CS 380 - GPU and GPGPU Programming
Lecture 29: GPU Virtual Texturing + Virtual Geometry; Unreal Engine 5

Markus Hadwiger, KAUST

Reading Assignment #11 (until Nov 18)

Read (required):

- Look at Vulkan *sparse resources*, especially *sparse partially-resident images*
  - `https://docs.vulkan.org/spec/latest/chapters/sparsemem.html`
- Read about shadow mapping
  - `https://en.wikipedia.org/wiki/Shadow_mapping/`
- Look at Unreal Engine 5 virtual texturing
  - `https://dev.epicgames.com/documentation/en-us/unreal-engine/virtual-texturing-in-unreal-engine/`
- Look at Unreal Engine 5 MegaLights
  - `https://dev.epicgames.com/documentation/en-us/unreal-engine/megalights-in-unreal-engine/`

Read (optional):

- CUDA Warp-Level Primitives
  - `https://developer.nvidia.com/blog/using-cuda-warp-level-primitives/`
- Warp-aggregated atomics
  - `https://developer.nvidia.com/blog/cuda-pro-tip-optimized-filtering-warp-aggregated-atomics/`

Next Lectures

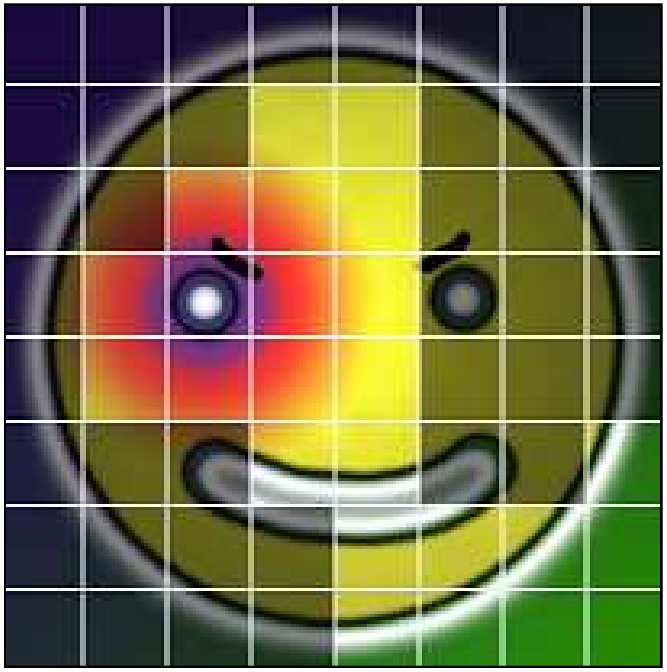
Lecture 30: Mon, Nov 18: Quiz #3

GPU Virtual Texturing

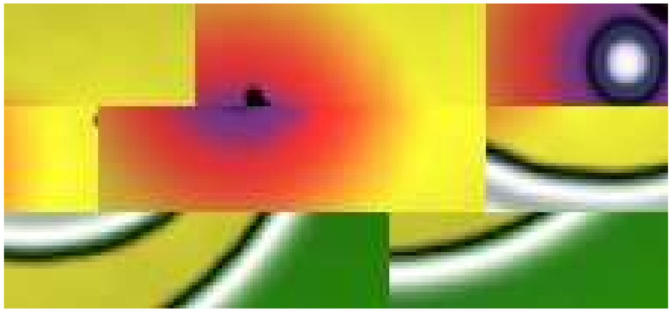
Virtual Texturing

Divide texture up into tiles

- Commit only *used* tiles to memory
- Store data in separate physical texture



Virtual Texture

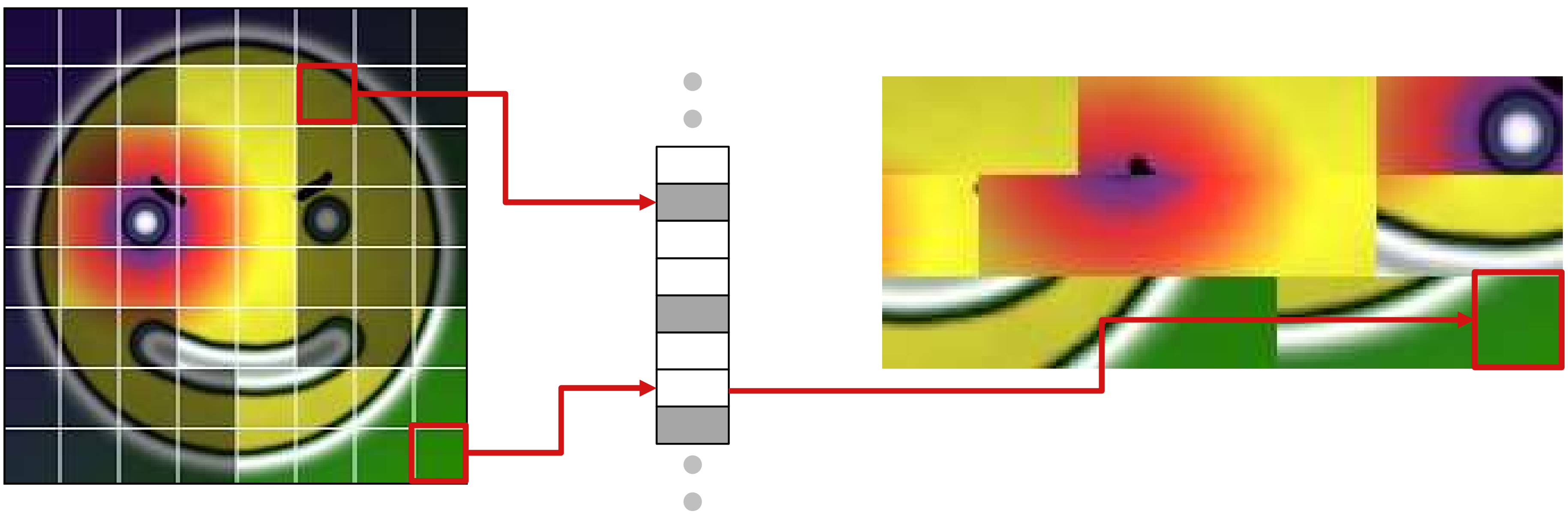


Physical Texture

Virtual Texturing

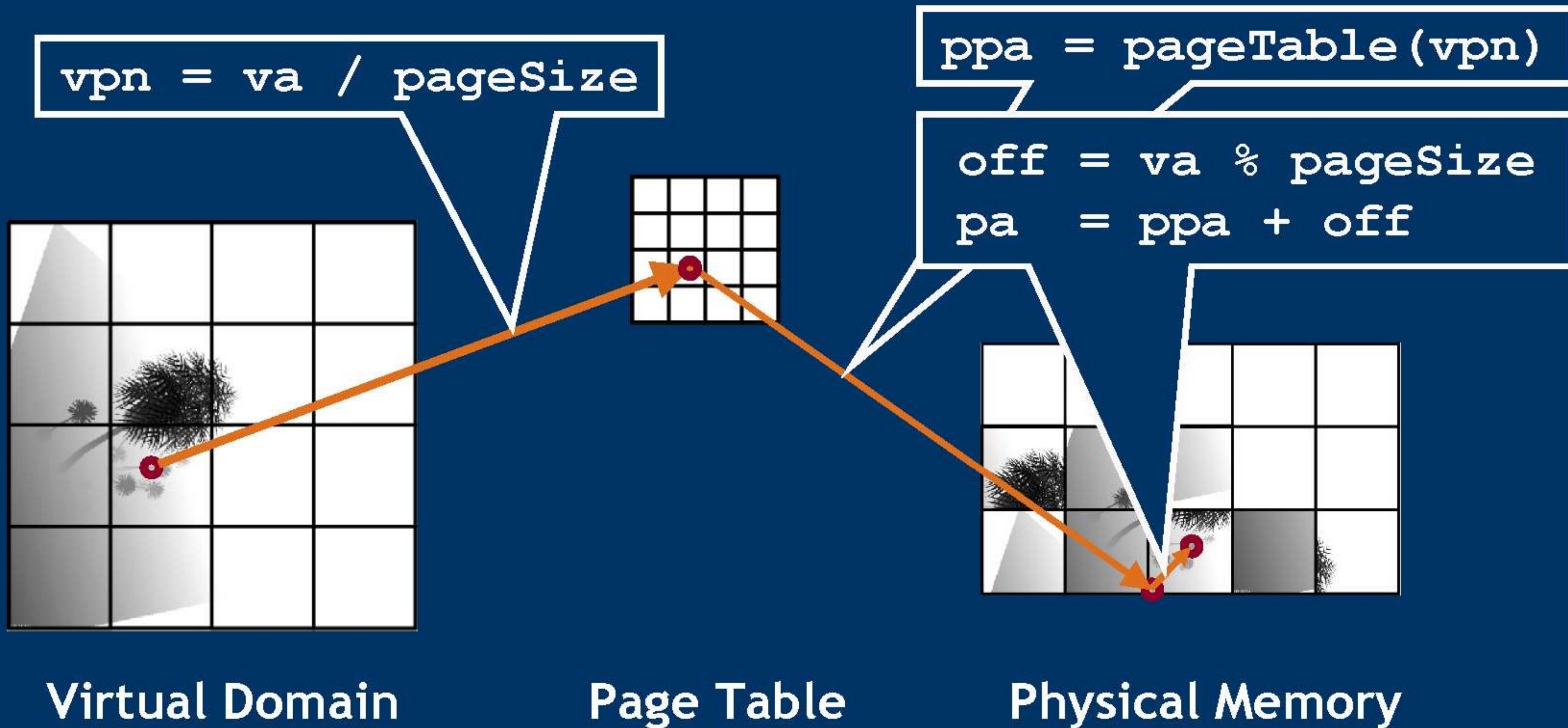
Use indirection table to map virtual to physical

