SIGGRAPH2015
Xroads of Discovery

SIGGRAPH 2015: Advances in Real-Time Rendering in Games

GPU-Driven Rendering Pipelines

Ulrich Haar, Lead Programmer 3D, Ubisoft Montreal

Sebastian Aaltonen, Senior Lead Programmer, RedLynx a Ubisoft Studio

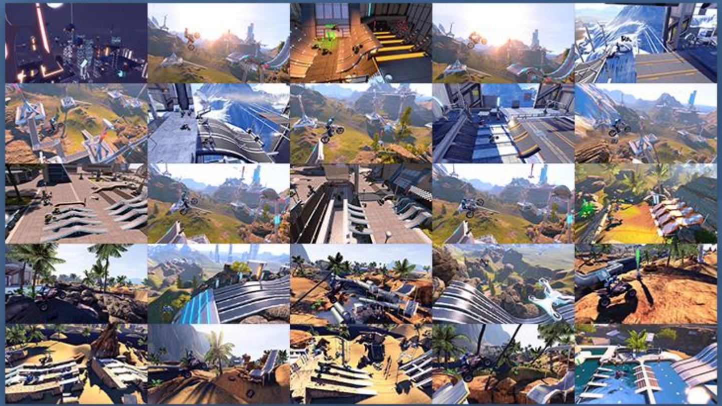
Topics

- Motivation
- Mesh Cluster Rendering
- Rendering Pipeline Overview
- Occlusion Depth Generation
- Results and future work

GPU-Driven Rendering?

- GPU controls what objects are actually rendered
- “draw scene” GPU-command
  - n viewports/frustums
  - GPU determines (sub-)object visibility
  - No CPU/GPU roundtrip
- Prior work [SBOT08]

Motivation (RedLynx)



- Modular construction using in-game level editor
- High draw distance. Background built from small objects.
- No baked lighting. Lots of draw calls from shadow maps.
- CPU used for physics simulation and visual scripting

Motivation

Assassin’s Creed Unity

- Massive amounts of geometry: architecture

Motivation

Assassin’s Creed Unity

- Massive amounts of geometry: seamless interiors

Motivation

Assassin’s Creed Unity

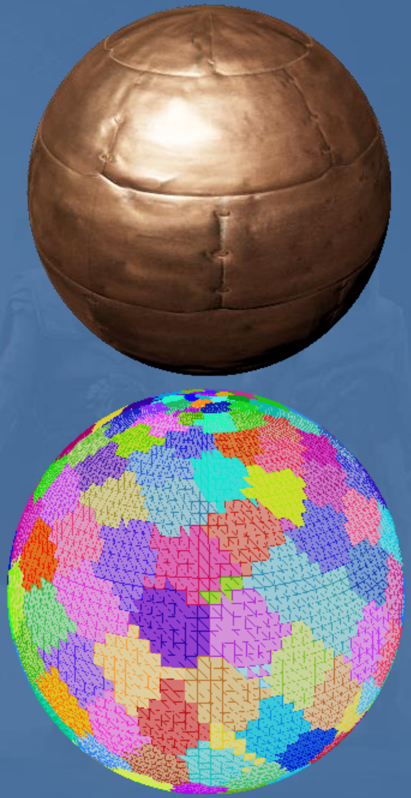
- Massive amounts of geometry: crowds

Motivation
Assassin's Creed Unity

- Modular construction (partially automated)
- ~10x instances compared to previous Assassin's Creed games
- CPU scarcest resource on consoles

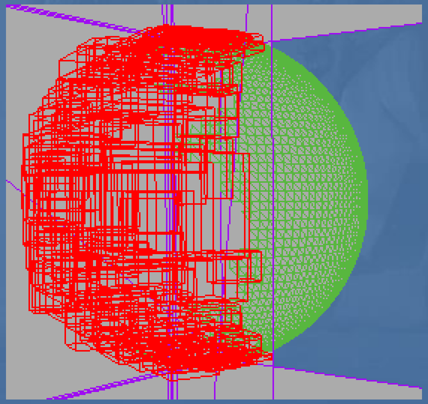
Mesh Cluster Rendering

- Fixed topology (64 vertex strip)
- Split & rearrange all meshes to fit fixed topology (insert degenerate triangles)
- Fetch vertices manually in VS from shared buffer [Riccio13]
- DrawInstancedIndirect
- GPU culling outputs cluster list & drawcall args



Mesh Cluster Rendering

- Arbitrary number of meshes in single drawcall
- GPU-culled by cluster bounds [Greene93] [Shopf08] [Hill11]
- Faster vertex fetch
- Cluster depth sorting



Mesh Cluster Rendering (ACU)

- Problems with triangle strips:
  - Memory increase due to degenerate triangles
  - Non-deterministic cluster order
- MultiDrawIndexedInstancedIndirect:
  - One (sub-)drawcall per instance
  - 64 triangles per cluster
  - Requires appending index buffer on the fly

Rendering Pipeline Overview

- CPU
- GPU

COARSE FRUSTUM CULLING

BUILD BATCH HASH
UPDATE INSTANCE GPU DATA

BATCH DRAWCALLS

INSTANCE CULLING (FRUSTUM/OCCLUSION)

CLUSTER CHUNK EXPANSION

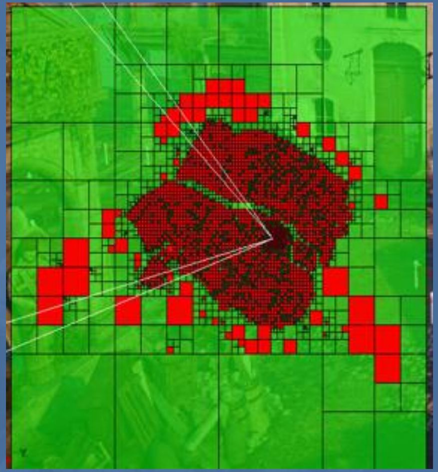
CLUSTER CULLING
(FRUSTUM/OCCLUSION/TRIANGLE BACKFACE)

INDEX BUFFER COMPACTION

MULTI-DRAW

Rendering pipeline overview

- CPU quad tree culling
- Per instance data:
  - E.g. transform, LOD factor...
  - Updated in GPU ring buffer
  - Persistent for static instances
- Drawcall hash build on non-instanced data:
  - E.g. material, renderstate, …
- Drawcalls merged based on hash



Rendering Pipeline Overview

INSTANCE CULLING (FRUSTUM/OCCLUSION)

Instance0	Instance1	Instance2	Instance3	…

Transform
Bounds
Mesh

The stream of instances contains a list of offsets into a GPU buffer per instance that allows the GPU to access information like transform, instance bounds etc.

CLUSTER CHUNK EXPANSION

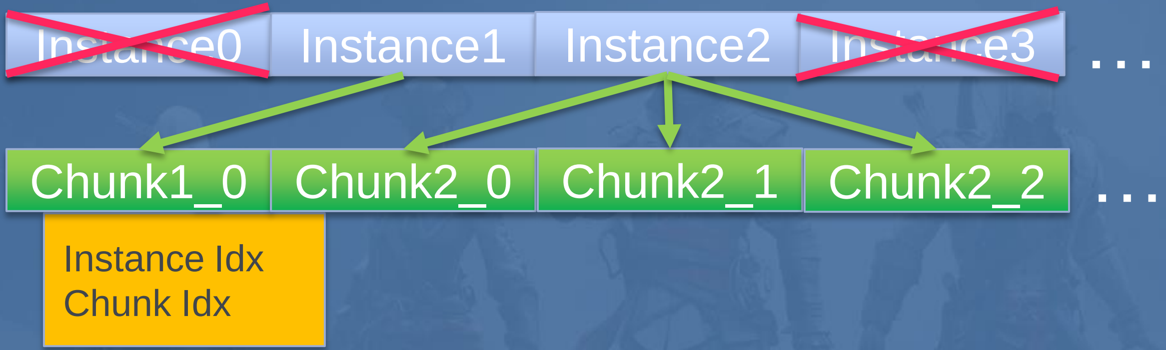
CLUSTER CULLING
(FRUSTUM/OCCLUSION/TRIANGLE BACKFACE)

INDEX BUFFER COMPACTION

MULTI-DRAW

Rendering Pipeline Overview

INSTANCE CULLING (FRUSTUM/OCCLUSION)



CLUSTER CHUNK EXPANSION

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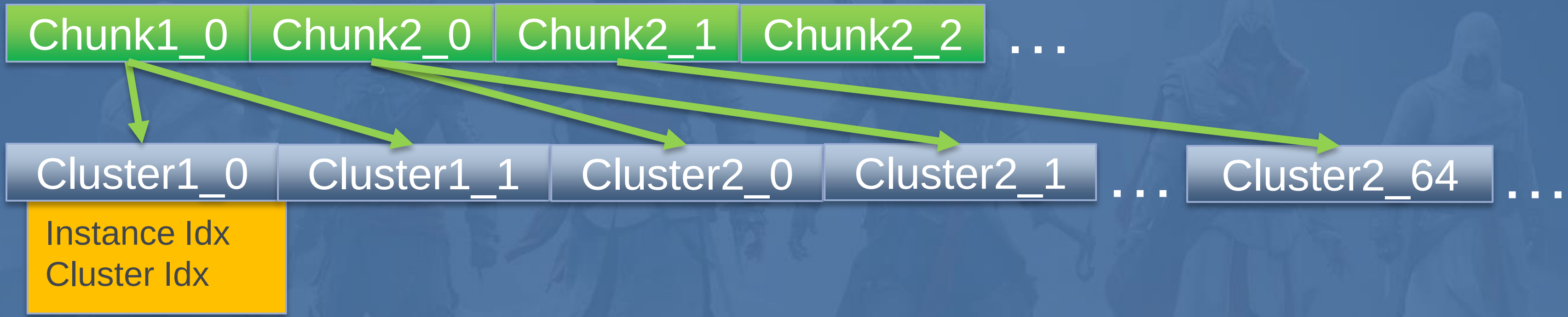

