THE DEVIL IS IN THE DETAILS
IDTECH 666

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Initial Requirements

- Performance: 60hz @ 1080p
- Speed up art workflow
- Multi-platform scalability
- KISS
  - Minimalistic code
  - No shader permutations insanity: ~100 shaders, ~350 pipe states
- Next Gen Visuals
  - HDR, PBR
  - Dynamic and unified lighting, shadows and reflections
  - Good anti-aliasing and VFX
## Anatomy of a Frame

<table>
<thead>
<tr>
<th>Frame</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadow Caching</td>
<td>~3.0 ms</td>
</tr>
<tr>
<td>Pre-Z</td>
<td>~0.5 ms</td>
</tr>
<tr>
<td>Opaque Forward Passes</td>
<td>~6.5 ms</td>
</tr>
<tr>
<td>• Prepare cluster data</td>
<td></td>
</tr>
<tr>
<td>• Textures composite, compute lighting</td>
<td></td>
</tr>
<tr>
<td>• Output: L-Buffer, thin G-Buffer, feedback UAV</td>
<td></td>
</tr>
<tr>
<td>Deferred Passes</td>
<td>~2.0 ms</td>
</tr>
<tr>
<td>• Reflections, AO, fog, final composite</td>
<td></td>
</tr>
<tr>
<td>Transparency</td>
<td>~1.5 ms</td>
</tr>
<tr>
<td>• Particles light caching, particles / VFX, glass</td>
<td></td>
</tr>
<tr>
<td>Post-Process (Async)</td>
<td>~2.5 ms</td>
</tr>
</tbody>
</table>
Data Structure for Lighting & Shading

- A derivation from
  - “Clustered Deferred and Forward Shading” [Olson12]
  - “Practical Clustered Shading” [Person13]

- Just works™
  - Transparent surfaces
    - No need for extra passes or work
  - Independent from depth buffer
  - No false positives across depth discontinuities
  - More Just Works™ in next slides
Preparing Clustered Structure

- Frustum shaped voxelization / rasterization process
  - Done on CPU, 1 job per depth slice
- Logarithmical depth distribution
  - Extended near plane and far plane
  - \[ Z\text{Slice} = \text{Near}_z \times \left( \frac{\text{Far}_z}{\text{Near}_z} \right)^{\frac{\text{slice}}{\text{num slices}}} \]
- Voxelize each item
  - An item can be: light, environment probe or a decal
  - Item shape is: OBB or a frustum (projector)
  - Rasterization bounded by screen space \( \min_{xy} \max_{xy} \) and depth bounds
Preparing Clustered Structure

- Refinement done in clip space
  - A cell in clip space is an AABB
  - N Planes vs cell AABB
  - OBB is 6 planes, frustum is 5 planes
  - Same code for all volumes
  - SIMD

```c
//Pseudo-code - 1 job per depth slice (if any item)
for (y = MinY; y < MaxY; ++y) {
    for (x = MinX; x < MaxX; ++x) {
        intersects = N planes vs cell AABB
        if (intersects) {
            Register item
        }
    }
}
```
Preparing Clustered Structure

- **Structures**
  - **Offset list:**
    - 64 bits x Grid Dim X x Grid Dim Y x Grid Dim Z
  - **Item list:**
    - 32 bits x 256 x Worst case ( Grid Dim X x Avg Grid Dim Y x Grid Dim Z )

- **Offset List, per element**
  - Offset into item list, and light / decal / probe count

- **Item List, per element**
  - 12 bits: Index into light list
  - 12 bits: Index into decal list
  - 8 bits: Index into probe list

- **Grid resolution is fairly low res: 16 x 8 x 24**
  - False positives: Early out mitigates + item list reads are uniform ( GCN )
Preparing Clustered Structure

Hotspot:
~300 light sources
~1.2k decals
Preparing Clustered Structure

Hotspot:

~300 light sources
~1.2k decals
Detailing the World

- Virtual-Texturing\textsuperscript{[10]} updates
- Albedo, Specular, Smoothness, Normals, HDR Lightmap
  - HW sRGB support
  - Baked Toksvig\textsuperscript{[11,12,13,14]} into smoothness for specular anti-aliasing
- Feedback buffer UAV output directly to final resolution
- Async compute transcoding
  - Cost mostly irrelevant
- Design flaws still present
  - E.g. Reactive texture streaming = texture popping
Detailing the World

- Decals embedded with geometry rasterization
- Realtime replacement to Mega-Texture “Stamping”
  - Faster workflow / Less disk storage
- Just Works ™
  - Normal map blending
  - Linear correct blending for all channels
  - Mipmapping / Anisotropy *
  - Transparency
  - Sorting
  - 0 drawcalls
- 8k x 8k decal atlas
  - BC7
Detailing the World