- This is also known as a *page table*



ASM Data Structure (Adaptive Shadow Maps)

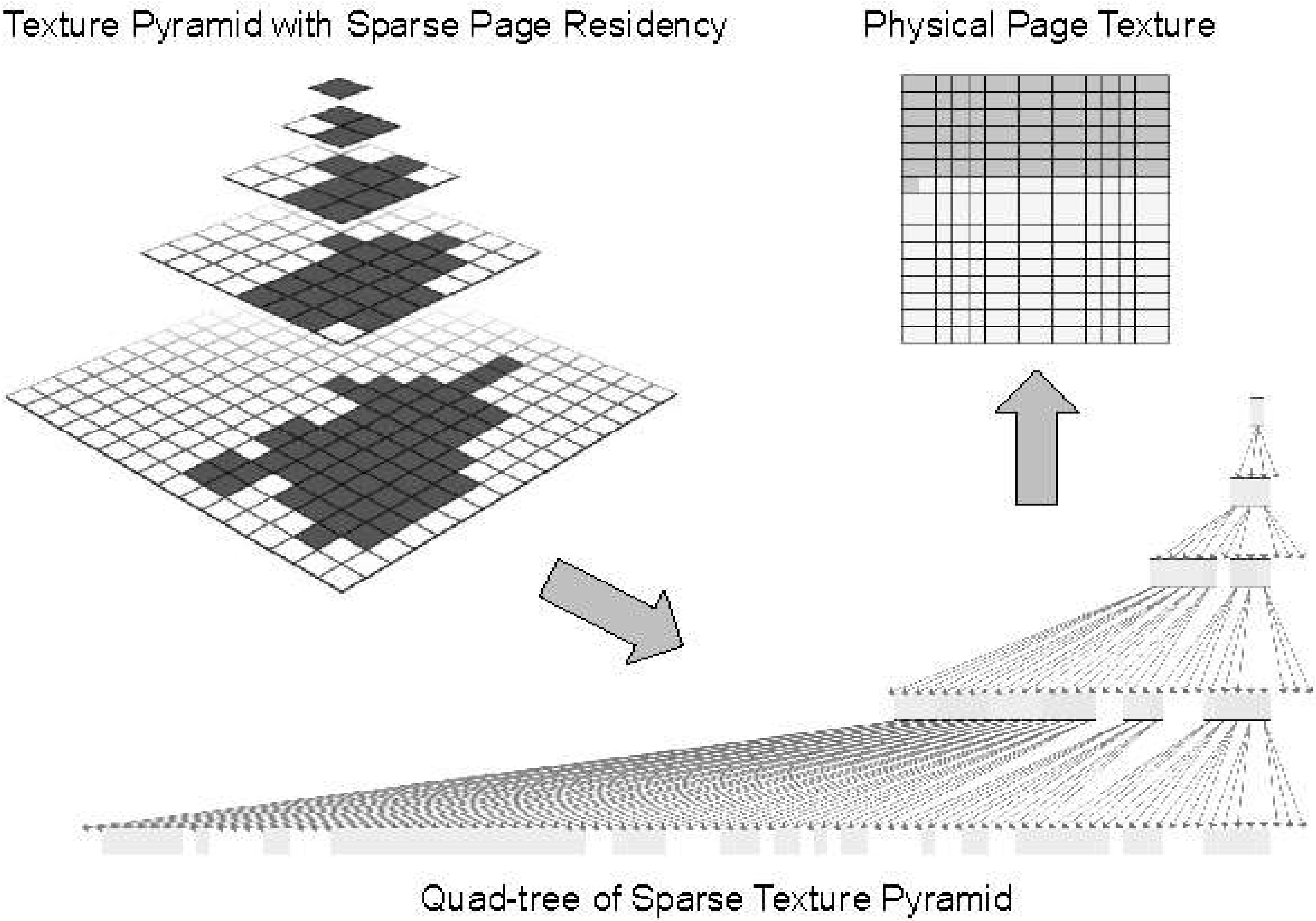
- **Page table example**



Aaron Lefohn
University of California, Davis

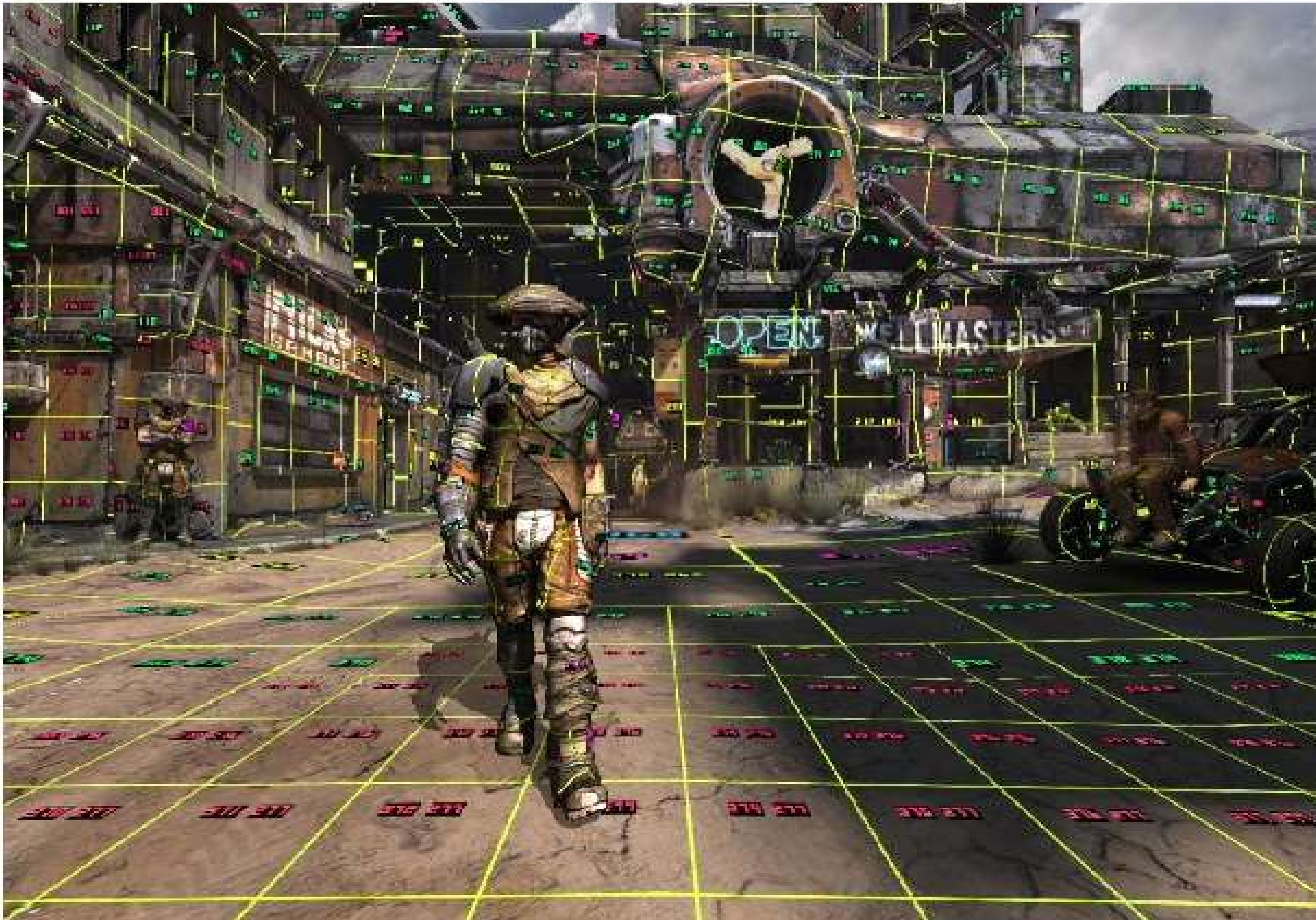
Virtual Texturing

Virtual Texturing



Virtual Texturing

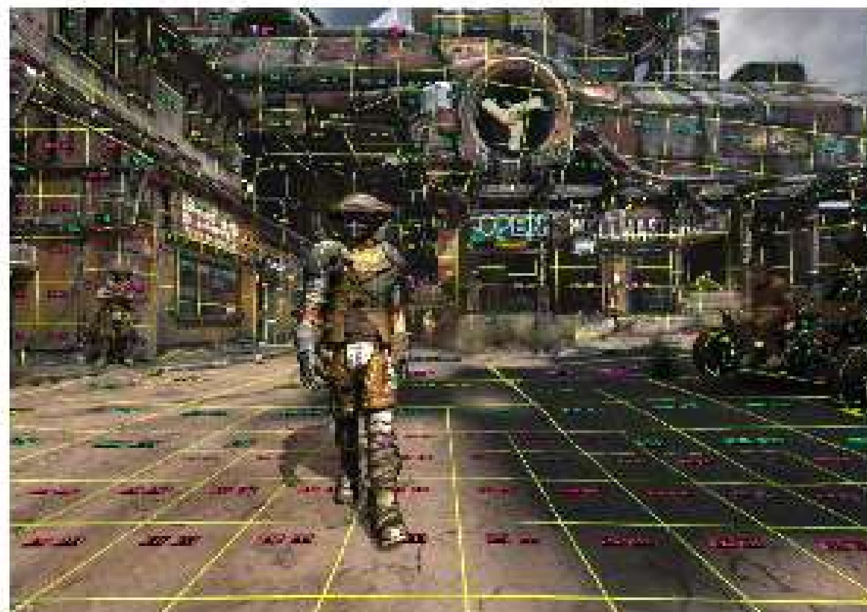
Virtual Texturing



Virtual Texturing

A few interesting issues...