CLUSTER CULLING
(FRUSTUM/OCCLUSION/TRIANGLE BACKFACE)

INDEX BUFFER COMPACTION

MULTI-DRAW

Rendering Pipeline Overview

INSTANCE CULLING (FRUSTUM/OCCLUSION)

CLUSTER CHUNK EXPANSION

CLUSTER CULLING
(FRUSTUM/OCCLUSION/TRIANGLE BACKFACE)

~~Cluster1_0~~ Cluster1_1 ~~Cluster2_0~~ Cluster2_1 … Cluster2_64 …

Index1_1 Index2_1 … Index2_64 …

Triangle Mask
Read/Write Offsets

INDEX BUFFER COMPACTION

MULTI-DRAW

Rendering Pipeline Overview

INSTANCE CULLING (FRUSTUM/OCCLUSION)

CLUSTER CHUNK EXPANSION

CLUSTER CULLING
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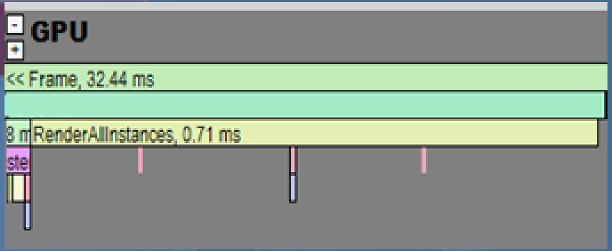
INDEX BUFFER COMPACTION



Index1_1 | Index2_1 ... Index2_64 ...

INDEX COMPACTION

Instance0		Instance1		Instance2			
0	1	0	1	0	1	2	...

Compacted index buffer

MULTI-DRAW

Rendering Pipeline Overview

INSTANCE CULLING (FRUSTUM/OCCLUSION)

CLUSTER CHUNK EXPANSION

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Rendering Pipeline Overview

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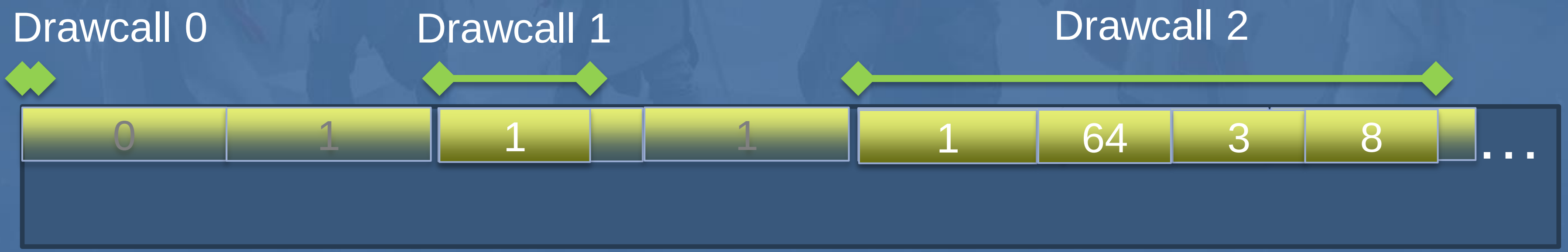
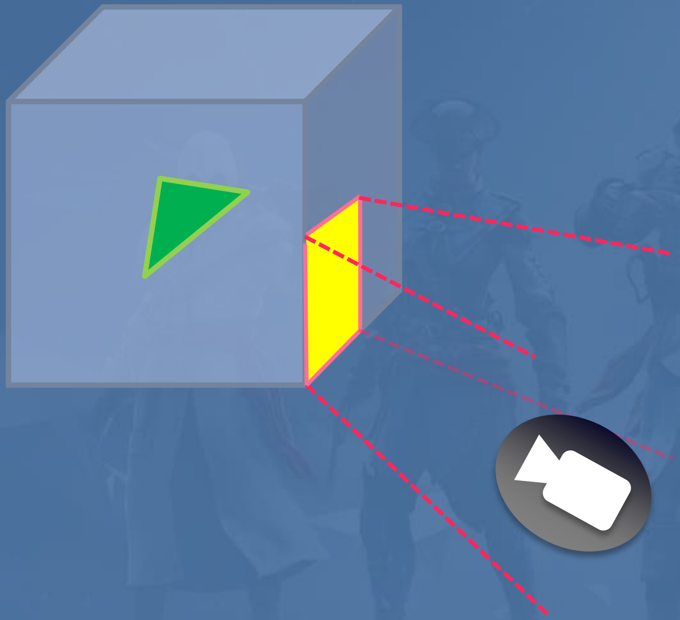
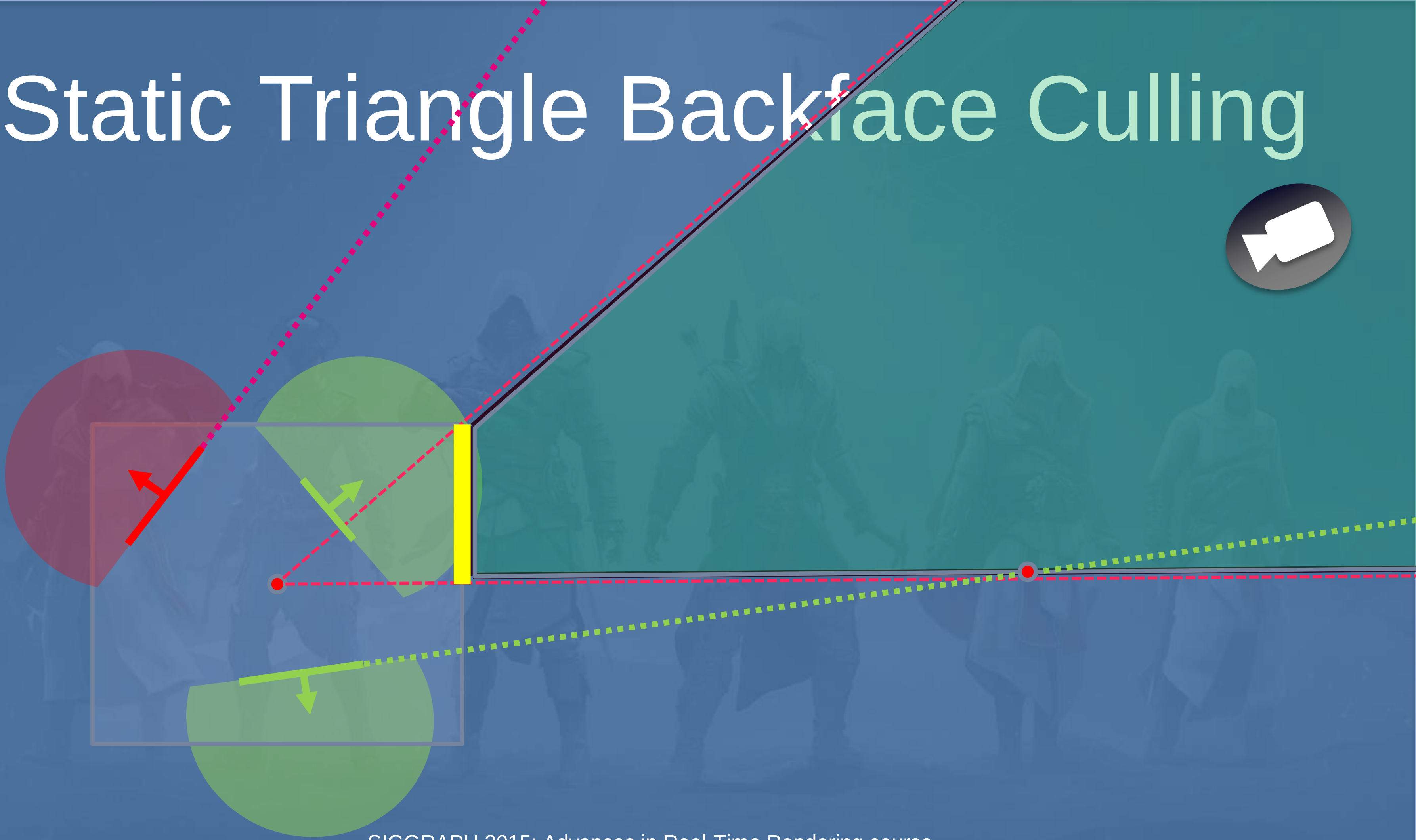


Static Triangle Backface Culling



- Bake triangle visibility for pixel frustums of cluster centered cubemap
- Cubemap lookup based on camera
- Fetch 64 bits for visibility of all triangles in cluster

