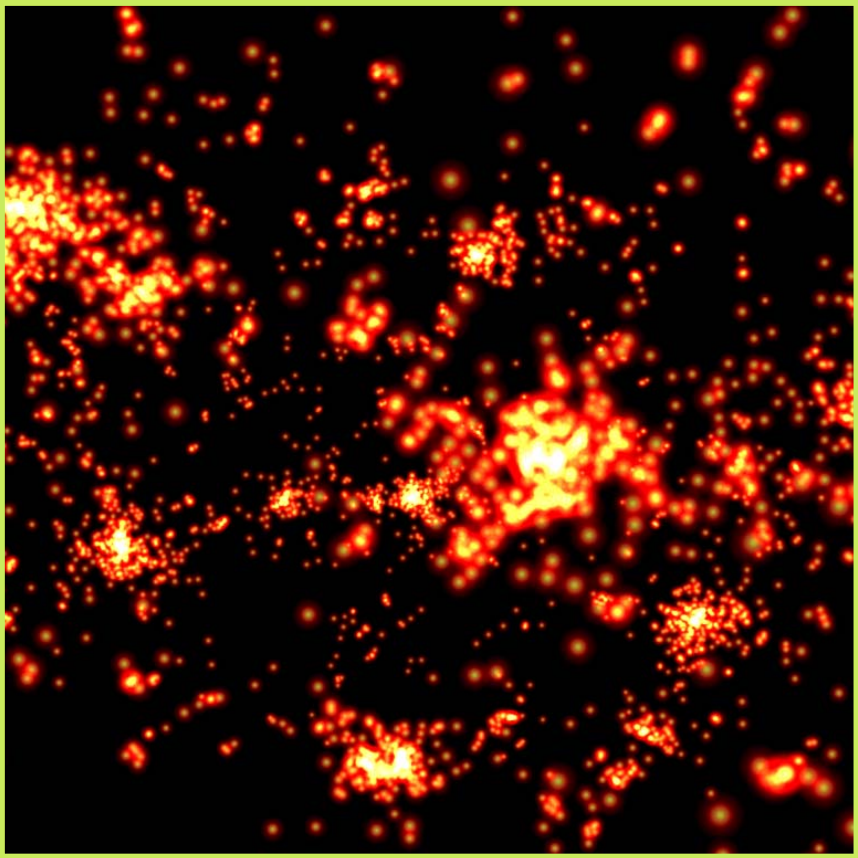
Example: Particle Simulation



1 Million Particles

Demo by Simon Green

Example: N-Body Simulation



Nyland et al., GP^2 poster

- Brute force ☹
- N = 4096 particles
- N^2 gravity computations

- 16M force comps. / frame
- ~25 flops per force
- 17+ fps

- 7+ GFLOPs sustained

The Future

- Increasing flexibility
  - Always adding new features
  - Improved vertex, fragment languages
- Easier programming
  - Non-graphics APIs and languages?
  - Brook for GPUs
    - http://graphics.stanford.edu/projects/brookgpu

The Future

- Increasing performance
  - More vertex & fragment processors
  - More flexible with better branching
- GFLOPs, GFLOPs, GFLOPs!
  - Fast approaching TFLOPs!
  - Supercomputer on a chip
- Start planning ways to use it!