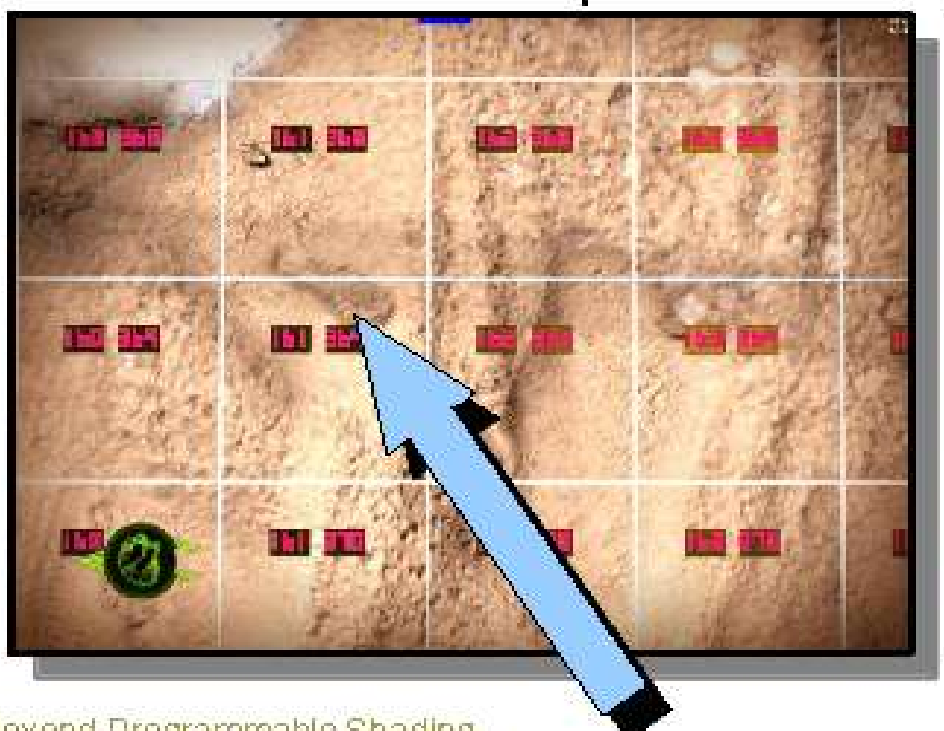
- Texture filtering
- Thrashing due to physical memory oversubscription
- LOD transitions under high latency

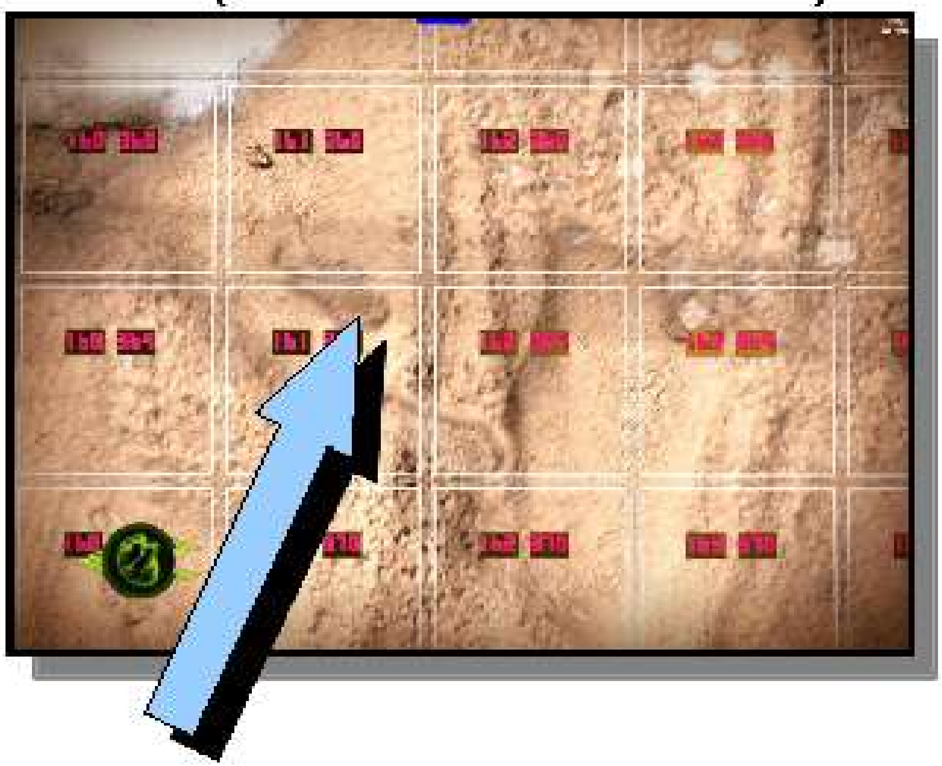


RAGE with PRTs (Image courtesy of id Software)

Virtual Texturing - Filtering

- We tried no filtering at all
- We tried bilinear filtering without borders
- Bilinear filtering with border works well
- Trilinear filtering reasonably but still expensive
- Anisotropic filtering possible via TXD (texgrad)
  - 4-texel border necessary (max aniso = 4)
  - TEX with implicit derivs ok too (on some hardware)



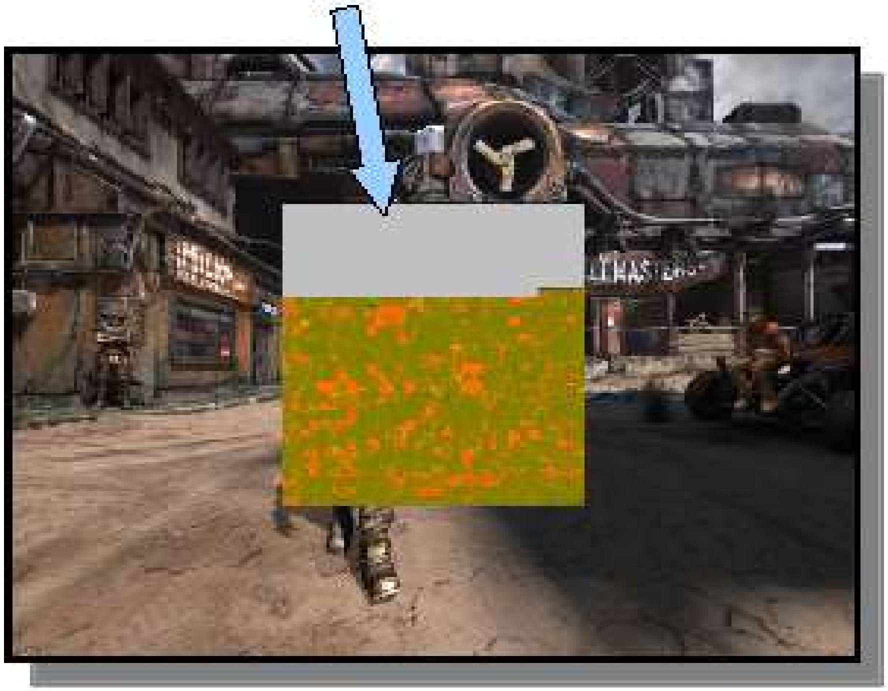


Virtual Texturing - Thrashing

- Sometimes you need more physical pages than you have
- With conventional virtual memory, you must thrash
- With virtual texturing, you can globally adjust feedback LOD bias until working set fits