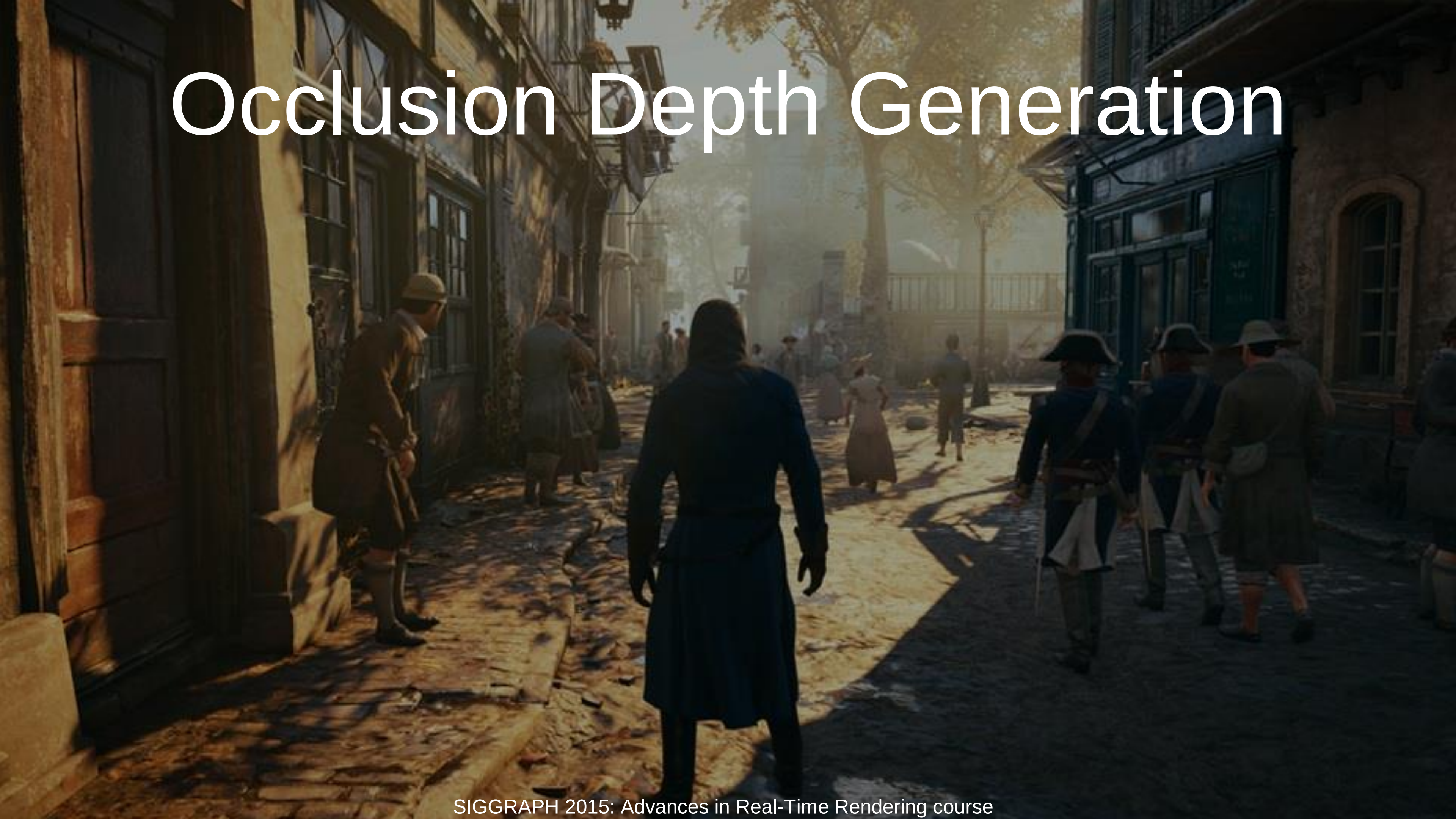
Static Triangle Backface Culling



Static Triangle Backface Culling

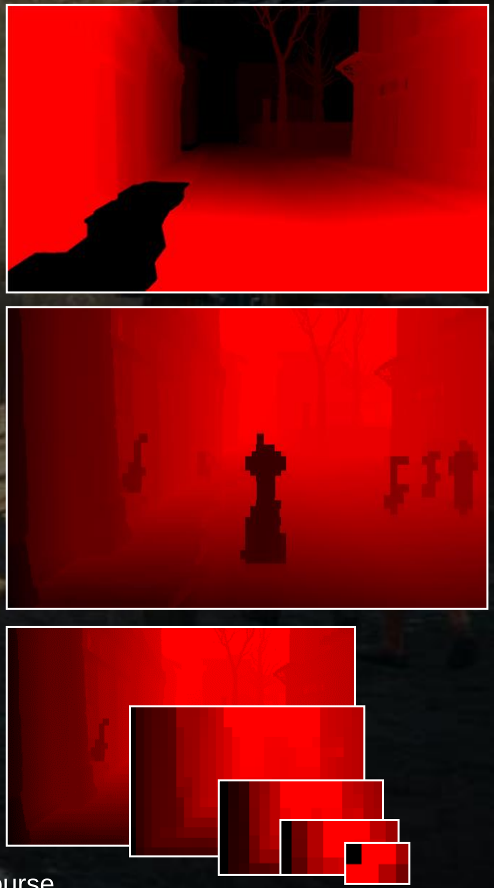
- Only one pixel per cubemap face (6 bits per triangle)
- Pixel frustum is cut at distance to increase culling efficiency (possible false positives at oblique angles)
- 10-30% triangles culled

Occlusion Depth Generation



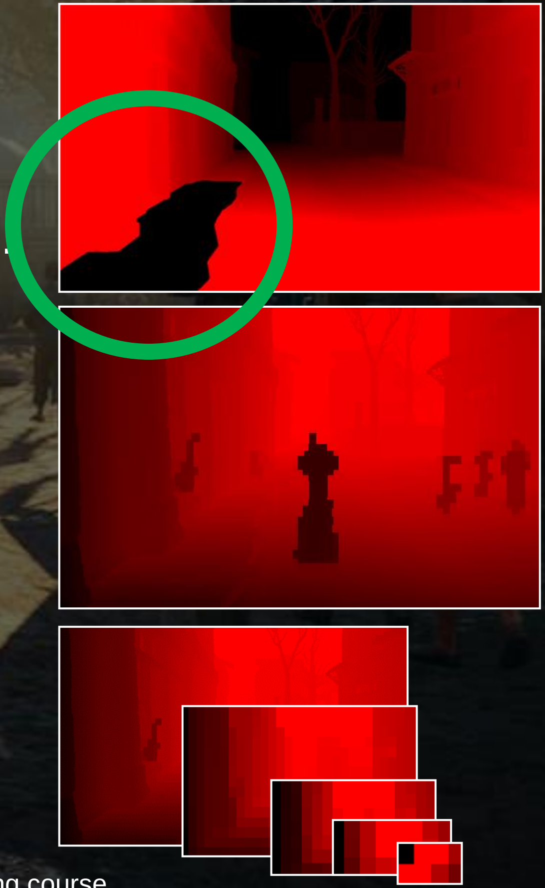
Occlusion Depth Generation

- Depth pre-pass with best occluders
- Rendered in full resolution for High-Z and Early-Z
- Downsampled to 512x256
- Combined with reprojection of last frame's depth
- Depth hierarchy for GPU culling



Occlusion Depth Generation

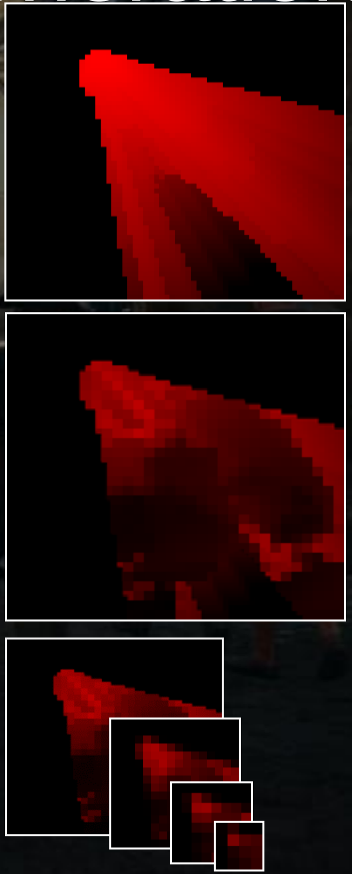
- 300 best occluders (~600us)
- Rendered in full resolution for High-Z and Early-Z
- Downsampled to 512x256 (100us)
- Combined with reprojection of last frame's depth (50us)
- Depth hierarchy for GPU culling (50us)



