Practical DirectX 12
- Programming Model and Hardware Capabilities

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AMD & NVIDIA
Agenda

- DX12 Best Practices
- DX12 Hardware Capabilities
- Questions
Expectations

Who is DX12 for?

- Aiming to achieve maximum GPU & CPU performance
- Capable of investing engineering time
- Not for everyone!
Engine Considerations

Need IHV specific paths

- Use DX11 if you can’t do this

Application replaces portion of driver and runtime

- Can’t expect the same code to run well on all consoles, PC is no different
- Consider architecture specific paths

Look out for NVIDIA and AMD specifics
Work Submission

- Multi Threading
- Command Lists
- Bundles
- Command Queues
Multi-Threading

DX11 Driver:
- Render thread (producer)
- Driver thread (consumer)

DX12 Driver:
- Doesn't spin up worker threads.
- Build command buffers directly via the CommandList interface

Make sure your engine scales across all the cores
- Task graph architecture works best
- One render thread which submits the command lists
- Multiple worker threads that build the command lists in parallel
Command Lists

Command Lists can be built while others are being submitted

- Don’t idle during submission or Present
- Command list reuse is allowed, but the app is responsible for stopping concurrent-use

Don’t split your work into too many Command Lists

Aim for (per-frame):

- 15-30 Command Lists
- 5-10 ‘ExecuteCommandLists’ calls
Command Lists #2

Each `ExecuteCommandLists` has a fixed CPU overhead
- Underneath this call triggers a flush
- So batch up command lists

Try to put at least 200μs of GPU work in each
`ExecuteCommandLists`, preferably 500μs

Submit enough work to hide OS scheduling latency
- Small calls to `ExecuteCommandLists` complete faster than the OS scheduler can submit new ones
Command Lists #3

Example:
What happens if not enough work is submitted?

- Highlighted ECL takes \( \sim 20 \mu s \) to execute
- OS takes \( \sim 60 \mu s \) to schedule upcoming work
- \( \implies 40 \mu s \) of idle time
Bundles

Nice way to submit work early in the frame
Nothing inherently faster about bundles on the GPU
  • Use them wisely!
Inherits state from calling Command List – use to your advantage
  • But reconciling inherited state may have CPU or GPU cost
Can give you a nice CPU boost
  • NVIDIA: repeat the same 5+ draw/dispatches? Use a bundle
  • AMD: only use bundles if you are struggling CPU-side.
Multi-Engine

- 3D Queue
- Compute Queue
- Copy Queue
Compute Queue #1

Use with great care!

- Seeing up to a 10% win currently, if done correctly

Always check this is a performance win

- Maintain a non-async compute path
- Poorly scheduled compute tasks can be a net loss

Remember hyperthreading? Similar rules apply

- Two data heavy techniques can throttle resources, e.g. caches

If a technique suitable for pairing is due to poor utilization of the GPU, first ask “why does utilization suck?”

- Optimize the compute job first before moving it to async compute
Compute Queue #2

<table>
<thead>
<tr>
<th>Good Pairing</th>
<th>Poor Pairing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Compute</td>
<td>Compute</td>
</tr>
<tr>
<td>Shadow Render (I/O limited)</td>
<td>Light culling (ALU heavy)</td>
</tr>
<tr>
<td></td>
<td>G-Buffer (Bandwidth limited)</td>
</tr>
<tr>
<td></td>
<td>SSAO (Bandwidth limited)</td>
</tr>
</tbody>
</table>

(Technique pairing doesn’t have to be 1-to-1)
Compute Queue #3

Unrestricted scheduling creates opportunities for poor technique pairing

- **Benefits are;**
  - Simple to implement

- **Downsides are;**
  - Non-determinism frame-to-frame
  - Lack of pairing control
Compute Queue #4

Prefer explicit scheduling of async compute tasks through smart use of fences

- Benefits are;
  - Frame-to-frame determinism
  - App control over technique pairing!

- Downsides are;
  - It takes a little longer to implement

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3D

- Command List
  - Fence
  - Command List
  - Fence
  - Command List
  - Fence

- Z-Prepass
  - Fill G-Buffer

- Signal GPU: 1

- Shadow Maps (Depth Only)

- Wait GPU: 2

- Light Culling

- Signal GPU: 2

COMPUTE

- Command List
  - Fence
  - Command List
  - Fence
  - Command List
  - Fence

- Wait GPU: 1
Copy Queue

Use the copy queue for background tasks
- Leaves the Graphics queue free to do graphics

Use copy queue for transferring resources over PCIE
- Essential for asynchronous transfers with multi-GPU

Avoid spinning on copy queue completion
- Plan your transfers in advance

NVIDIA: Take care when copying depth+stencil resources – copying only depth may hit slow path
Hardware State

- Pipeline State Objects (PSOs)
- Root Signature Tables (RSTs)
Pipeline State Objects #1

Use sensible and consistent defaults for the unused fields

The driver is not allowed to thread PSO compilation
- Use your worker threads to generate the PSOs
- Compilation may take a few hundred milliseconds
Pipeline State Objects #2

Compile similar PSOs on the same thread
- e.g. same VS/PS with different blend states
- Will reuse shader compilation if state doesn’t affect shader
- Simultaneous worker threads compiling the same shaders will wait on the results of the first compile.
Root Signature Tables #1

Keep the RST small
- Use multiple RSTs
- There isn’t one RST to rule them all...