32 x 32 pages

8x8 pages

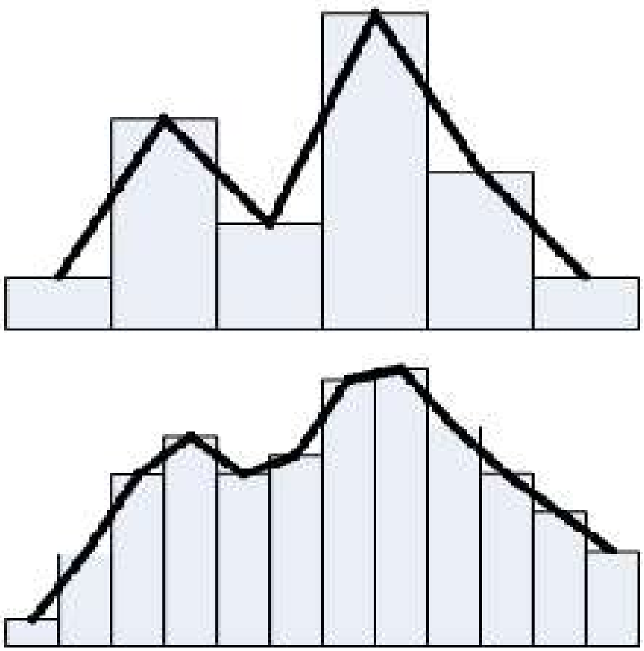


1024 Physical Pages

64 Physical Pages

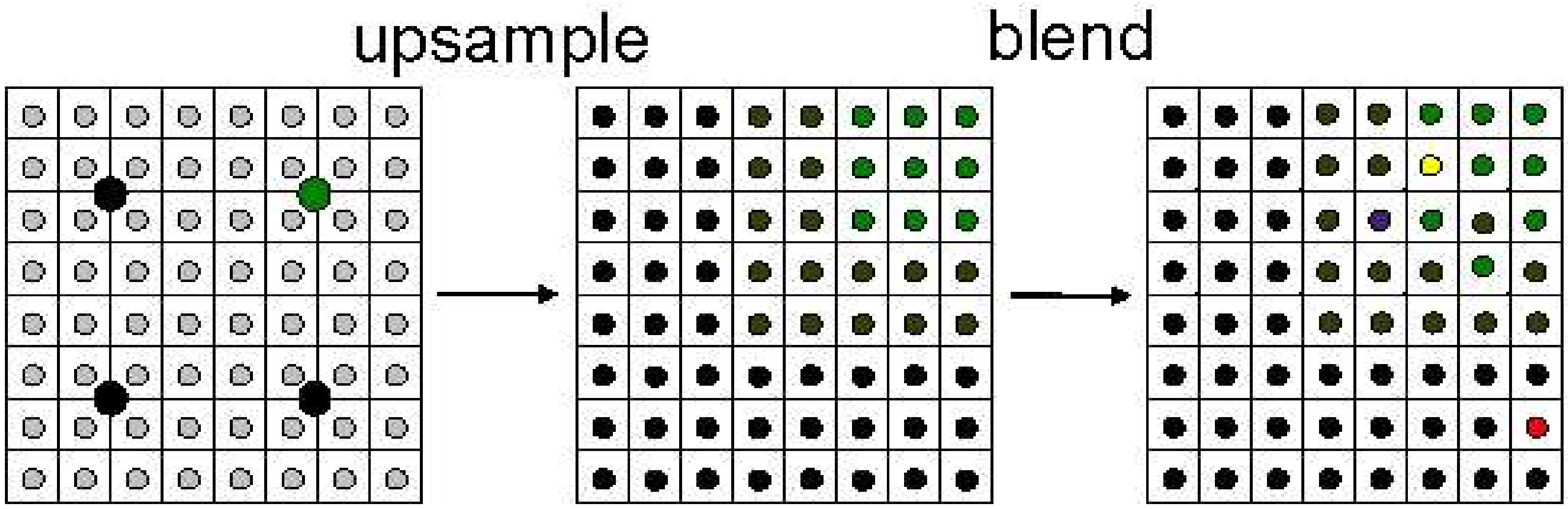
Virtual Texturing – LOD Snap

- Latency between first need and availability can be high
  - Especially if optical disk read required (>100 msec seek!)
- Visible snap happens when magnified texture changes LOD
- If we used trilinear filtering, blending in detail would be easy
- Instead continuously update physical pages with blended data



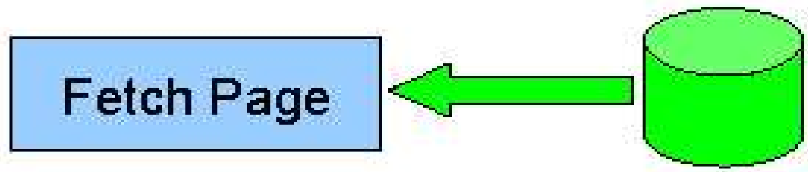
Virtual Texturing – LOD Snap

- Upsample coarse page immediately
- Then blend in finer data when available



Virtual Texturing - Management

- Analysis tells us what pages we need
- We fetch what we can



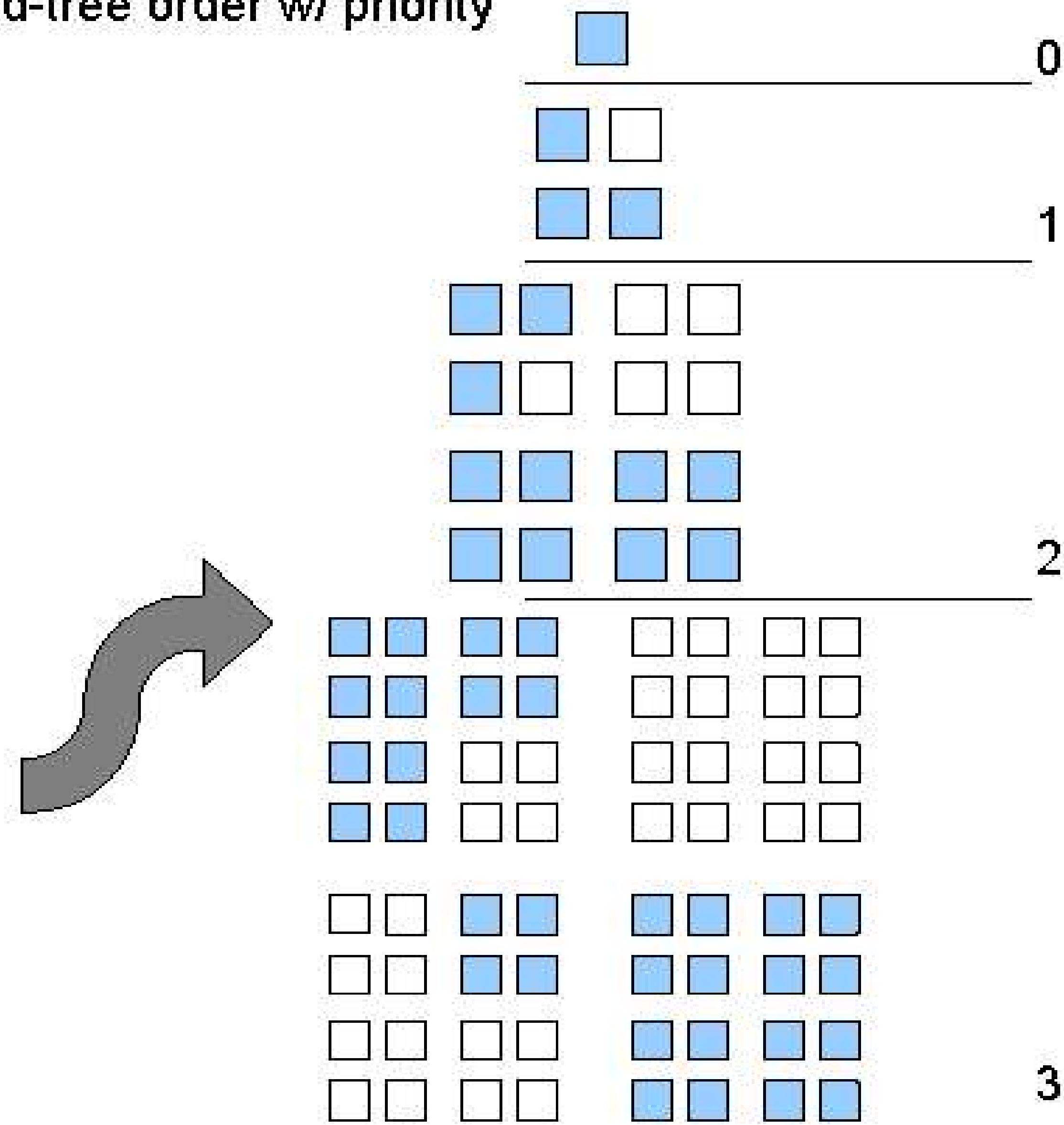
- But this is a real-time app... so no blocking allowed
- Cache handles hits, schedules misses to load in background
- Resident pages managed independent of disk cache
- Physical pages organized as quad-tree per virtual texture
- Linked lists for free, LRU, and locked pages

Virtual Texturing - Feedback

- Feedback Analysis
  - Gen ~breadth-first quad-tree order w/ priority

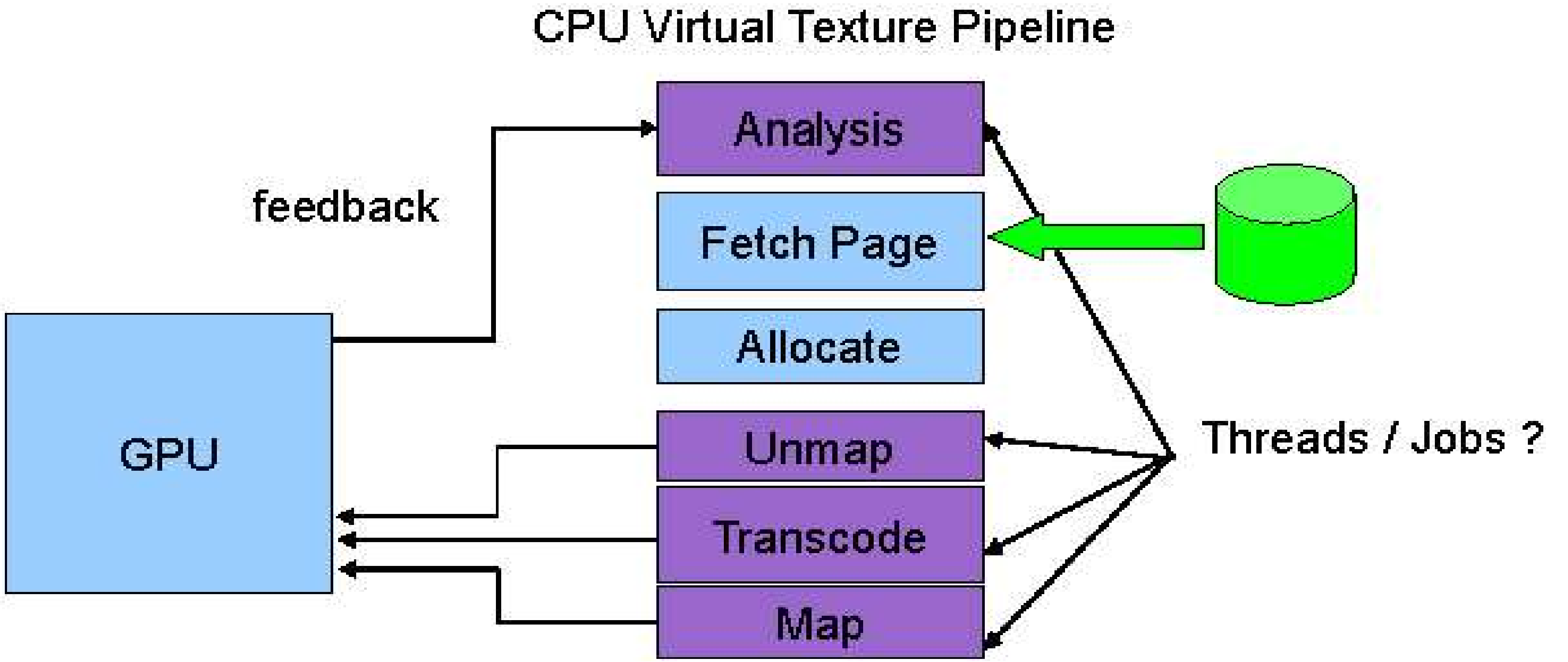
Color Buffer

Feedback Buffer



Virtual Texturing - Pipeline

- Compute intensive complex system with dependencies that we want to run in parallel on all the different platforms