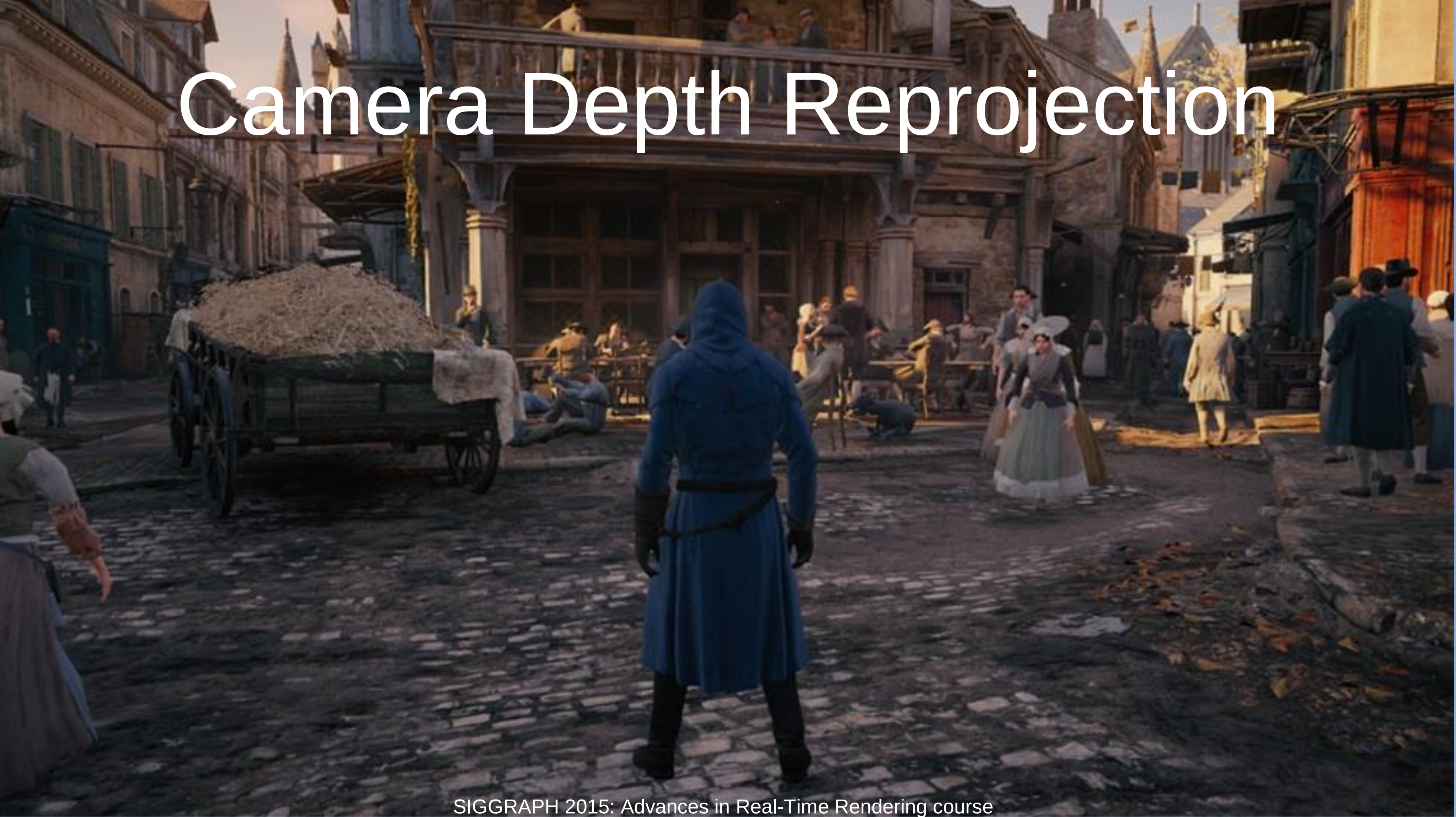
(*PS4 performance)

Shadow Occlusion Depth Generation

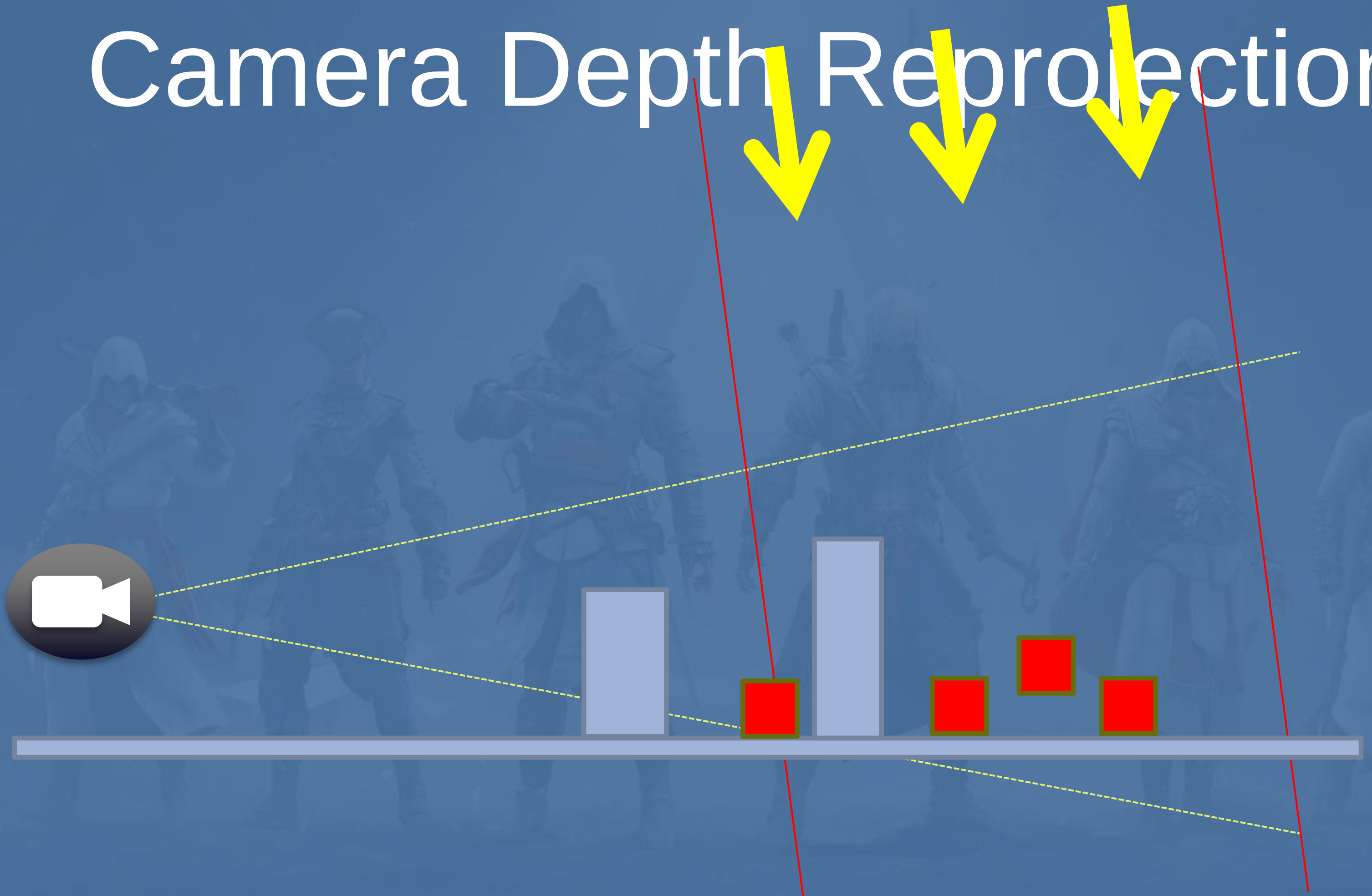
- For each cascade
- Camera depth reprojection (~70us)
- Combine with shadow depth reprojection (10us)
- Depth hierarchy for GPU culling (30us)



