A Trip Down The (2011) Rasterization Pipeline

Aaron Lefohn - Intel / University of Washington
Mike Houston – AMD / Stanford
This talk

• Overview of the real-time rendering pipeline available in ~2011 corresponding to graphics APIs:
  – DirectX 11
  – OpenGL 4.x

• Discuss
  – What changes from DX9 to DX11
  – Key uses of these new features
General Rasterization Pipeline

- Geometry processing:
  - Transforms geometry, generates more geometry, computes per-vertex attributes

- Rasterization:
  - Sets up a primitive (e.g., triangle), and finds all samples inside the primitive

- Pixel processing
  - Interpolates vertex attributes, and computes pixel color
DX10
Remember DX9?

Input Assembler

Vertex Shader

Rasterization

Pixel Shader

Output Merger

Memory

Index buffer

Vertex Buffer

Texture

Depth/Stencil

Render Target

Winter 2011 – Beyond Programmable Shading
DX10

Input Assembler

Vertex Shader

Geometry Shader

Rasterization

Pixel Shader

Output Merger

Memory

Index buffer

Vertex Buffer

Texture

Stream Output

Texture

Texture

Depth/Stencil

Render Target

Winter 2011 – Beyond Programmable Shading

Slide by Tomas Akenine-Möller
**DX10 Increased Shading Capability**

• In addition to adding a new pipeline stage, DX10 greatly increased programmability of vertex and fragment stages
  – All shader stages have same limitations (unified shading cores)
  – Pixel/fragment shaders “grow up”
    – Instruction limits, register limits, flow control, etc.
    – Well-specified floating point precision requirements
    – Write up to 8, fp32x4 outputs per fragment
Geometry Shader

• Input
  – Vertices of a full primitive (1 for point, 2 for line, 3 for triangle)
  – Vertices of edge-adjacent primitives
  – Primitive ID - allows to fetch or compute per-face data

• Output
  – Point-, line- or triangle strip
  – Sent to rasterizer or vertex buffer in memory
  – Variable output size
    – makes it hard to parallelize
Geometry Shader

- Usage examples
  - **Point Sprite Tessellation**: The shader takes in a single vertex and generates four vertexes (two output triangles) that represent the four corners of a quad.

  - **Wide Line Tessellation**: The shader receives two line vertexes and generates four vertexes for a quad that represents a widened line.

  - Other uses: generation of shadow volumes and cube maps.
Point Sprites and Wide Lines

• Smoke represented by point sprites
  – Points converted to quads in geometry shader

• Hair represented by “wide lines”
  – Lines converted to quads in geometry shader

Render-To-Volume

Geometry
Shader

Winter 2011 – Beyond Programmable Shading
Single Pass Render-To-Cubemap

Geometry Shader

Winter 2011 – Beyond Programmable Shading
Direct3D 10.1 Features

Full anti-aliasing control

- Application control over:
  - Multi-sample AA (smooth edges)
  - Super-sample AA (smooth edges and interior)
  - Selecting sample patterns
  - Pixel coverage mask
    - High-quality vegetation, motion blur, particles...

- Minimum of 4 samples/pixel required
DX11
Remember DX10?

Input Assembler → Vertex Shader → Geometry Shader → Rasterization → Pixel Shader → Output Merger

Memory:
- Index buffer
- Vertex Buffer
- Texture
- Stream Output
- Render Target
- Depth/Stencil
- Texture

Winter 2011 – Beyond Programmable Shading

Slide by Tomas Akenine-Möller
DX11 Tessellation example: Displaced subdivision surfaces

Winter 2011 – Beyond Programmable Shading
DX11 - new stages for tessellation

- New **Programmable** stages
  - Hull Shader
  - Domain Shader
- Fixed Function Stage
  - Tessellator
Tessellation - Input Assembler

- New Patch primitive type
- Outputs vertices to vertex shader and patch control points to hull shader
Tessellation - Vertex Shader

- One invocation per control point
- For example, skin/animate the control points

Slide by Tomas Akenine-Möller
Hull Shader

- HS works on an entire patch
- HS can access all the input and output control points
- Typical functions
  - Assigns edge LODs
  - Change the basis

Input Assembler
Vertex Shader
Hull Shader
Tessellator
Domain Shader
Geometry Shader
Rasterization
Pixel Shader
Output Merger

Winter 2011 – Beyond Programmable Shading

Slide by Tomas Akenine-Möller
Tessellator

• TS inputs are edge LODs and additional knob values
  – Inner tessellation + tess mode

• TS generates \((u,v)\) coordinates and connectivity information

• The \((u,v)\) coordinates are in the domain \([0,1]\)
  – Calculated using fixed point math to ensure water tight edges
Domain Shader

- One domain shader invocation per (u,v) pair
- DS gets (u,v) from tessellator and control points from HS
- Computes a real 3D point from a domain location (u,v)
  - For example, displace the point using displacement map
  - Project the point
- Calculate auxiliary per vertex data
  - Texture coordinates
  - Tangent space vectors
An example through the tessellation pipeline

- Input
- Vertex shader
- Tessellator
- Domain shader
- Rasterization
- Pixel shader
- Output

Slide by Tomas Akenine-Möller
DX11 Tessellation Examples: Codemasters DiRT2

Slides from “DiRT2 DirectX 11 Technology“, Thomas and Story, GDC 2010
Original Mesh

