# Interactive Rendering In The Post-GPU Era

Matt Pharr

Graphics Hardware 2006

# Last Five Years

- Rise of programmable GPUs
  - 100s/GFLOPS compute
  - 10s/GB/s bandwidth
- Architecture characteristics have deeply influenced s/w and algorithm development
- Revolution in interactive graphics as software has exploited new hardware

# Next Five Years: A Second Revolution

- Continued GPU innovation
- CPUs finally providing FLOPS as well
  - Don't require nearly as much parallelism
- Shared memory/high bandwidth interconnect enable flexible computation model
- Future role of today's graphics APIs is unclear

# Overview

- The transition to programmable GPUs and the importance of computation in interactive rendering
- New heterogeneous architectures
- Implications for graphics software
  - Implementation challenges and opportunities
  - Increasing importance of software to drive complex hardware
- Longer-term trends and convergence?

neoptica

# Offline Rendering 5 Years Ago


Shrek (PDI/Dreamworks)

neoptica

# Interactive 5 Years Ago


Quake 3 (id Software)

# Modern Offline Rendering

Madagascar (PDI/Dreamworks)

# Modern Interactive Rendering


Project Gotham Racing

neoptica

# Modern Offline Rendering

Starship Troopers 2 (Tippett Studio)

# Modern Interactive Rendering


I-8 (Insomniac Games)

neoptica

# What's Happened In The Last 5 Years?

- GPUs have taken advantage of semiconductor trends to deliver performance
- GPU strengths/weaknesses have sparked innovation in algorithms and software
  - Interactive graphics is about computation
- Interactive is delivering near-offline quality 1,000,000x faster

# GPU Architecture Has Led To Algorithmic Innovation

- GPU performance cliffs are large
  - Must stay on fast path
  - Easier to achieve good GPU utilization than good CPU utilization?
- Benefits from staying on fast path are enormous
- Everyone has a GPU
  - Many more developers working in this space
  - Millions of GPUs in PCs: incentive to use them efficiently

neoptica

# Three Phases Of Hardware-Accelerated Graphics

- Configurable fixed-function graphics
  - Register combiners, multipass
- Programmable shading
  - Vertex and fragment shaders, texture composition, pattern generation, lighting models
- Programmable graphics
  - Shaders implement graphics algorithms using complex data structures

neoptica

# Example: Displacement Mapping Redefined

- Classic technique from offline rendering
- Texture map defines offset from base surface
- Offline approach:
  - Finely tessellate to pixel-sized triangles
  - Move triangle vertices appropriately
  - Discard triangles when done with them

neoptica

# Displacement Mapping Redefined

- Offline approach not suited to current hardware
  - GPU is balanced for ~8 pixel big triangles
  - Not enough vertex processing power for many small triangles
  - Small triangles not good for rasterizer/fragment processor
- Therefore, developers must invent new techniques better suited to the hardware