Put frequently changed slots first

Aim to change one slot per draw call

Limit resource visibility to the minimum set of stages
- Don’t use D3D12_SHADER_VISIBILITY_ALL if not required.
- Use the DENY_*_SHADER_ROOT_ACCESS flags

Beware, no bounds checking is done on the RST!

Don’t leave resource bindings undefined after a change of Root Signature
Root Signature Tables #2

**AMD:** Only constants and CBVs changing per draw should be in the RST

**AMD:** If changing more than one CBVs per draw, then it is probably better putting the CBVs in a table

**NVIDIA:** Place all constants and CBVs in RST
- Constants and CBVs in the RST do speed up shaders
- Root constants don’t require creating a CBV == less CPU work
Memory Management

- Command Allocators
- Resources
- Residency
Command Allocators

Aim for number of recording threads * number of buffered frames + extra pool for bundles
  • If you have hundreds of allocators, you are doing it wrong

Allocators only grow
  • Can never reclaim memory from an allocator
  • Prefer to keep them assigned to the command lists

Pool allocators by size where possible
## Resources – Options?

<table>
<thead>
<tr>
<th>Type</th>
<th>Physical Page</th>
<th>Virtual Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Committed</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Heap</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>Placed</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>Reserved</td>
<td>✗</td>
<td>✔️</td>
</tr>
</tbody>
</table>
Committed Resources

Allocates the minimum size heap required to fit the resource

App has to call MakeResident/Evict on each resource

App is at the mercy of OS paging logic
  • On ‘MakeResident’, the OS decides where to place resource
  • You're stuck until it returns
Heaps & Placed Resources

Creating larger heaps

- In the order of 10-100 MB
- Sub-allocate using placed resources

Call MakeResident/Evict per heap

- Not per resource 😊

This requires the app to keep track of allocations

- Likewise, the app needs to keep track of free/used ranges of memory in each heap
Residency

MakeResident/Evict memory to/from GPU

- CPU + GPU cost is significant so batch MakeResident and UpdateTileMappings
- Amortize large work loads over multiple frames if necessary
- Be aware that Evict might not do anything immediately

MakeResident is **synchronous**

- MakeResident will not return until the resource is resident
- The OS can go off and spend a LOT of time figuring out where to place resources. You're stuck until it returns
- Be sure to call on a worker thread
Residency #2

How much vidmem do I have?

- IDXGIAdapter3::QueryVideoMemoryInfo(...)
- Foreground app is guaranteed a subset of total vidmem
  - The rest is variable, app should respond to budget changes from OS

App must handle MakeResident fail.

- Usually means there’s not enough memory available
- But can happen even if there is enough memory (fragmentation)

Non-resident read is a page fault! Likely resulting in a fatal crash

What to do when there isn’t enough memory?
Vidmem Over-commitment

Create overflow heaps in sysmem, and move some resources over from vidmem heaps.

- The app has an advantage over any driver/OS here, arguably it knows what’s most important to keep in vidmem

**Idea:** Test your application with 2 instances running
Resources: Practical Tips

Aliasing targets can be a significant memory saving
  - Remember to use aliasing barriers!
Committed RTV/DSV resources are preferred by the driver

**NVIDIA:** Use a constant buffer instead of a structured buffer when reads are coherent. e.g. tiled lighting
Synchronization

- Barriers
- Fences
Barriers #1

Don’t let resource barriers become a performance barrier!