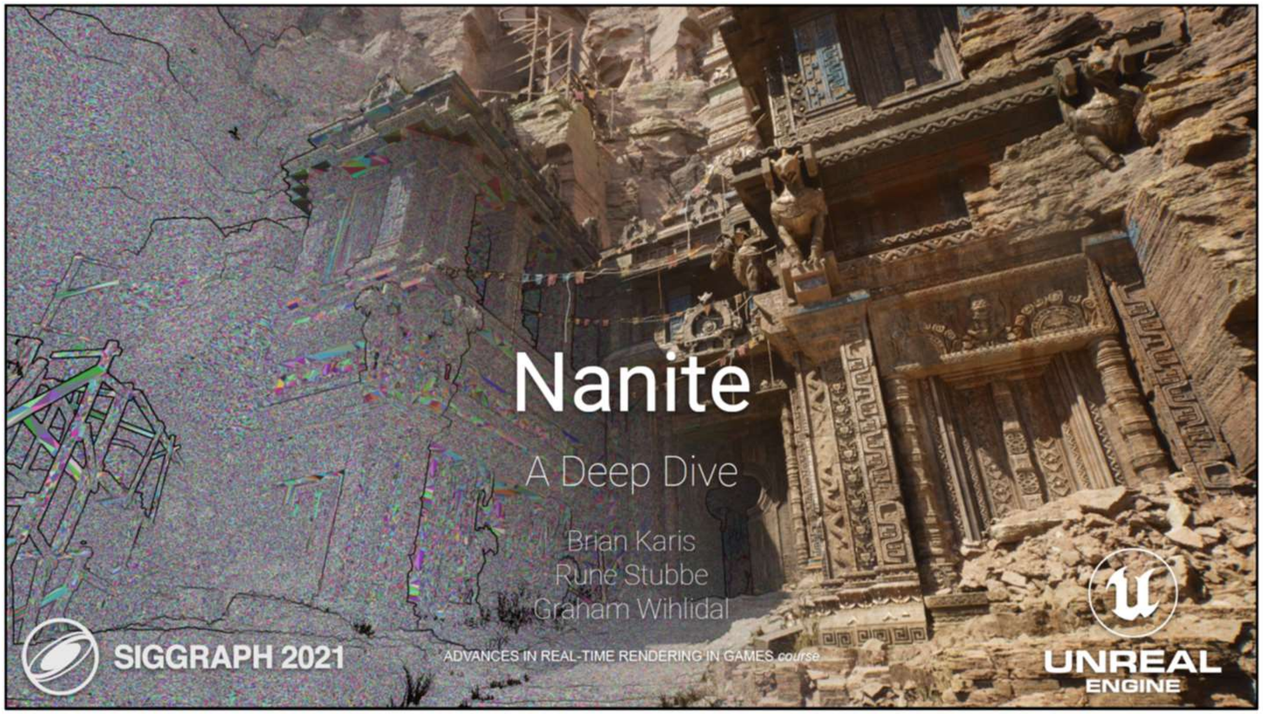


Virtual Geometry (and Texturing)

Unreal Engine 5 Virtual Geometry: Nanite

A Deep Dive into Nanite Virtualized Geometry (Siggraph 2021 course talk)
https://www.youtube.com/watch?v=eviSykqSUUw

Brian Karis, Epic Games



See also

- Keynote at HPG 2022:
  Journey to Nanite, Brian Karis
  https://www.youtube.com/watch?v=NRnj_lnpORU
- Lumen: Real-time Global Illumination in Unreal Engine 5 (Siggraph 2022 course talk),
  Daniel Wright et al., Epic Games
  https://advances.realtimerendering.com/s2022/SIGGRAPH2022-Advances-Lumen-Wright%20et%20al.pdf

Virtual Geometry

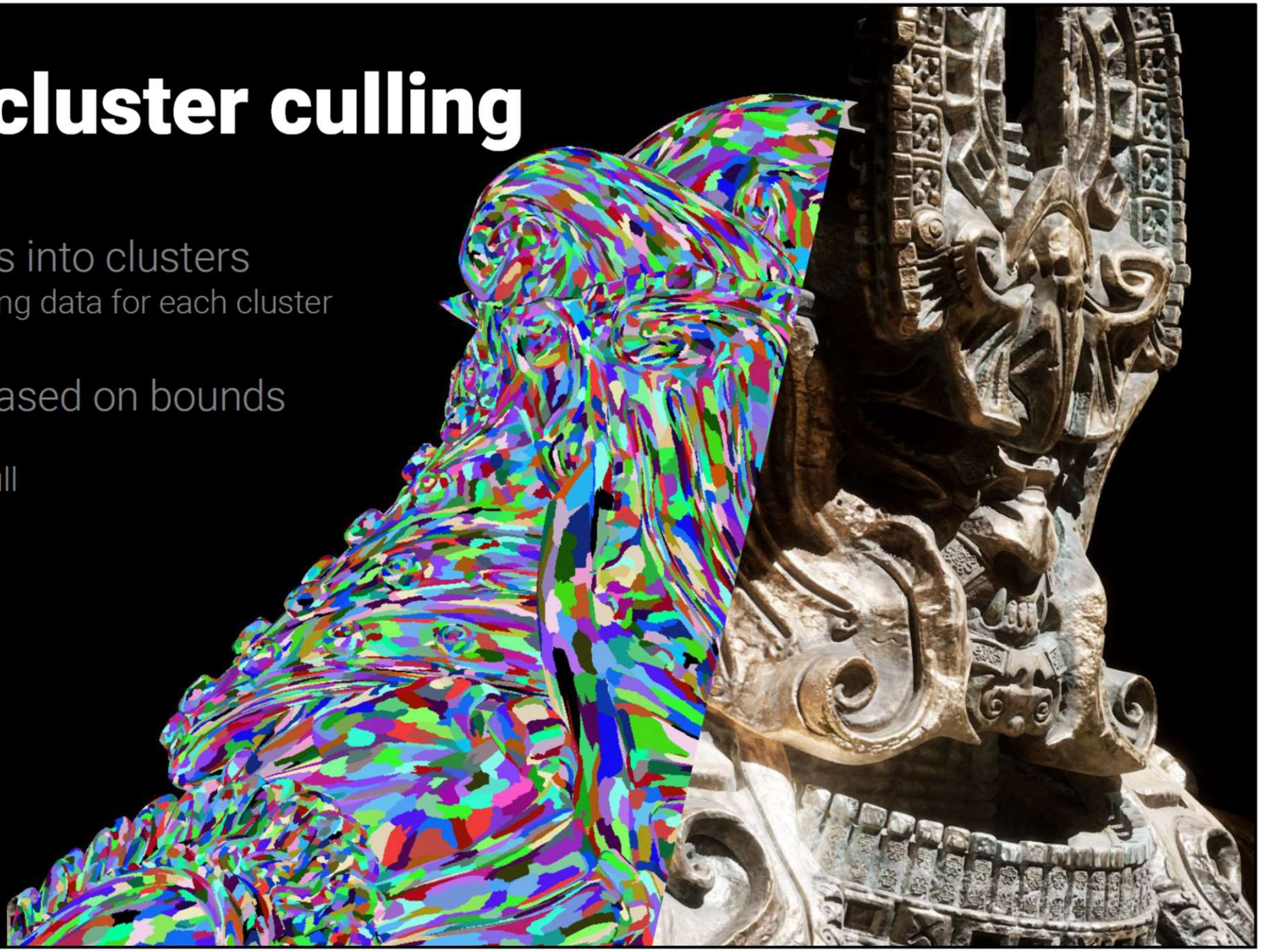
The Dream

- Virtualize geometry like we did textures
- No more budgets
    - Polycount
    - Draw calls
    - Memory
- Directly use film quality source art
    - No manual optimization required
- No loss in quality