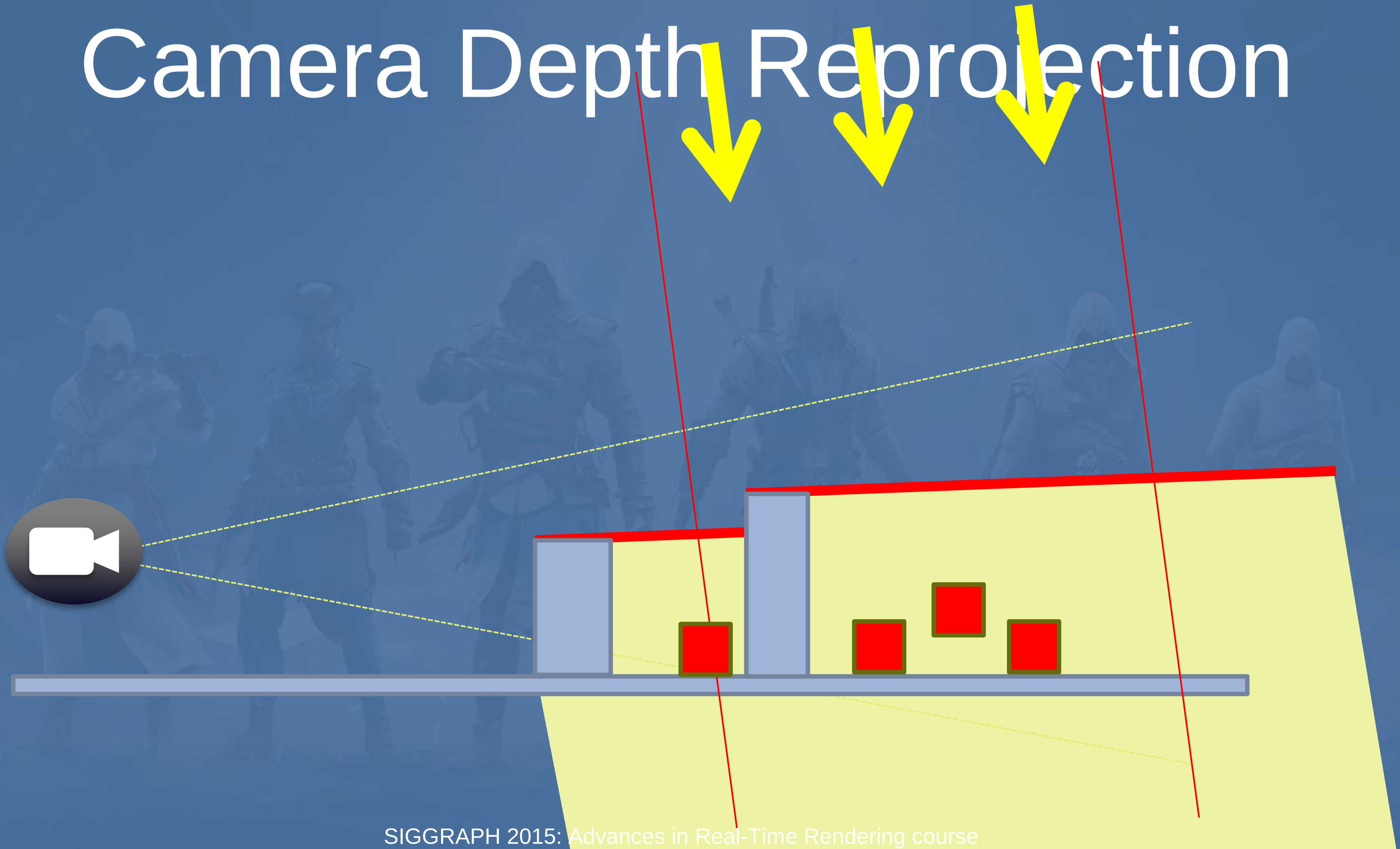
Camera Depth Reprojection



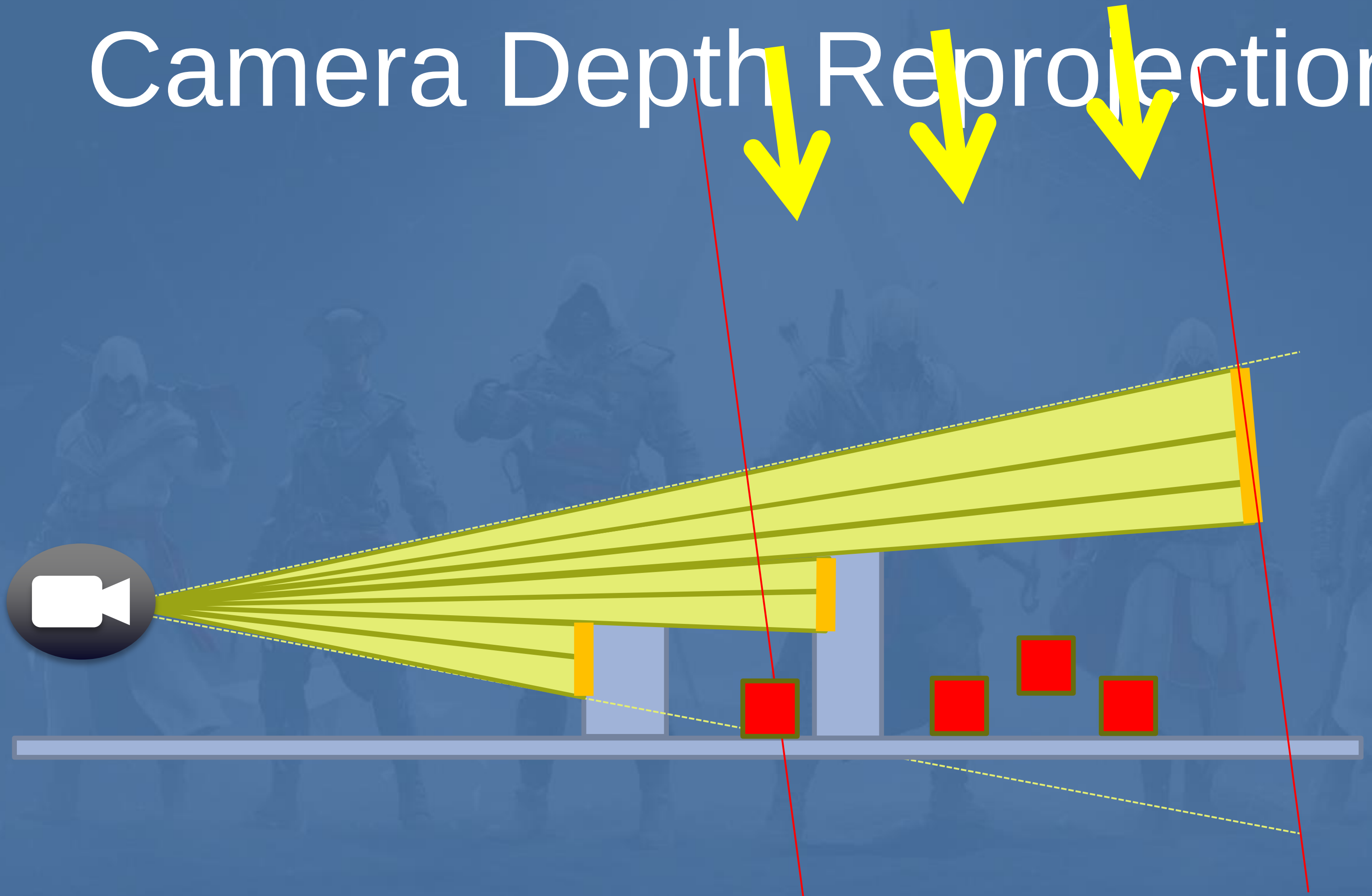
Camera Depth Reprojection



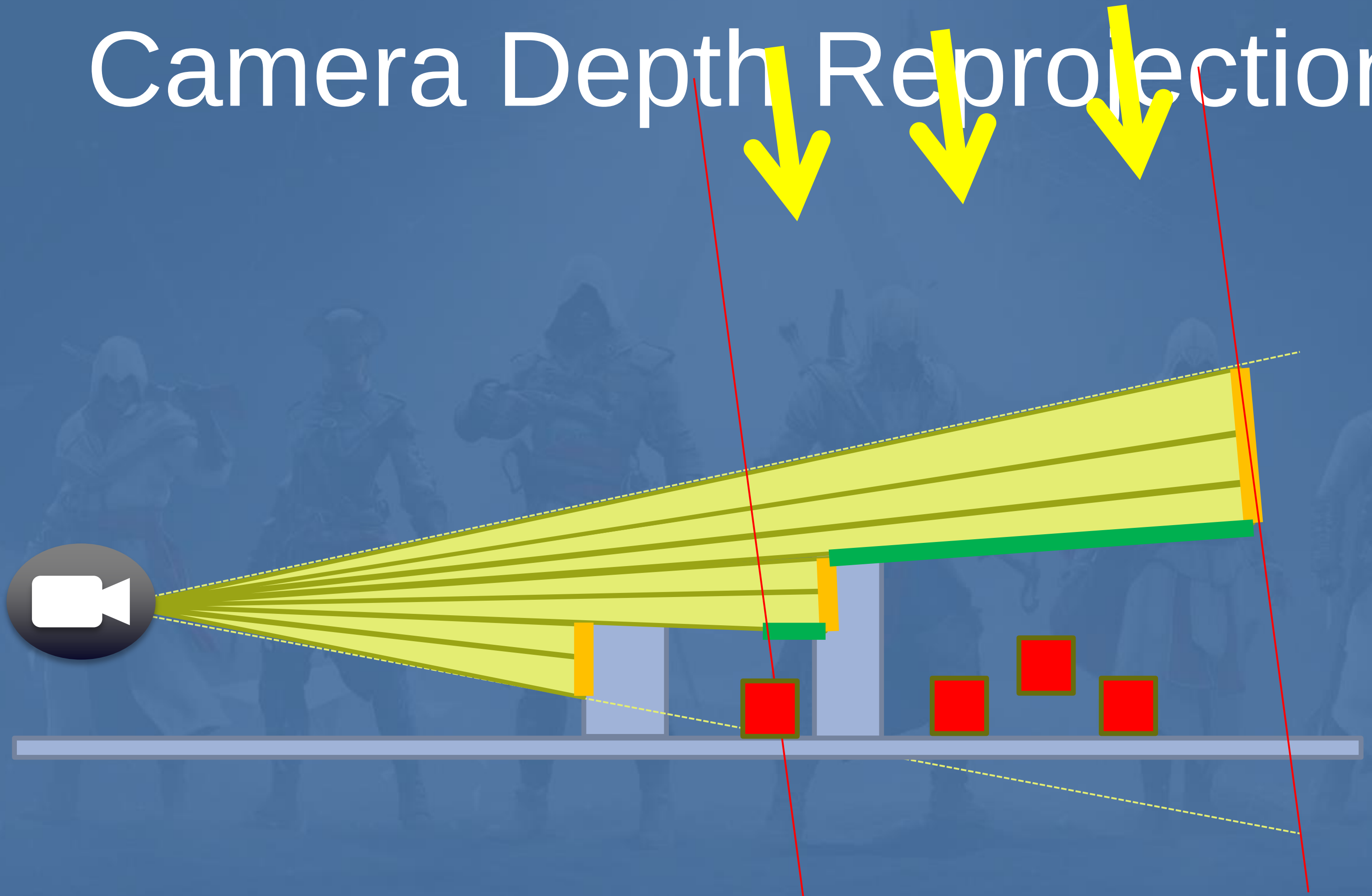
Camera Depth Reprojection



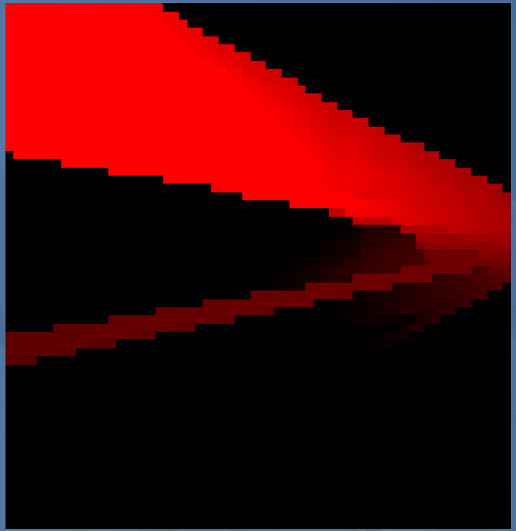
Camera Depth Reprojection



Camera Depth Reprojection

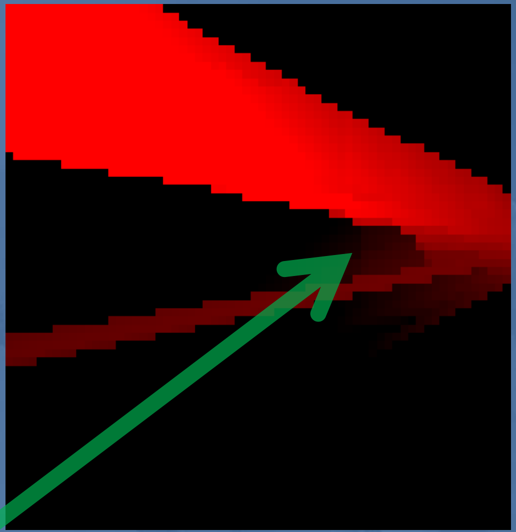


Camera Depth Reprojection



Light Space Reprojection

Camera Depth Reprojection



Reprojection “shadow” of the building

Camera Depth Reprojection

- Similar to [Silvennoinen12]
- But, mask not effective because of fog:
  - Cannot use min-depth
  - Cannot exclude far-plane
- 64x64 pixel reprojection
- Could pre-process depth to remove redundant overdraw

Results

CPU:

- 1-2 Orders of magnitude less drawcalls
- ~75% of previous AC, with ~10x objects

GPU:

- 20-40% triangles culled (backface + cluster bounds)
- Only small overall gain: <10% of geometry rendering
- 30-80% shadow triangles culled

Work in progress:

- More GPU-driven for static objects
- More batch friendly data

Future

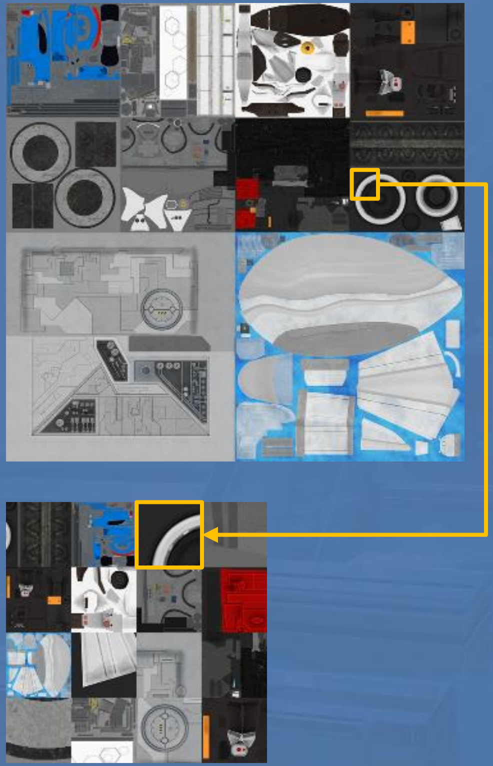