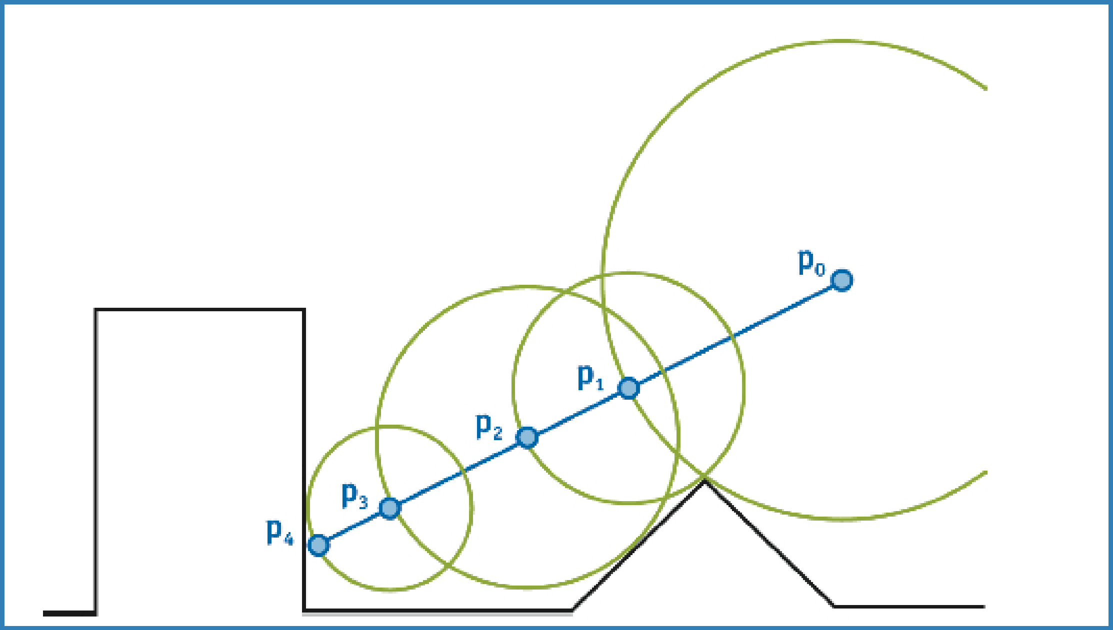
neoptica

# Displacement Mapping Redefined

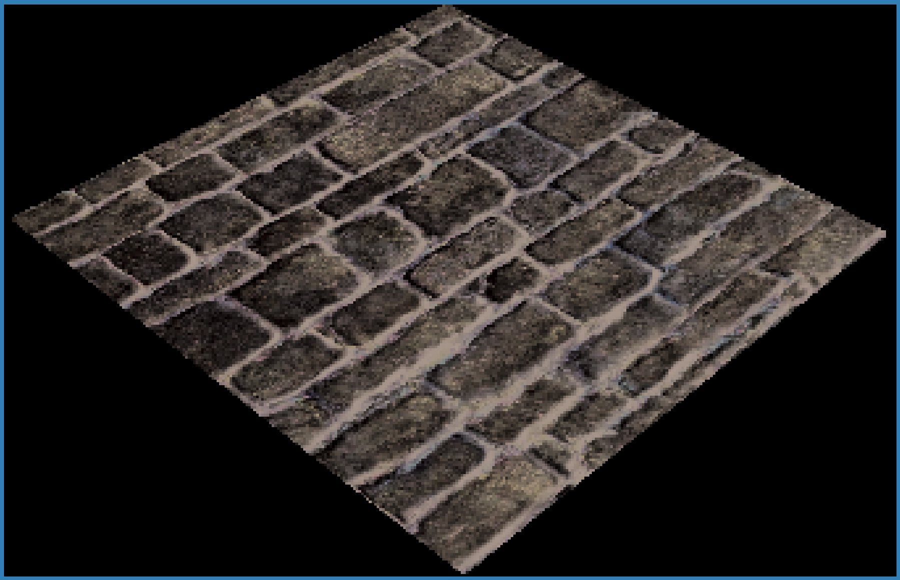
- Draw bigger triangles, do work in fragment processor
  - Better match to GPU's strengths and weaknesses
- Representative approach: Donnelly's distance map-based ray tracing
  - Small 3D table stores representation of empty space above displaced surface
  - Fragment shader marches through space until surface intersection is found

neoptica

# Distance Map Sphere Tracing

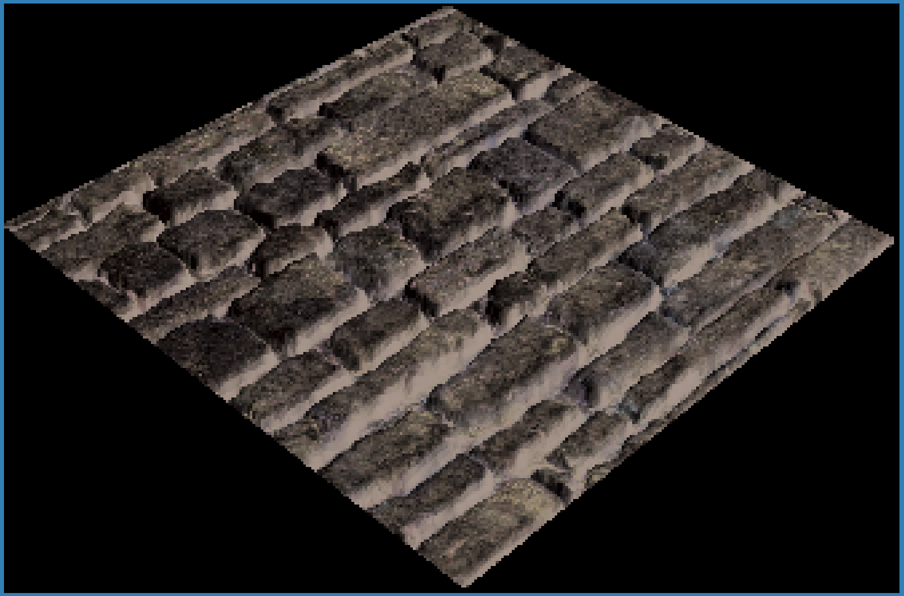


# Bump Mapping



Will Donnelly

# Displacement Mapping



Will Donnelly

# Data Structures Are Central To Interactive Rendering

The most important value of GPU programmability is not procedural texture generation, but the ability to use data structures in interactive rendering

neoptica

# Data Structures For Interactive Rendering

- Programmable graphics >> programmable shading
- Examples:
  - Distance map for displacement mapping
  - Quadtree for adaptive shadow map refinement
  - Hierarchical disk tree for dynamic ambient occlusion
- GPGPU mindset is needed to use the GPU this way
  - How do I make this data-parallel processor run data-parallel algorithms to achieve a desired result?
  - This expertise is not widely held…