Virtual Geometry

Triangle cluster culling

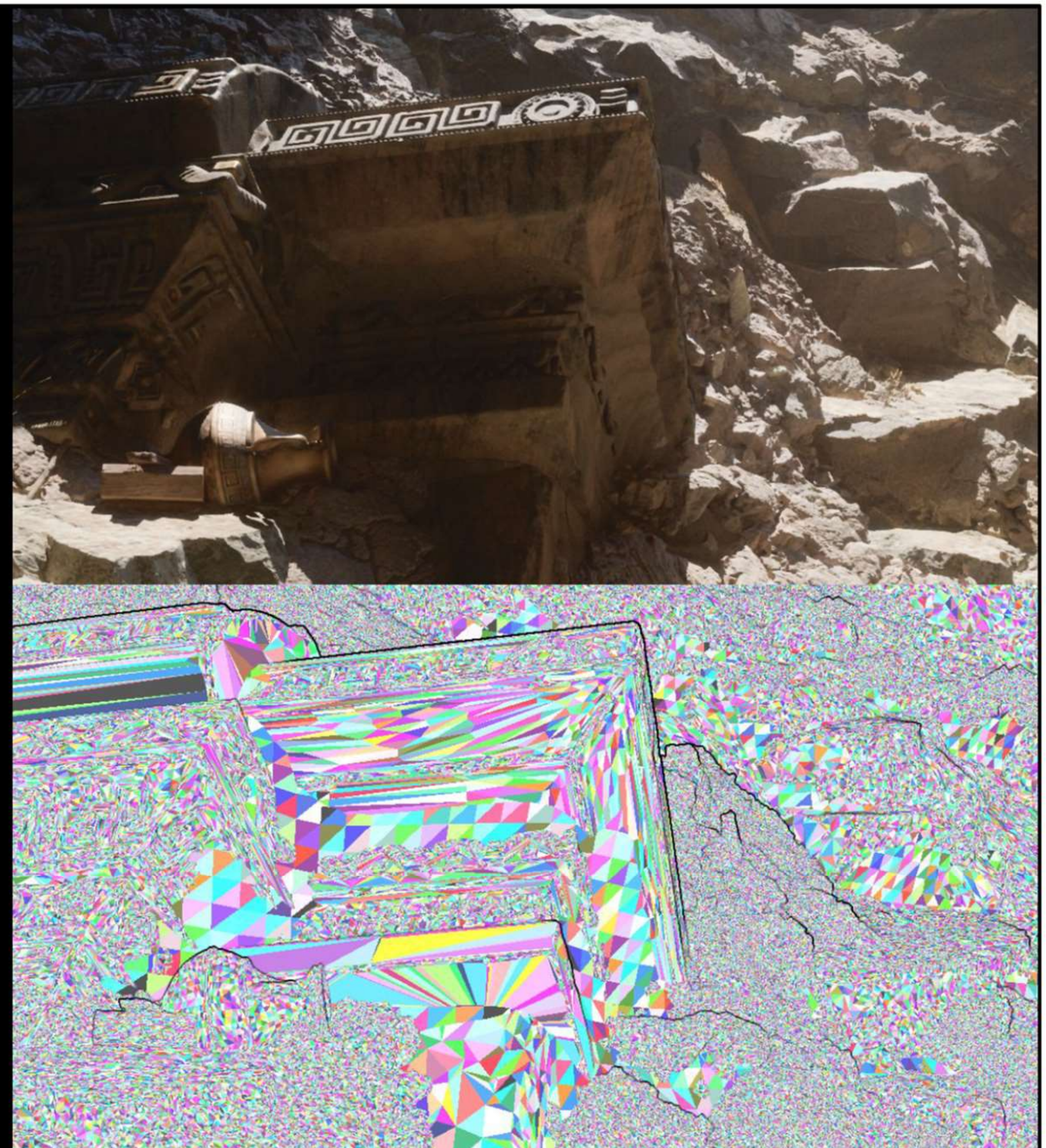
- Group triangles into clusters
  - Build bounding data for each cluster
- Cull clusters based on bounds
  - Frustum cull
  - Occlusion cull



Virtual Geometry

Pixel scale detail

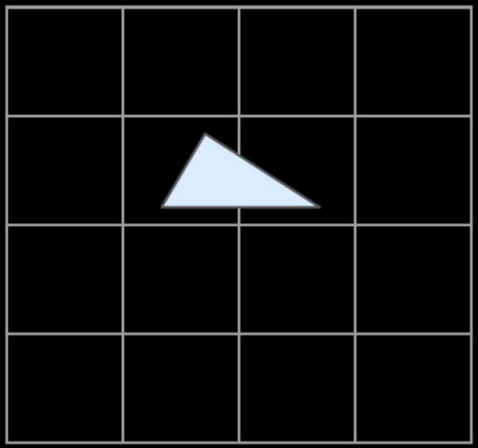
- Can we hit pixel scale detail with triangles > 1 pixel?
  - Depends how smooth
  - In general no
- We need to draw pixel sized triangles



SIGGRAPH 2021

Tiny triangles

- Terrible for typical rasterizer
- Typical rasterizer:
  - Macro tile binning
  - Micro tile 4x4
  - Output 2x2 pixel quads
  - Highly parallel in pixels not triangles
- Modern GPUs setup 4 tris/clock max
  - Outputting SV_PrimitiveID makes it even worse
- Can we beat the HW rasterizer in SW?

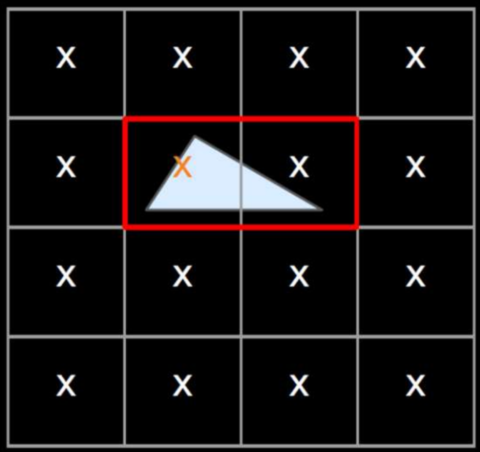


Software Rasterization

3x faster!

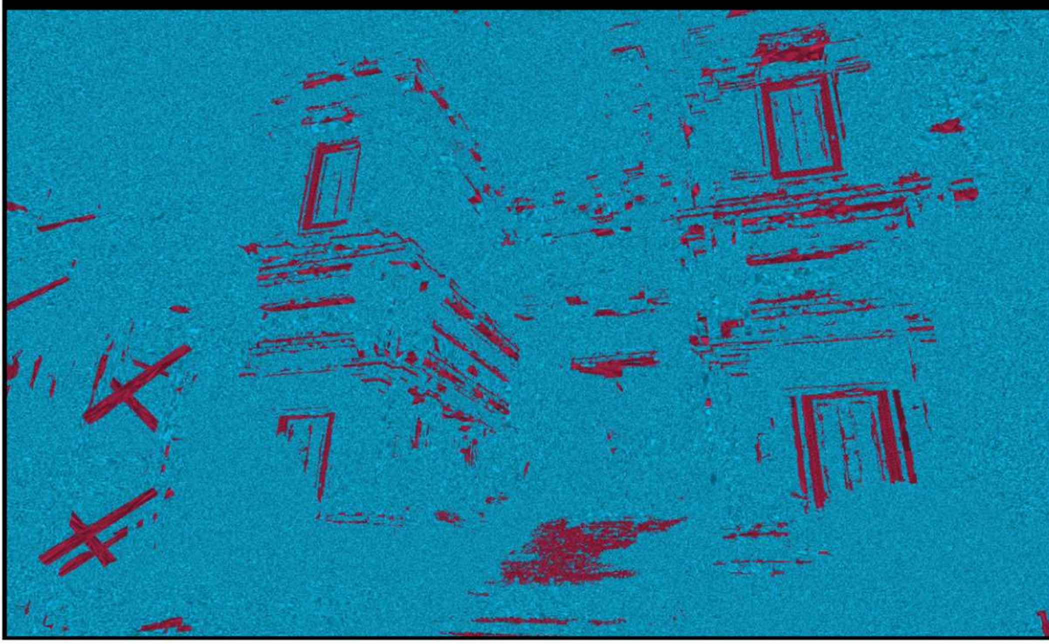
Micropoly software rasterizer

- 128 triangle clusters => threadgroup size 128
- 1 thread per vertex
  - Transform position
  - Store in groupshared
  - If more than 128 verts loop (max 2)
- 1 thread per triangle
  - Fetch indexes
  - Fetch transformed positions
  - Calculate edge equations and depth gradient
  - Calculate screen bounding rect
  - For all pixels in rect
    - If inside all edges then write pixel