- Bindless textures
- GPU-driven vs. DX12/Vulkan

RedLynx Topics

- Virtual Texturing in GPU-Driven Rendering
- Virtual Deferred Texturing
- MSAA Trick
- Two-Phase Occlusion Culling
- Virtual Shadow Mapping

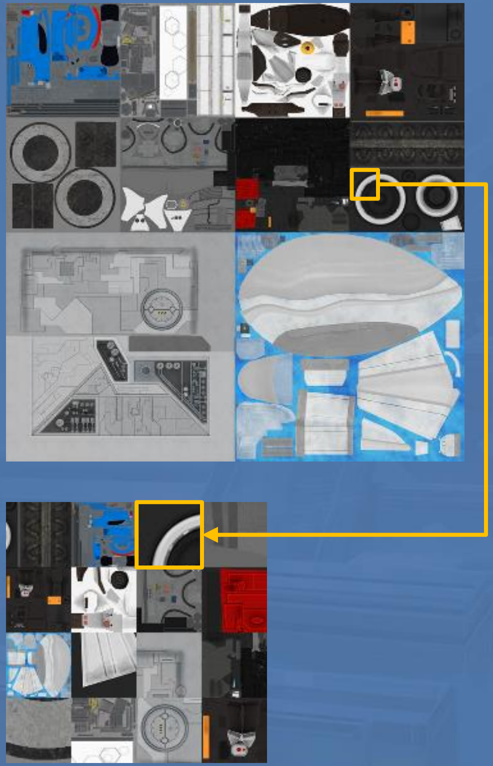
Virtual Texturing

- **Key idea:** Keep only the visible texture data in memory [Hall99]
- Virtual **256k^2** texel atlas
- **128^2** texel pages
- **8k^2** texture page cache
  - 5 slice texture array: Albedo, specular, roughness, normal, etc.
  - DXT compressed (BC5 / BC3)



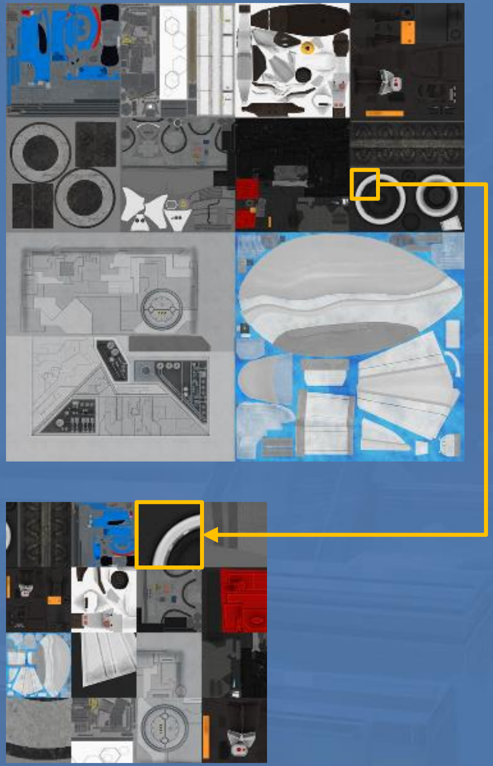
GPU-Driven Rendering with VT

- Virtual texturing is the biggest difference between our and AC: Unity's renderer
- **Key feature:** All texture data is available at once, using just a single texture binding
- No need to batch by textures!



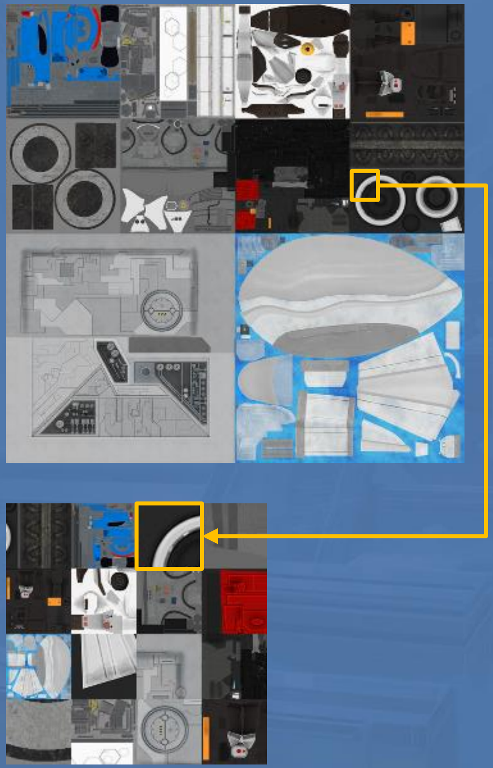
Single Draw Call Rendering

- Viewport = single draw call (x2)
- Dynamic branching for different vertex animation types
  - Fast on modern GPUs (+2% cost)
- Cluster depth sorting provides gain similar to depth prepass
- Cheap OIT with inverse sort