# One Little Problem…

- What if the displacement texture is computed by the GPU?
  - e.g. for a deforming displaced surface
- Need to also compute a new data structure for efficient sphere tracing
- No problem to do that on the powerful GPU… right?

neoptica

# Dynamic Data Structures Are A Big Problem

- GPU is good at traversing data structures, very bad at building them
- Data structure construction generally has little available parallelism
  - The GPU requires a lot of parallelism for performance
- There isn't enough bandwidth for the CPU to build them dynamically

neoptica

# Dynamic Data Structures Are A Big Problem

- Sorting, reductions, etc., to build data structures on the GPU are possible
  - Getting good performance is very difficult
  - A lot of bandwidth is burned along the way
- Only experts have the necessary knowledge
  - Deep understanding of the hardware is needed
- Amdahl’s law: inefficient data structure construction will increasingly be the bottleneck

# What's New In Hardware Architectures?


The Getaway 3 (SCEE)

neoptica

# Next-Generation Heterogeneous Architectures

- We are again in a time of architectural change
  - CPUs are going parallel, starting to offer FLOPS
- High bandwidth interconnects let CPU and GPU work together
  - Heterogeneous compute resources are available
- New architectures address GPU weaknesses
  - Equally revolutionary implications for interactive graphics

neoptica

# The PC of 2006

- 2 core CPU
  - 30 GFLOPS
- GPU
  - 200 GFLOPS
- Interconnects
  - 1 GB/s CPU to GPU
  - 8 GB/s CPU to system memory
  - 30 GB/s GPU to graphics memory

# What's Wrong With Today's PC?

- CPU still doesn't have spare FLOPS for interactive graphics
- 1 GB/s on PCI-E prohibits CPU-GPU round trips
- The only processor with FLOPS, the GPU, requires much parallelism for performance
- GPU has limited memory writes
  – Improved somewhat by DX10

neoptica

# Game Console Architecture: XBox 360

- 3-core PPC CPU @ 3.2GHz
  - 115 GFLOPS
- Xenos GPU
  - 240 GFLOPS
  - EDRAM framebuffer
- Interconnects
  - 10GB/s CPU to shared memory
  - 20GB/s GPU to shared memory

neoptica

# Game Console Architecture: PS3

- STI Cell @ 3.2GHz (one PPU, seven SPUs)
  - ~200 GFLOPS
- RSX GPU
  - ~200 GFLOPS
- Interconnects
  - 25GB/s Cell to main memory
  - 20GB/s Cell to GPU, 15GB/s GPU to Cell
  - 22GB/s GPU to graphics memory

neoptica

# Heterogeneous Architecture Implications

- At 720p resolution, 60 frames per second…
  - 200 GFLOPS gives ~3000 FLOPS/pixel
  - 20GB/s allows 75 floats of communication/pixel
    - 150 halfs
  - (Peak performance)
- Developer can choose: provide little parallelism and manage memory latency, or prodive a lot and ignore it

neoptica

# Good News About The New World Order

- GFLOPS are available on both the CPU and the GPU
  - Can have performance even with much less parallelism
  - Can consider algorithms not suited to GPU alone
- Bandwidth enables algorithm decomposition between CPU and GPU
  - While still maintaining interactivity
  - Goodbye to the one-way graphics pipeline

# Good News About Dynamic Data Structures

- These architectures have the potential to build complex data structures at runtime:
  - GPU computes data
  - CPU builds data structure based on result
  - GPU uses data structure
- This can play to the strengths of both processors

neoptica

# Using The GPU More Efficiently With Help From the CPU

- The one-way PC graphics pipeline is a blunt hammer
  - CPU can use occlusion query, etc, to try to drive GPU more efficiently, but little information is available to it
  - And the GPU is unable to issue commands to itself
  - (DX10 geometry shaders do help here)
- Heterogeneous architectures can do much better
  - GPU does some work
  - CPU examines intermediate results
  - CPU gives GPU more work

neoptica

# Example: Efficient Data Structure Traversal

- The GPU can traverse tree data structures
  - E.g. ambient occlusion disk trees, kd-trees, lightcuts, shadow quad-trees, …
- If a large collection of nearby fragments all traverse the same top level nodes, computation is wasted
- CPU can start traversal until divergence, then let GPU continue from there
  - Analogies to Reshetov et al Multi-Level Ray Tracing

neoptica

# Many Other Opportunities

- More efficient deferred shading
- Skip rendering cube map faces and shadow maps that are not needed
- Adaptive refinement
- Can do a smaller superset of the necessary computation for rendering an image than if GPU alone was doing the rendering