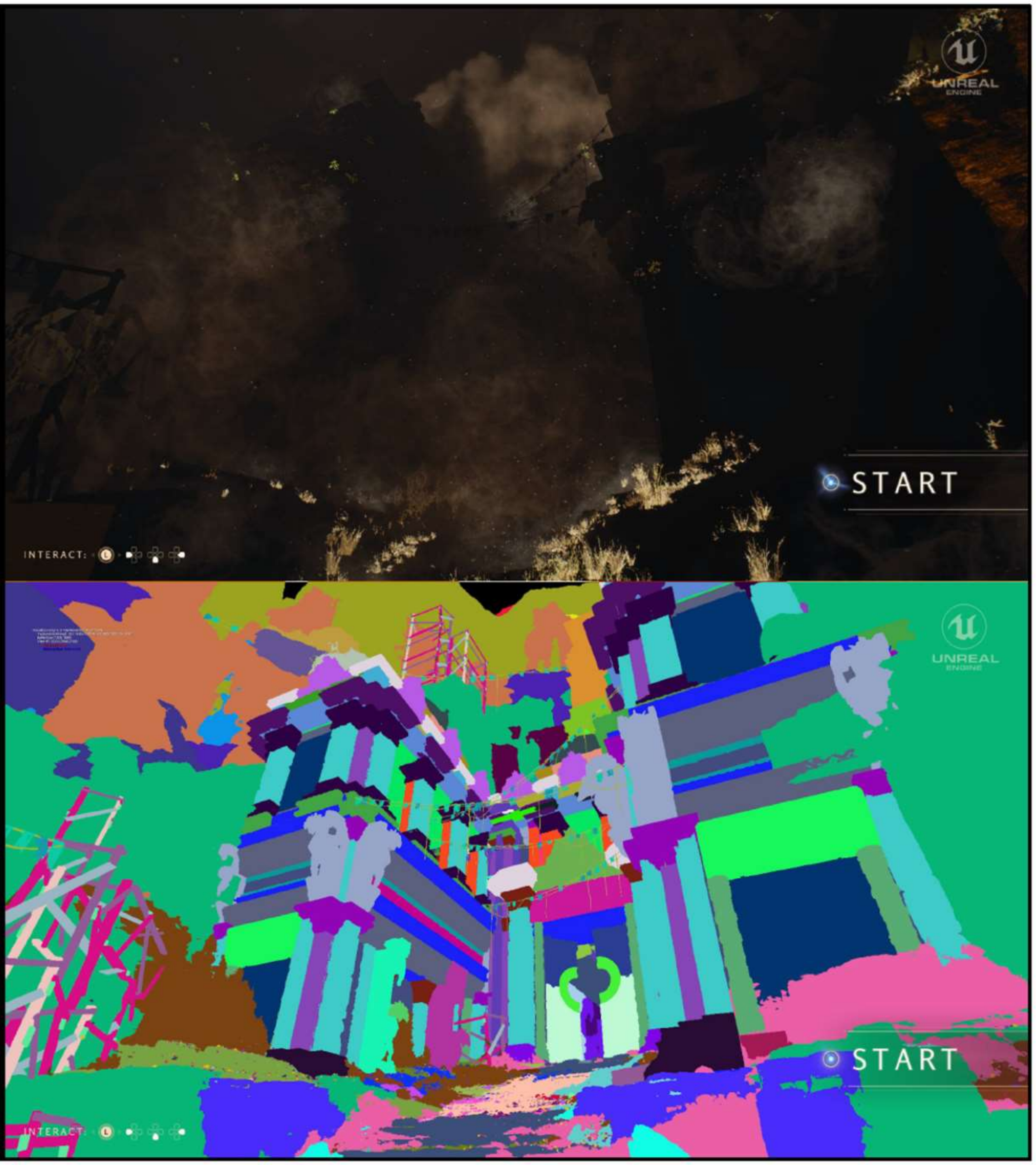
Hardware Rasterization

- What about big triangles?
  - Use HW rasterizer
- Choose SW or HW per cluster
- Also uses 64b atomic writes to UAV



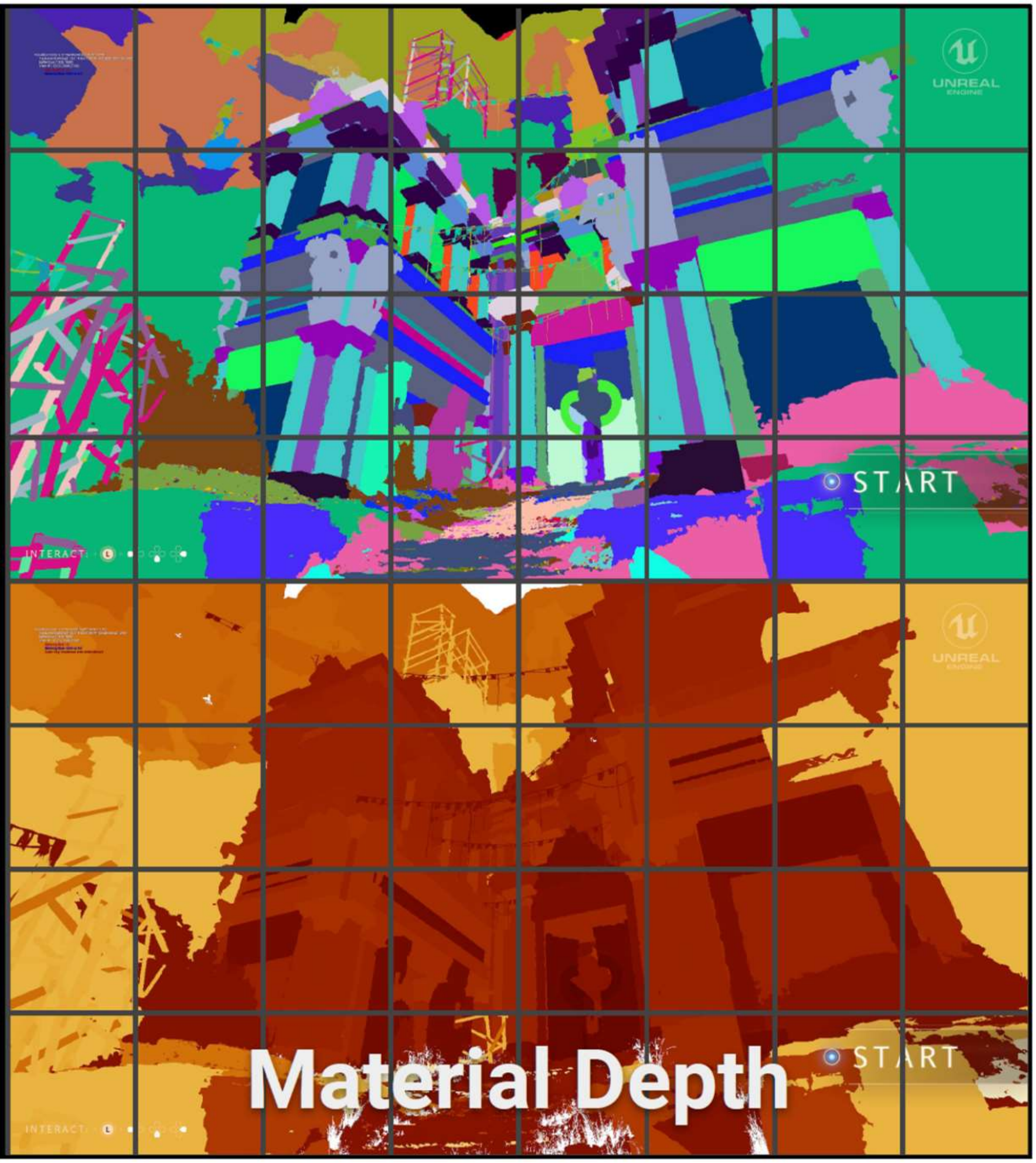
Material shading

- Full screen quad per unique material
- Skip pixels not matching this material ID
- CPU unaware if some materials have no visible pixels
  - Material draw calls issued regardless
  - Unfortunate side effect of GPU driven
- How to do efficiently?
  - Don't test every pixel for matching material ID for every material pass



Material culling

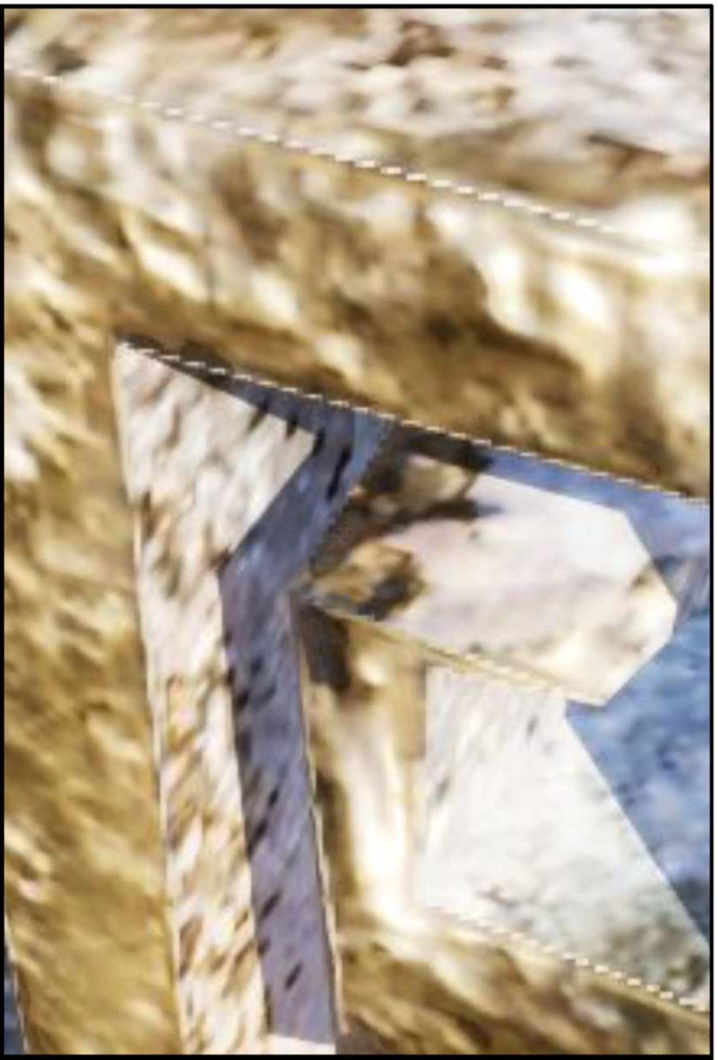
- Material covers small portion of the screen
  - HiZ handles this OK
  - We can do better
- Coarse tile classification / culling
  - Render 8x4 grid of tiles per material
  - Same shading approach as full screen quads
- Tile killed in vertex shader from 32b mask
  - X=NaN



UV derivatives

- Still a coherent pixel shader so we have finite difference derivatives
- Pixel quads span
  - Triangles ⇦ Good!
- Also span
  - Depth discontinuities
  - UV seams
  - Different objects