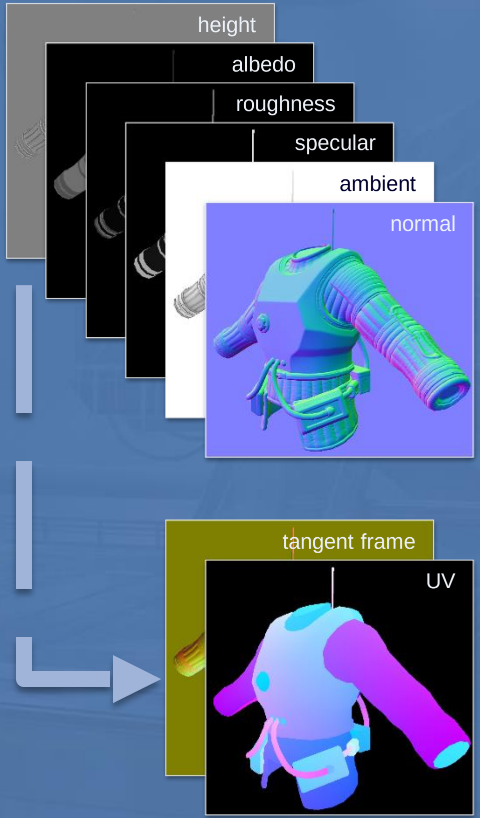
Additional VT Advantages

- Complex material blends and decal rendering results are stored to VT page cache
- Data reuse amortizes costs over hundreds of frames
- Constant memory footprint, regardless of texture resolution and the number of assets



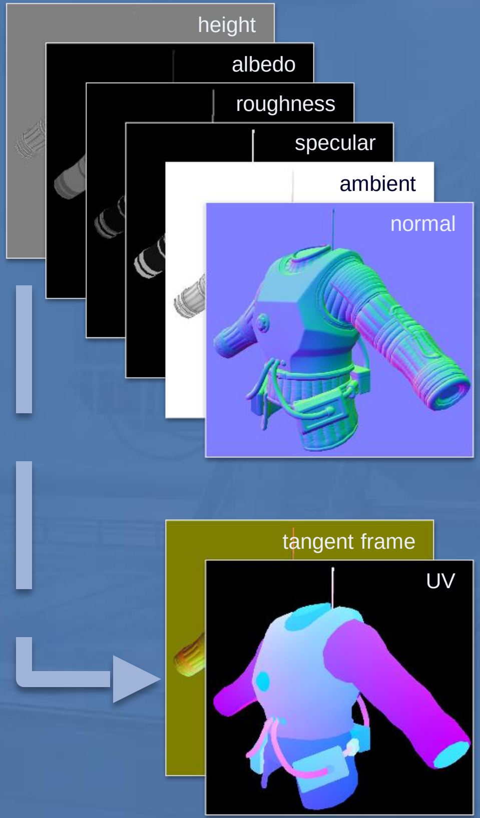
Virtual Deferred Texturing

- **Old Idea:** Store UVs to the G-buffer instead of texels [Auf.07]
- **Key feature:** VT page cache atlas contains all the currently visible texture data
- 16+16 bit UV to the **8k^2** texture atlas gives us **8 x 8** subpixel filtering precision



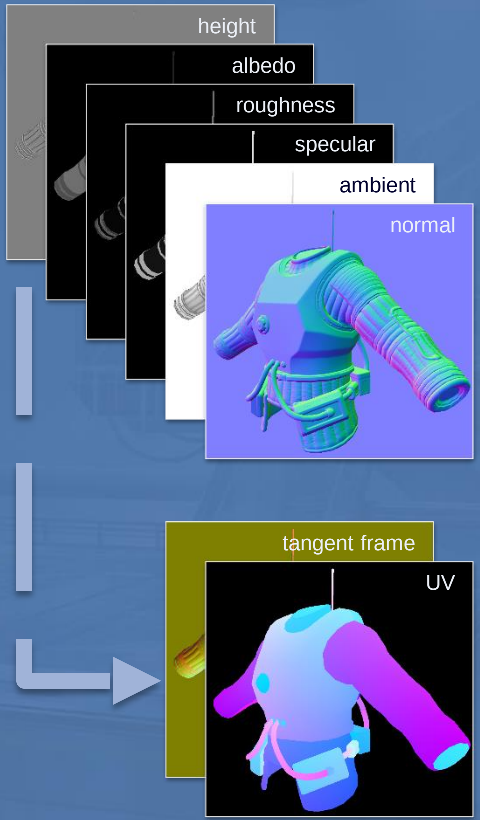
Gradients and Tangent Frame

- Calculate pixel gradients in screen space. UV distance used to detect neighbors.
- No neighbors found → bilinear
- Tangent frame stored as a 32 bit quaternion [Frykholm09]
- Implicit mip and material id from VT. Page = UV.xy / 128.

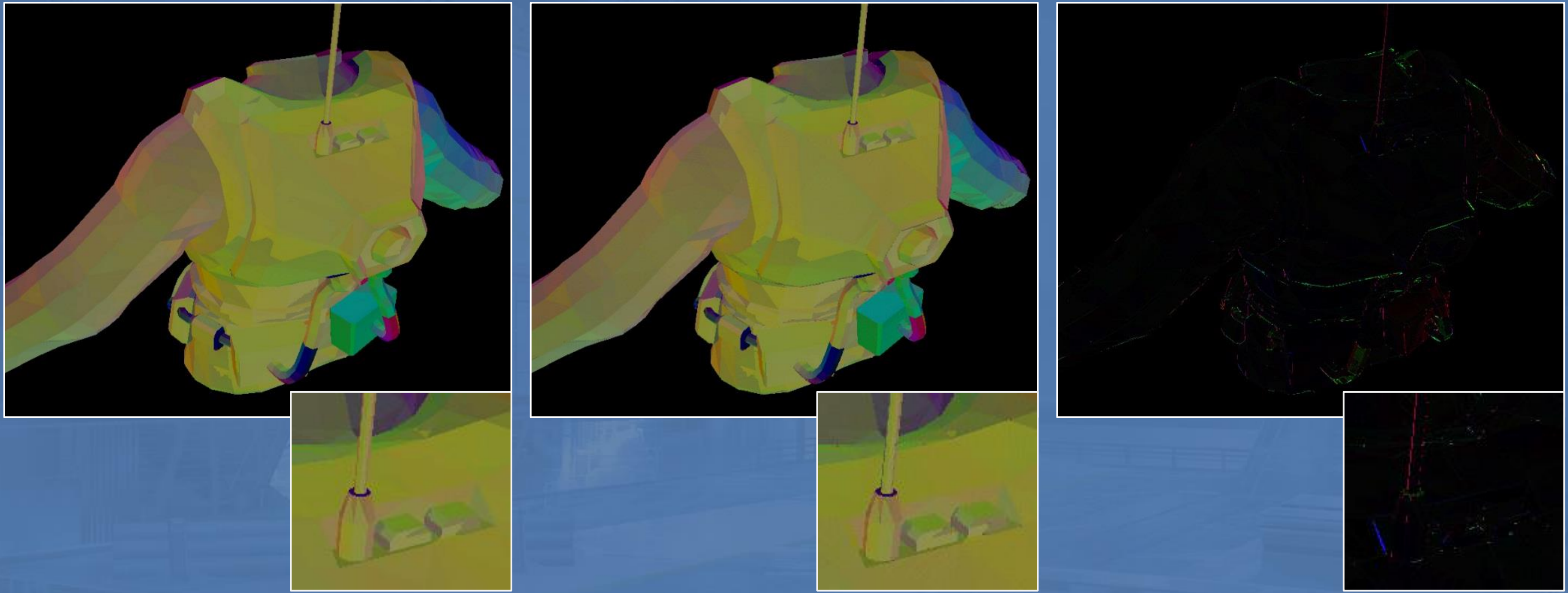


Recap & Advantages

- 64 bits. Full fill rate. No MRT.
- Overdraw is dirt cheap
  - Texturing deferred to lighting CS
- Quad efficiency less important
- Virtual texturing page ID pass is no longer needed



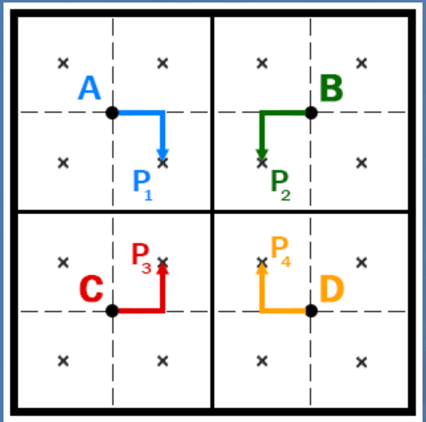
Gradient reconstruction quality



Ground truth Reconstructed Difference (x4)

MSAA Trick

- **Key Observation:** UV and tangent can be interpolated
- **Idea:** Render the scene at 2x2 lower resolution (540p) with ordered grid 4xMSAA pattern
- Use Texture2DMS.Load() to read each sample separately in the lighting compute shader



$$P_1 = A + \frac{1}{4}\overrightarrow{AB} + \frac{1}{4}\overrightarrow{AC}$$

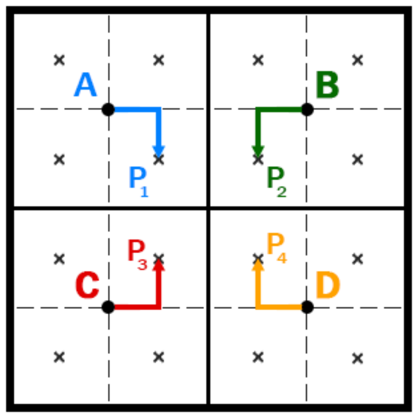
$$P_2 = B + \frac{1}{4}\overrightarrow{BA} + \frac{1}{4}\overrightarrow{BD}$$

$$P_3 = C + \frac{1}{4}\overrightarrow{CA} + \frac{1}{4}\overrightarrow{CD}$$

$$P_4 = D + \frac{1}{4}\overrightarrow{DC} + \frac{1}{4}\overrightarrow{DB}$$

1080p Reconstruction

- Reconstruct 1080p into LDS
- Edge pixels are perfectly reconstructed. MSAA runs the pixel shader for both sides.
- Interpolate the inner pixels’ UV and tangent
- Quality is excellent. Differences are hard to spot.