Slide from GDC 2010 Presentation,
"DiRT2 DirectX11 Technology,
Tomas Thomas, Codemasters
Jon Story, AMD
Original Mesh

Slide from GDC 2010 Presentation

“DIRT2 DirectX11 Technology,
Tomas Thomas, Codemasters
Jon Story, AMD
PN-Triangles + Displacements
PN-Triangles + Displacements

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters, Jon Story, AMD
Original Mesh

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters, Jon Story, AMD
Original Mesh

Slide from GDC 2010 Presentation,
"DiRT2 DirectX11 Technology,
Tomas Thomas, Codemasters
Jon Story, AMD
Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters
Jon Story, AMD
Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters Jon Story, AMD
Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters Jon Story, AMD
PN-Triangles + Displacements

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters
Jon Story, AMD
PN-Triangles + Displacements

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters Jon Story, AMD
Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters Jon Story, AMD
PN-Triangles

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters
Jon Story, AMD
PN-Triangles + Displacements

Slide from GDC 2010 Presentation,
"DiRT2 DirectX11 Technology,
Tomas Thomas, Codemasters
Jon Story, AMD
Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters
Jon Story, AMD
PN-Triangles

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters Jon Story, AMD
PN-Triangles + Displacements

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters
Jon Story, AMD
Displacement Mapped Surface

Slide from GDC 2010 Presentation, "DiRT2 DirectX11 Technology, Tomas Thomas, Codemasters, Jon Story, AMD
Displacement Mapping: OFF
Displacement Mapping: ON
DX11 Pixel Shader
DirectX11 Pixel Shader Changes

• Read and write anywhere in memory
  – “Unordered access views” (UAVs)
  – Pixel shaders can now write somewhere other than pixel position (!)

• Atomic read-modify-write operations
  – add, subtract, min, max, compare-exchange, ..., or, xor
DX11 Pixel Shader Implications

• **Pixel shaders can build data structures other than images**
  – Scatter/gather and atomic operations
  – “Render to user-defined data structure”

• Limitations
  – Atomic RMW operations only on 32-bit integers (no atomic struct RMW)
  – No critical sections / mutexes
Real-time A-Buffer Generation

Pixel Shader 5 Example
Order Independent Transparency I

“Real-Time Concurrent Linked List Construction on the GPU,”
Yang et al., EGSR 2010
The Problem with Transparency

“Real-Time Concurrent Linked List Construction on the GPU,” Yang et al., EGSR 2010

Sorting is hard!

With Sorting

No Sorting

Skeleton hidden

Arm appears in front of body

Sorting is hard!

Winter 2011 – Beyond Programmable Shading
Solution: Sort Fragments Per Pixel

• Create A-Buffer using DX11 rendering pipeline

• Render pass 1
  – Store linked list of fragments per-pixel in 2 separate buffers
    – UAV 1: Storage for all [RGBA,Z,next] values from all fragments
    – UAV 2: “Image-sized” storage for a head pointer per pixel position

• Render pass 2
  – Full-screen pass that sorts and blends fragments to create pixel color
DX11 A-Buffer

• Pros
  – Correct solution to order-independent transparency
  – Runs at interactive rates on current hardware

• Cons
  – A-buffers use unbounded amount of memory
  – Performance variable depending on order fragments stored in memory
DX11 ComputeShader / DirectCompute

• “Out-of-pipeline” new programming model for “general” computation, designed to interact tightly with the graphics API (language is HLSL)

• Similar in semantics and capability to OpenCL and CUDA

• We will discuss DirectCompute later in the course
Summary

• Jump from DX9 to DX11 (OGL2 to OGL4)
  – Adds 4 new pipeline stages (hull, tessellator, domain, geometry)
  – Makes shader stages far more general compute engines
  – Enables users to render to user-defined data structures (and defer visibility determination)
  – Greatly relaxes memory model of shaders (especially scatter/atomics)
  – Adds DirectCompute, which begins to blur lines between pipeline and user-defined parallel programs
  – Is still new wrt adoption in the game world (but a number of DX11 titles shipping)

• Get to know DX11/GL4 well---you can do *a lot* within the confines of the rendering pipeline
Backup
Geometry Shader Example
Shadow volume generation
Geometry Shader Example

Generalized displacement maps

- Displacement Mapping (Direct3D 10)
New DX10 and DX10.1 features heavily used for shadow techniques in production games

Examples of some from “High Quality Direct3D 10.0 & 10.1 Accelerated Techniques”, Story and Gruen, GDC 2009
HDAO Off (depth only)
- 40 Gathers
- No filtering needed
HDAO Buff (depth & materials)
- 80 Gathers (could use alot less)
- No filtering needed
Tom Clancy’s HAWX
Publisher: Ubisoft
Developer: Ubisoft Romania
Stormrise
Publisher: SEGA
Developer: The Creative Assembly Australia
BattleForge
Publisher: EA
Developer: EA Phenomic
From DICE’s Frostbite Engine: Uniform Shadow Filtering
From DICE’s Frostbite Engine: Unique Weight Shadow Filtering
From DICE’s Frostbite Engine: Standard 2x2 Shadow Filtering
From DICE’s Frostbite Engine: 5x5 Unique Weight Filtering
Tom Clancy’s HAWX
Publisher: Ubisoft
Developer: Ubisoft Romania
Blurred VSM
Tom Clancy's HAWX
Publisher: Ubisoft
Developer: Ubisoft Romania
Unique Weight Shadows