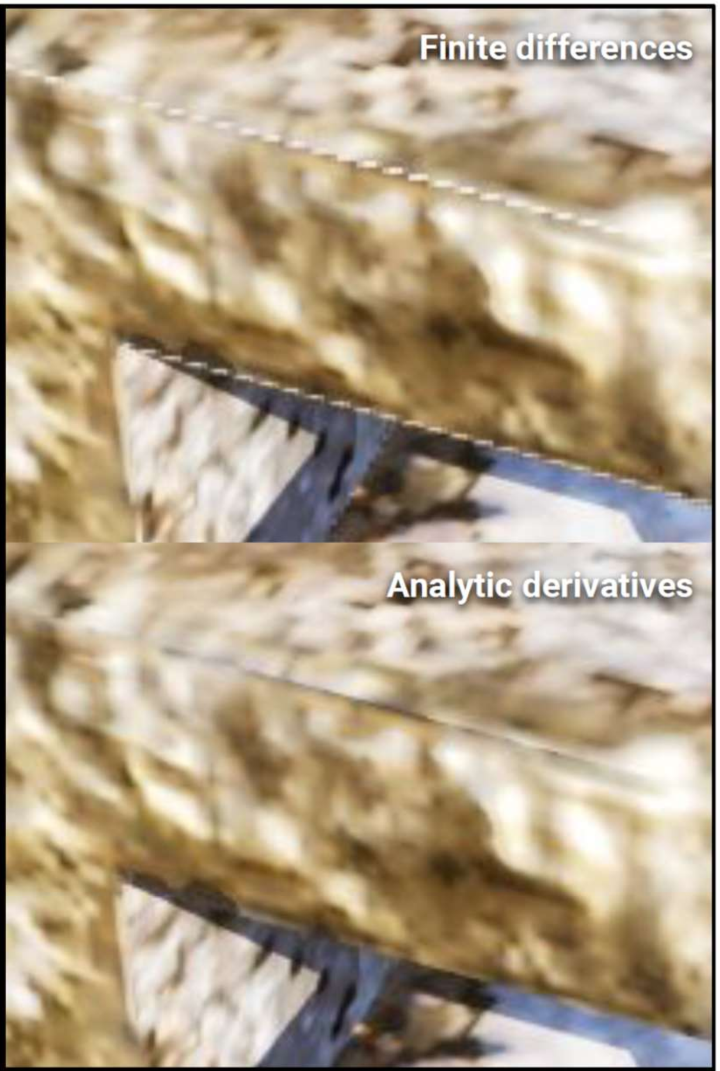
} Not good!



Analytic derivatives

- Compute analytic derivatives
  - Attribute gradient across triangle
- Propagate through material node graph using chain rule
- If derivative can't be evaluated analytically
  - Fall back to finite differences
- Used to sample textures with SampleGrad

- Additional cost tiny
  - <2% overhead for material pass
  - Only affects calculations that affect texture sampling
  - Virtual texturing code already does SampleGrad



Pipeline numbers

Main pass

Instances pre-cull	896322
Instances post-cull	3668
Cluster node visits	39274
Cluster candidates	1536794
Visible clusters SW	184828
Visible clusters HW	6686

Post pass

Instances pre-cull	102804
Instances post-cull	365
Cluster node visits	19139
Cluster candidates	458805
Visible clusters SW	7370
Visible clusters HW	536

Total rasterized

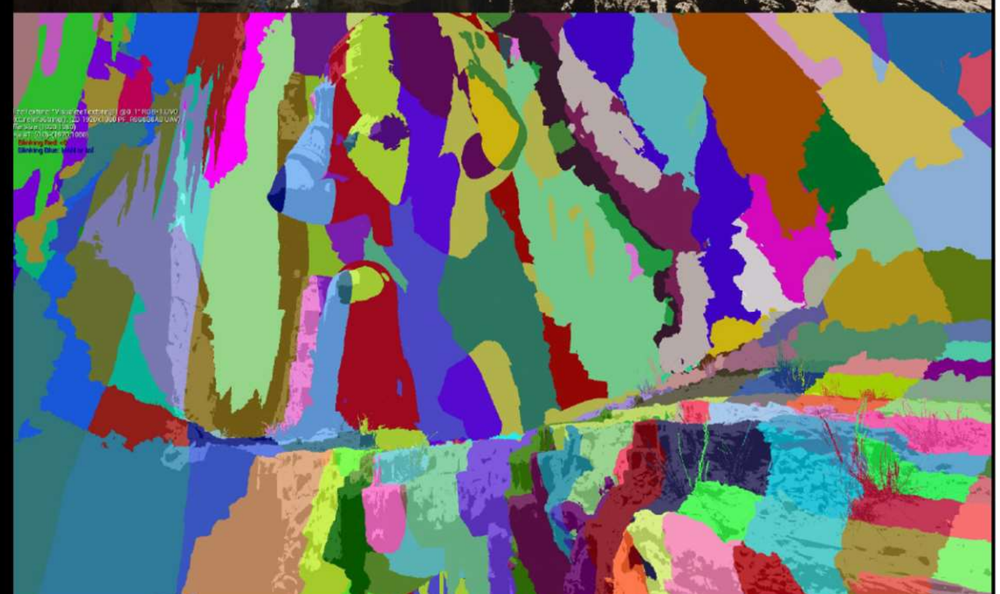
Clusters	199,420
Triangles	25,041,711
Vertices	19,851,262

Nanite shadows

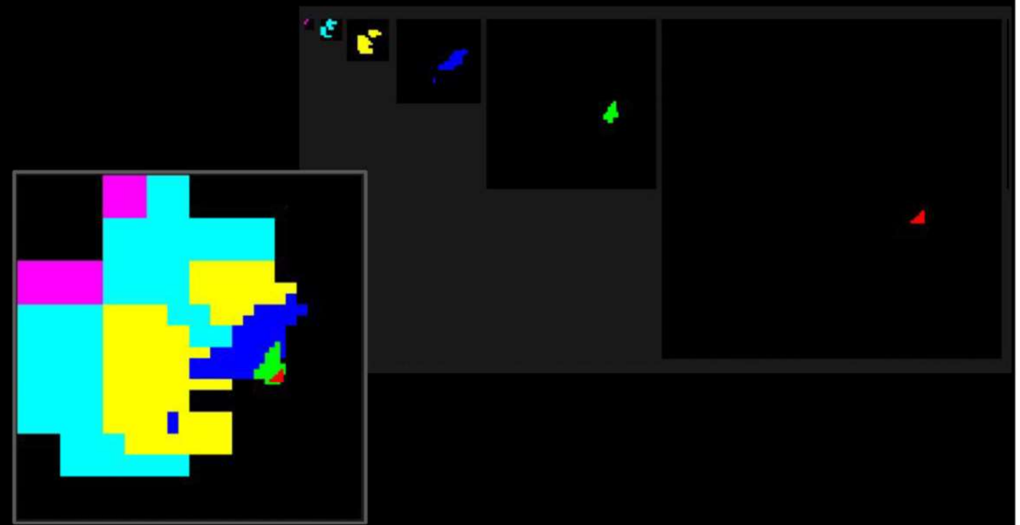
- Ray trace?
  - DXR isn't flexible enough
    - Complex LOD logic
    - Custom triangle encoding
    - No partial BVH updates
- Want a raster solution
  - Leverage all our other work
- Most lights don't move
  - Should cache as much as possible

Virtual shadow maps

- Nanite enables new techniques
- 16k x 16k shadow maps everywhere
    - Spot: 1x projection
    - Point: 6x cube
    - Directional: Nx clipmaps
- Pick mip level where 1 texel = 1 pixel
- Only render the shadow map pixels that are visible
- Nanite culled and LODed to the detail required



Virtual shadow maps



- Page size = 128 x 128
- Page table = 128 x 128, with mips

- Mark needed pages
  - Screen pixels project to shadow space
  - Pick mip level where 1 texel = 1 pixel
  - Mark that page

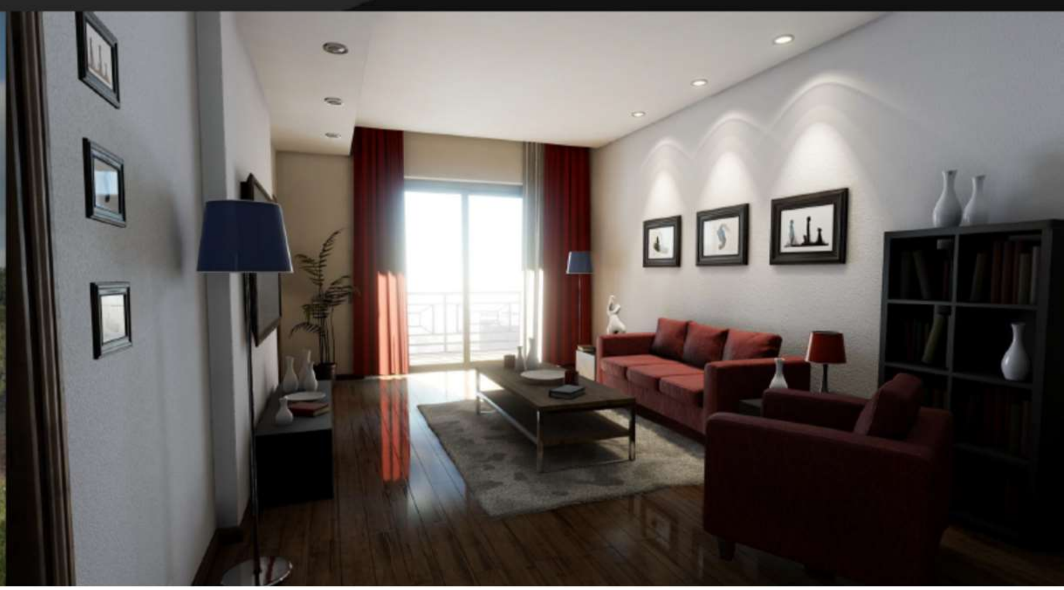
- Allocate physical pages for all needed

- If cached page already exists use that
  - And wasn't invalidated
  - Remove from needed page mask

Lumen: Fully Dynamic Global Illumination

The Dream - dynamic indirect lighting

- Unlock new ways for players to interact with game worlds
- Instant results for lighting artists
    - No more lighting builds
- Huge open worlds that couldn't have ever been baked
- Indoor quality comparable to baked lighting



MegaLights: Thousands of Light Sources

Thank you.