- **Box Projected**
  - $e_0$, $e_1$, $e_2$ is OBB normalized extents, $p$ is position

$$M_{\text{decalProj}} = M_{\text{scale}} \cdot M_{\text{decal}}^{-1}$$

$$M_{\text{scale}} = \begin{bmatrix} \frac{0.5}{\text{sizeX}} & 0 & 0 & 0.5 \\ 0 & \frac{0.5}{\text{sizeY}} & 0 & 0.5 \\ 0 & 0 & \frac{0.5}{\text{sizeZ}} & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$M_{\text{decal}} = \begin{bmatrix} e_{0x} & e_{1x} & e_{2x} & p_x \\ e_{0y} & e_{1y} & e_{2y} & p_y \\ e_{0z} & e_{1z} & e_{2z} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- **Indexing into decal atlas**
  - Per decal: Scale & bias parameter. E.g.

```cpp
const float4 albedo = tex2Dgrad( decalsAtlas, uv.xy * scaleBias.xy + scaleBias.zw, uvDDX, uvDDY );
```
Detailing the World

- Manually placed by artists
  - Including blending setup
  - A generalization for “Blend Layers”
- Limited to 4k per view frustum
  - Generally 1k or less visible
- Lodding
  - Art setups max view distance
  - Player quality settings affect view distance as well
- Works on dynamic non-deformable geometry
  - Apply object transformation to decal
Detailing the World
Detailing the World
Detailing the World
Detailing the World
Detailing the World
Lighting

- Single / unified lighting code path
  - For opaque passes, deferred, transparencies and decoupled particle lighting (slides 23-27)
- No shader permutations insanity
  - Static / coherent branching is pretty good these days – use it!
  - Same shader for all static geometry
  - Less context switches
- Components
  - Diffuse indirect lighting: Lightmap for static geometry, irradiance volumes for dynamics
  - Specular indirect lighting: Reflections (environment probes, SSR, specular occlusion)
  - Dynamic: Lights & shadows
//Pseudocode

ComputeLighting( inputs, outputs ) {
    Read & Pack base textures

    for each decal in cell {
        early out fragment check
        Read textures
        Blend results
    }

    for each light in cell {
        early out fragment check
        Compute BRDF / Apply Shadows
        Accumulate lighting
    }

}
Lighting

- Shadows are cached / packed into an Atlas
  - PC: 8k x 8k atlas (high spec), 32 bit
  - Consoles: 8k x 4k, 16 bit
- Variable resolution based on distance
- Time slicing also based on distance
- Optimized mesh for static geometry
- Light doesn’t move?
  - Cache static geometry shadow map
  - No updates inside frustum? Ship it
  - Update? Composite dynamic geometry with cached result
  - Can still animate (e.g., flicker)
- Art setup / Quality settings affect all above
Lighting

- Index into shadow frustum projection matrix
- Same PCF lookup code for all light types
  - Less VGPR pressure
- This includes directional lights cascades
  - Dither used between cascades
  - Single cascade lookup
- Attempted VSM and derivatives
  - All with several artefacts
  - Conceptually has good potential for Forward
    - Eg. decouple filtering frequency from rasterization
Lighting

- First person arms self-shadows
  - Dedicated atlas portion. Disabled on consoles to save atlas space

First Person Self-Shadows: On

First Person Self-Shadows: Off
(Notice light leaking)
Lighting

- Keep an eye on VGPR pressure
  - Pack data that has long lifetime. e.g: float4 for an HDR color ↔ uint, RGBE encoded
  - Minimize register lifetime
  - Minimize nested loops / worst case path
  - Minimize branches
  - 56 VGPRS on consoles (PS4)
    - Higher on PC due to compiler inefficiency 😞 ( @ AMD compiler team, pretty plz fix - throwing perf out )
- For future: half precision support will help
  - Nvidia: use UBOs / Constant Buffer (required partitioning buffers = more / ugly code)
  - AMD: Prefer SSBOs / UAVs
Transparencies

- Rough glass approximation
  - Top mip is half res, 4 mips total
  - Gaussian kernel ( approximate GGX lobe )
  - Blend mips based on surface smoothness
  - Refraction transfers limited to 2 per frame for performance

- Surface parameterization / variation via decals

Glass Roughness Variation
Particle Lighting

- **Per-vertex?**
  - No higher frequency details (e.g. shadows)

- **Per-vertex + tessellation**  
  - Requires large subdivision level
  - Not good for GCN / Consoles

- **Per-pixel?**
  - That’s a lot of pixels / costly

- **Mixed resolution rendering?**
  - Nguyen04? Problematic with sorting
  - Aliasing MSAA target? Platform specific
Decoupled Particle Lighting

- Observation
  - Particles are generally low frequency / low res
  - Maybe render a quad per particle and cache lighting result?
- Decouples lighting frequency from screen resolution = Profit
  - Lighting performance independent from screen resolution
  - Adaptive resolution heuristic depending on screen size / distance
    - E.g. 32x32, 16x16, 8x8
- Exact same lighting code path
- Final particle is still full res
  - Loads lighting result with a Bicubic kernel.

Adaptive resolution
//Pseudocode - Particle shading becomes something like this

Particles( inputs, outputs ) {
    
    const float3 lighting = tex2D( particleAtlas, inputs.texcoord );
    result = lighting * inputs.albedo;

    ...