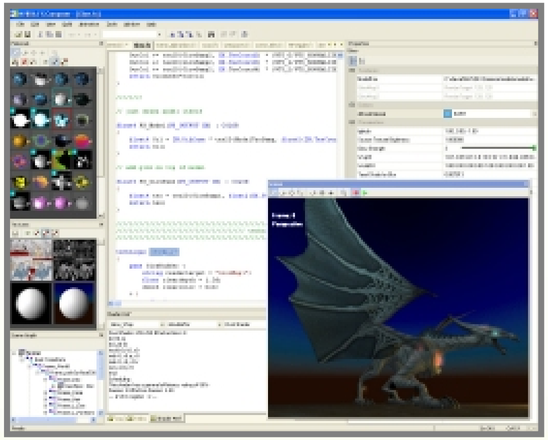
More Information

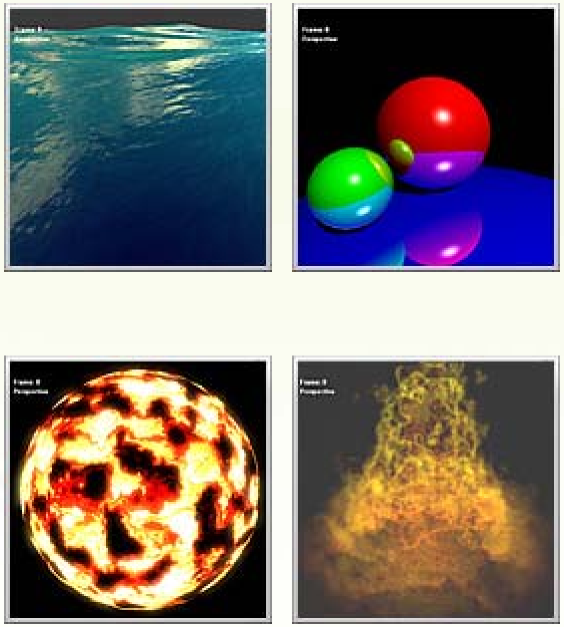
- GPU Gems 2
  - 20 Chapters on GPGPU Programming
- GPGPU news, research links and forums
  - www.GPGPU.org
- developer.nvidia.com
- Questions?

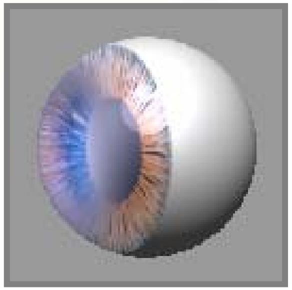
developer.nvidia.com

The Source for GPU Programming

- Latest documentation
- SDKs
- Cutting-edge tools
  - Performance analysis tools
  - Content creation tools
- Hundreds of effects
- Video presentations and tutorials
- Libraries and utilities
- News and newsletter archives


EverQuest® content courtesy Sony Online Entertainment Inc.





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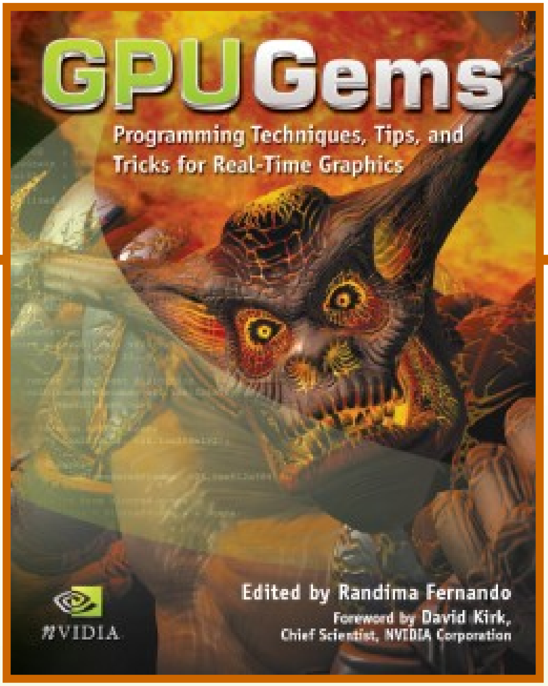

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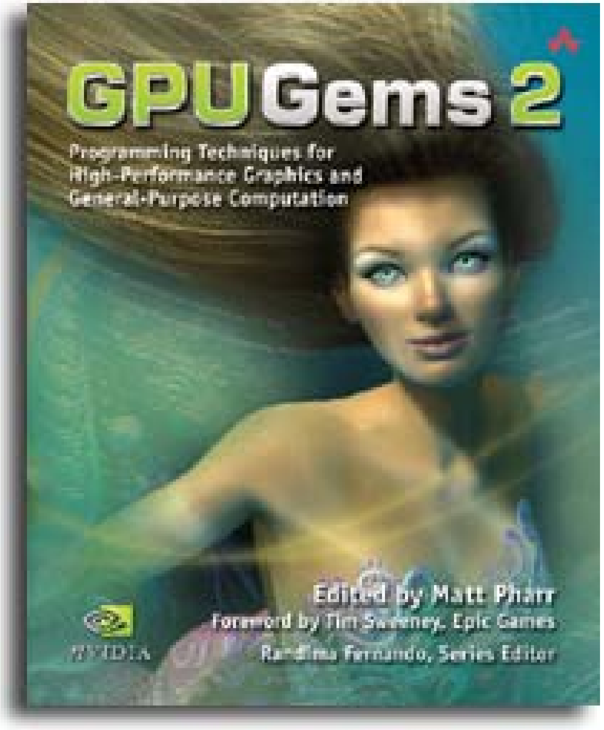

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