**Batch barriers together**

Use the minimum set of usage flags
  - Avoiding redundant flushing

Avoid read-to-read barriers
  - Get the resource in the right state for all subsequent reads

Use “split-barriers” when possible
Barriers #2

COPY_SOURCE will probably be significantly more expensive than SHADERRESOURCE

- Enables access on the copy queue

Barrier count should be roughly double the number of surfaces written to
Fences

GPU Semaphore
  - e.g. Make sure GPU is done with resource before evict

Each fence is about the same CPU and GPU cost as ExecuteCommandLists

Don’t expect fences to trigger signals/advance at a finer granularity than once per ExecuteCommandLists call
Miscellaneous

- Multi-GPU
- Swap Chains
- Set Stable Power State
- Pixel vs Compute
Multi GPU

Functionality now embedded in DirectX 12 API
Trade-offs for cross-adapter vs. linked-node
  - See Juha Sjöholm’s talk later today for more on this
Explicitly sync resources across devices
  - Use proper CreationNodeMask
Be mindful of PCIe bandwidth
  - PCI 3.0 (8x) – 8GB/s (expect ~6GB/s)
  - PCI 2.0 (8x) – 4GB/s (expect ~3GB/s) ← Still common...
    - e.g. transferring a 4k HDR buffer will limit you to ~50/100 FPS right away
Swap Chains

App must do explicit buffer rotation!
- IDXGISwapChain3::GetCurrentBackBufferIndex()

To replicate VSYNC-OFF
- SetFullScreenState(TRUE)
- Use a borderless fullscreen window
- Flip model swap-chain mode

Very rich, new API!
Set Stable Power State

HRESULT ID3D12Device::SetStablePowerState( BOOL Enable );

- This reduces performance
- Alters performance ratio of GPU components within chip

Don’t do it! (Please)
Pixel vs Compute - Performance

<table>
<thead>
<tr>
<th>NVIDIA</th>
<th>AMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>❑ No shared memory?</td>
<td>❑ Benefit from depth/stencil rejection?</td>
</tr>
<tr>
<td>❑ Threads complete at same time?</td>
<td>❑ Requires graphics pipeline?</td>
</tr>
<tr>
<td>❑ High frequency cbuffer accesses?</td>
<td>❑ Want to leverage color compression?</td>
</tr>
<tr>
<td>❑ 2D buffer stores?</td>
<td>❑ Everything else 😊</td>
</tr>
<tr>
<td>❑ Using group shared memory?</td>
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<tr>
<td>❑ Expect out-of-order thread completion?</td>
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</tr>
<tr>
<td>❑ Using high # regs?</td>
<td></td>
</tr>
<tr>
<td>❑ 1D/3D buffer stores</td>
<td></td>
</tr>
</tbody>
</table>

Pixel Shader | Compute Shader | Pixel Shader | Compute Shader

Best performance gained from following these guidelines

(Consider the perf benefit of using async compute)
Hardware Features

- Conservative Rasterization
- Volume Tiled Resources
- Raster Ordered Views
- Typed UAV Loads
- Stencil Output
# Hardware Features Stats

<table>
<thead>
<tr>
<th></th>
<th><strong>AMD Radeon</strong></th>
<th></th>
<th><strong>NVIDIA GeForce</strong></th>
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<th><strong>Intel HD Graphics</strong></th>
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<tr>
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<td>Tier 2</td>
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<td>Tiled Resources</td>
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<td>Tier 3</td>
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<td>64</td>
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<td>full heap</td>
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<td>Resource Heap</td>
<td>Tier 2</td>
<td>Tier 1</td>
<td>Tier 2</td>
<td></td>
<td>Tier 2</td>
</tr>
</tbody>
</table>
Conservative Rasterization

Draws all pixels a primitive touches
- Different Tiers – See spec

Possible before through GS trick but relatively slow
- See; J. Hasselgren et. Al, “Conservative Rasterization“, GPU Gems 2

Now we can use rasterization do implement some nice techniques!
- See; Jon Story, “Hybrid Raytraced Shadows“, D3D day - GDC 2015
Ray traced shadows in, ‘Tom Clancy’s The Division’, using conservative rasterization
Volume Tiled Resources

Tiled resources from DX11.2, now available for volume/3D resources

- Tier 3 tiled resources

Tiles are still 64kb

- And tile mapping still needs to be updated from the CPU

Extreme memory/performance benefits

- Latency Resistant Sparse Fluid Simulation [Alex Dunn, D3D Day – GDC 2015]
Raster Ordered Views

Ordered writes

- Classic use case is OIT
  - See K+ Buffer OIT [Andreas A. Vasilakis, SIGGRAPH, 2014]
- Programmable blending
  - Completely custom blending, not bound by fixed HW

Use with care! Not free

- Watch the # conflicts
Typed UAV Loads

Finally, no more 32-bit restriction from the API

May allow you to remove console specific paths in engine

Loading from UAV slower than loading from SRV
  - So still use SRV for read-only access

// Can do this e.g.
RWTexture2D<float4>

// and in conjunction with ROV :)
RasterizerOrderedTexture2D<float4>
Stencil Output

Implementations?
- N-ary algorithm using stencil?
  - Previous; clear + N passes
  - Now; Single pass

Performance considerations
- Comparable to using depth out
Questions?

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# DX12PerfTweet