# A Few Little Details…

- Parallel programming is a notorious quagmire
  – Heterogeneous processors don't make it easier
  – Data synchronization and movement are tricky
- GPUs are the only type of parallel processor that has ever seen widespread success
  – …because developers generally don't know they are parallel!
  – And if you want to do programmable graphics rather than programmable shading, cracks start to show

neoptica

# What Is The Right Programming Model?

- GPU data-parallel languages (Cg, HLSL) do not map well to CPU model
- C/C++ don't map well to GPU model
- Need new approaches and abstractions
  - Unified language that spans all processors?
  - Native code + glue?
  - Functional programming (this time at last)?

neoptica

# Future Graphics APIs

- Whither OpenGL 3.0 and DX11?
  - Are these APIs for controlling the GPU, or APIs for interactive graphics?
    - i.e. how do they handle heterogeneous architectures?
  - Developers and GPU vendors generally have opposite views on this question
- Currently closely tied to the one-way PC graphics pipeline

neoptica

# Future Graphics APIs

- What is the role of a graphics API if graphics is about computation and data structures?
  - If API does not embrace all processors and make it easier to use them for graphics, it will become irrelevant
- Has the time come to kill the graphics API and expose the hardware instead?

# Exposing A GPU Hardware Abstraction

- Graphics drivers often are an impediment to using the GPU well
  - Details they abstract are increasingly important for developers to understand
  - Hide actual perf. characteristics of the h/w
  - Programmable graphics needs a more direct understanding of memory for performance

# Exposing A GPU Hardware Abstraction

- Closer-to-the-metal APIs like ATI's CTM?
  - Focus on exposing the GPU's computational capabilities
  - Expose GPU memory model directly
- More burden on h/w vendors to have clean orthogonal designs, though
- Developers are unlikely to be happy with vendor-specific APIs

neoptica

# Future Hardware

- What is the future of GPUs?
  - Continually increasing parallelism requirements are a problem for programmable graphics
  - (Less so for programmable shading)
- What is the future workload?
  - Graphics continues to offer a lot of parallelism
  - But more and more irregular computation
  - If CPU offloads irregular parts of the computation, what is left for the GPU is more homogeneous

# Future Hardware

- More reasons to build a single chip CPU and GPU than cost savings
  - Off-chip bandwidth will become more and more limited w.r.t. available computation
- Will hardware designers have a broad perspective that allows all processors to work well together for graphics?
  - Presumably a certain two of them will at least!

neoptica

# What Is The Right Future Architecture?

- Homogeneous vs heterogeneous?
  - 64 P4s or 8 P4s and 128 fragment processors?
  - More than a few CPUs are overkill for graphics and other parallelizable compute-intensive workloads
  - But the four processors on PS3 (PPU, SPU, vertex, fragment) are probably too many
- Sweet spot is probably a handful of CPUs and a lot of fragment processors/SPUs
  - (With a rasterizer and texture units)

# SPUs vs. Fragment Processors

- Two very different models for FP performance
- SPU
  - Arbitrary writes (to local store and main memory)
  - User-managed latency hiding
  - Only need one thread per SPU
- Fragment Processor
  - Limited writes
  - Memory latency hidden through parallelism
  - Requires many threads

neoptica

# Memory Models I

- GPU: limited writes, efficient streaming reads, no user data synchronization
- Shared memory multi-core CPU: all up to the application or support library

# Memory Models II: SPU

- Explicit DMA to/from main memory to local memory
- This is good discipline
  - Encourages operating on large chunks of data
  - Encourages data reuse
- Explicit transfers make communication clear
  - Useful information for low-level support libraries
- This style is necessary for perf. on CPUs anyway

neoptica

# Challenges In Building Interactive Renderers

- All increasing with new architectures
- Choosing the right algorithms
- Implementation complexity
  - Math is hard
  - Architectures are complex
  - Need to develop algorithms that span CPU and GPU
- Software must solve these problems for new hardware to have value

neoptica

# Summary

- New heterogeneous architectures have great promise for interactive graphics
  - Dynamic data structures
  - Efficient GPU utilization
  - An enabler for programmable graphics
- Challenges are significant
  - Programming model
  - Algorithm implementation
  - Designing the right hardware architectures

neoptica

# Thanks

- Neoptica: Craig Kolb, Aaron Lefohn, Paul Lalonde, Tim Foley, Geoff Berry
- Stanford: Mike Houston, Jeremy Sugarman, Daniel Horn, Kayvon Fatahalian, Pat Hanrahan
- John Owens
- Bill Mark
- Kiril Vidimce
- Doug Epps
- Eric Leven

neoptica

# Questions?