}
Decoupled Particle Lighting

- 4k x 4k particle light atlas
  - Size varies per-platform / quality settings
  - R11G11B10_FLOAT
- Dedicated atlas regions per-particle resolution
  - Some waste, but worked fine – ship it
- Fairly performant: ~0.1 ms
  - Worst cases up to ~1 ms
  - Still couple orders magnitude faster
  - Good candidate for Async Compute
Decoupled Particle Lighting

- Results
Post-Process
Optimizing Data Fetching (GCN)

- GCN scalar unit for non-divergent operations
- Great for speeding up data fetching
  - Save some VGPRs
  - Coherent branching
  - Fewer instructions (SMEM: 64 Bytes, VMEM: 16 Bytes)
- Clustered shading use case
  - Each pixel fetches lights/decals from its belonging cell
  - Divergent by nature, but worth analyzing
Clustered Lighting Access Patterns
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Analyzing the Data

- Most wavefronts only access one cell
- Nearby cells share most of their content
- Threads mostly fetch the same data
- Per-thread cell data fetching not optimal
  - Not leveraging this data convergence
- Possible scalar iteration over merged cell content
  - Don’t have all threads independently fetch the exact same data
Leveraging Access Patterns

- Data: Sorted array of item (light/decal) IDs per cell
  - Same structure for lights and decals processing
  - Each thread potentially accessing a different node
  - Each thread independently iterating on those arrays

- Scalar loads: Serialize iteration
  - Compute smallest item ID value across all threads
    - `ds_swizzle_b32 / minInvocationsNonUniformAMD`
  - Process item for threads matching selected index
    - Uniform index -> scalar instructions
    - Matching threads move to next index
Special Paths

- Fast path if touching only one cell [Fuller15]
  - Avoid computing smallest item ID, not cheap on GCN 1 & 2
  - Some additional (minor) scalar fetches and operations
- Serialization assumes locality between threads
  - Can be significantly slower if touching too many cells
  - Disabled for particle lighting atlas generation
- Opaque render pass, PS4 @ 1080p
  - Default: 8.9ms
  - Serialized iteration only: 6.7ms
  - Single cell fast path only: 7.2ms
  - Serialized iteration + fast path: 6.2ms
Dynamic Resolution Scaling

- Adapt resolution based on GPU load
  - Mostly 100% on PS4, more aggressive scaling on Xbox
- Render in same target, adjust viewport size
  - Intrusive: requires extra shader code
  - Only option on OpenGL
- Future: alias multiple render targets
  - Possible on consoles and Vulkan
- TAA can accumulate samples from different resolutions
- Upsample in async compute
Async Post Processing

- Shadow & depth passes barely use compute units
  - Fixed graphics pipeline heavy
- Opaque pass not 100% busy either
- Overlap them with post processing
  - Render GUI in premultiplied alpha buffer on GFX queue
  - Post process / AA / upsample / compose UI on compute queue
  - Overlap with shadows / depth / opaque of frame N+1
  - Present from compute queue if available
    - Potentially lower latency
GCN Wave Limits Tuning

- Setup different limits for each pass
  - Disable late alloc for high pixel/triangle ratio
- Restrict allocation for async compute
  - Avoid stealing all compute units
  - Mitigate cache thrashing
- Worth fine tweaking before shipping
  - Saved up to 1.5ms in some scenes in DOOM!
GCN Register Usage

- Think globally about register and LDS allocation
  - Do not always aim for divisors of 256
  - Bear in mind concurrent vertex / async compute shaders
- Fine tweaking to find sweet spot
- Example: DOOM opaque pass
  - GFX queue: 56 VGPRs for PS, 24 for VS
  - Compute queue: 32 VGPRs for upsample CS
  - 4PS + 1CS/VS or 3PS + 2CS + 1VS
  - Saves 0.7ms compared to a 64 VGPRs version
What's next?

- Decoupling frequency of costs = Profit
- Improve
  - Texture quality
  - Global illumination
  - Overall detail
  - Workflows
  - etc
Special Thanks

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- Entire id Software team

- Natalya Tatarchuk
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Thank you

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- Jean Geoffroy
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References

[1] “Clustered Deferred and Forward Shading”, Ola Olson et al., HPG 2012
Lighting

- Light types
  - Point, projector, directional (no explicit sun), area (quad, disk, sphere)
  - IBL (environment probe)

- Light shape
  - Most lights are OBBs: Acts as implicit "clip volume" to help art preventing light leaking
  - Projector is a pyramid

- Attenuation / Projectors
  - Uses art driven texture at this point
  - Stored in an atlas, similar indexing as decals
  - Art sometimes uses for faking shadows
  - BC4

- Environment Probes
  - Cube map array, index via probe ID
  - Fixed resolution, 128 x 128
  - BC6H
Deferred Passes

- Wanted dynamic and performant AO & reflections
  - Decoupling passes helps mitigate VGPR pressure
- 2 extra targets during forward opaque passes
  - Specular & smoothness: RGBA8
  - Normals: R16G16F
- Allows compositing probes with realtime reflections
- Final Composite
  - SSR, environment probes, AO / specular occlusion, fog