$$P_1 = A + \frac{1}{4}\overrightarrow{AB} + \frac{1}{4}\overrightarrow{AC}$$

$$P_2 = B + \frac{1}{4}\overrightarrow{BA} + \frac{1}{4}\overrightarrow{BD}$$

$$P_3 = C + \frac{1}{4}\overrightarrow{CA} + \frac{1}{4}\overrightarrow{CD}$$

$$P_4 = D + \frac{1}{4}\overrightarrow{DC} + \frac{1}{4}\overrightarrow{DB}$$

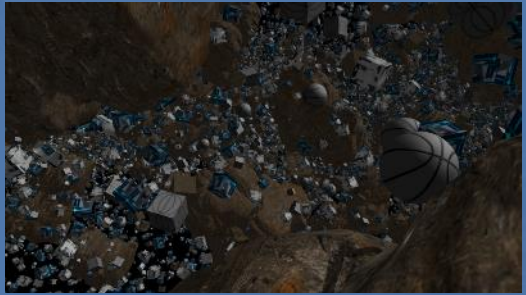
8xMSAA Trick Benchmark

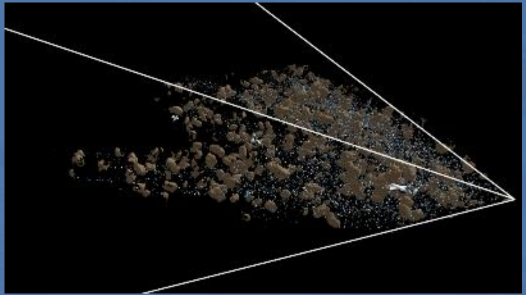
- 128 bpp G-Buffer
- One pixel is a 2x2 tile of ”2xMSAA pixels”
- Xbox One: 1080p + MSAA + 60 fps ☺

	2xMSAA	**MSAA trick**	**Reduction**
G-buffer rendering time	**3.03 ms**	**2.06 ms**	**-32%**
Pixel shader waves	83016	36969	-55%
DRAM memory traffic ESRAM (18 MB partial)	76.3 MB 15.0 MB	60.9 MB 29.1 MB	-20%

Two-Phase Occlusion Culling

- No extra occlusion pass with low poly proxy geometry
- Precise WYSIWYG occlusion
- Based on depth buffer data
- Depth pyramid generated from HTILE min/max buffer
- O(1) occlusion test (gather4)





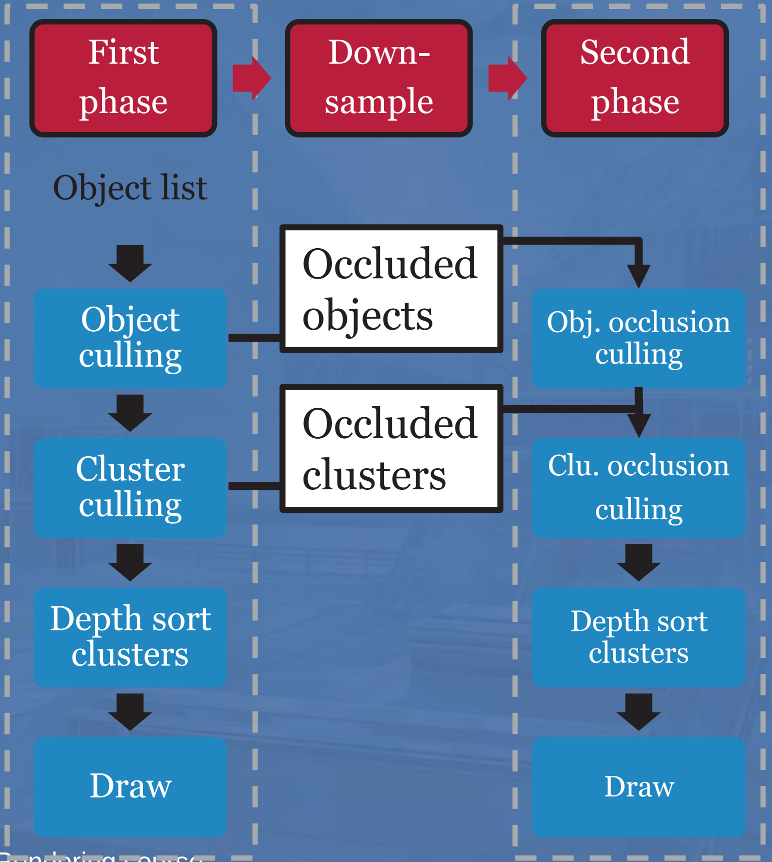
Two-Phase Occlusion Culling

1st phase

- Cull objects & clusters using last frame's depth pyramid
- Render visible objects

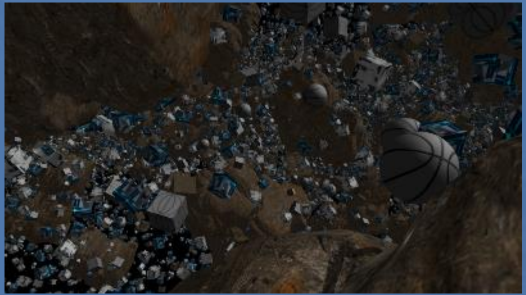
2nd phase

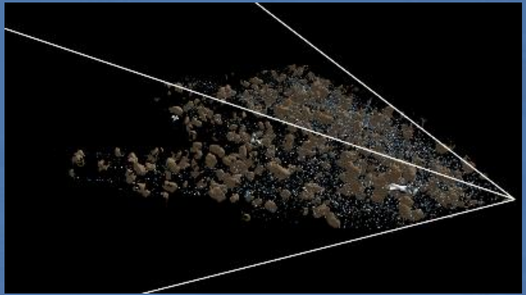
- Refresh depth pyramid
- Test culled objects & clusters
- Render false negatives



Benchmark

- "Torture" unit test scene
  - **250,000** separate moving objects
  - **1 GB** of mesh data (10k+ meshes)
  - **$8k^2$** texture cache atlas
- DirectX 11 code path
  - 64 vertex clusters (strips)
  - No ExecuteIndirect / MultiDrawIndirect
- Only two DrawInstancedIndirect calls





Benchmark Results

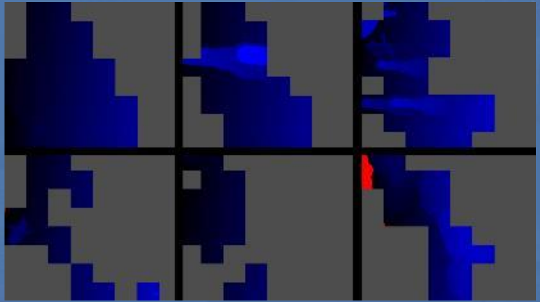
Xbox One, 1080p

GPU time	1^{st} phase	2^{nd} phase
Object culling + LOD	**0.28 ms**	**0.26 ms**
Cluster culling	**0.09 ms**	**0.04 ms**
Draw (G-buffer)	**1.60 ms**	**< 0.01 ms**
Pyramid generation	**0.06 ms**	
Total	**2.3 ms**	

CPU time: 0.2 milliseconds (single Jaguar CPU core)

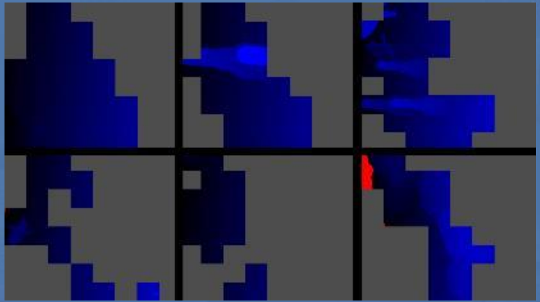
Virtual Shadow Mapping

- **128k²** virtual shadow map
- **256²** texel pages
- Identify needed shadow pages from the z-buffer [Fernando01].
- Cull shadow pages with the GPU-driven pipeline.
- Render all pages at once.



VTSM Quality and Performance

- Close to 1:1 shadow-to-screen resolution in all areas
- **Measured:** Up to 3.5x faster than SDSM [Lauritzen10] in complex “sparse” scenes
- Virtual SM slightly slower than SDSM & CSM in simple scenes



GPU-Driven Rendering + DX12

NEW DX12 (PC) FEATURES

- ExecuteIndirect
- Asynchronous Compute
- VS RT index (GS bypass)
- Resource management
- Explicit multiadapter
- Tiled resources + bindless
- Conservative raster + ROV

FEATURES IN OTHER APIs

- Custom MSAA patterns
- GPU side dispatch
- SIMD lane swizzles
- Ordered atomics
- SV_Barycentric to PS
- Exposed CSAA/EQAA samples
- Shading language with templates

References

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Ulrich Haar, Lead Programmer 3D
Ubisoft Montreal

Sebastian Aaltonen, Senior Lead Programmer
RedLynx, a Ubisoft Studio

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