High Zombie Throughput in Modern Graphics

Anton Krupkin
CTO and Founder, Saber Interactive
Denis Sladkov
Lead Graphics Programmer, Saber Interactive

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World War Z

- 4-player cooperative 3rd-person shooter
- Massive zombie crowds
- Powered by Saber Engine
- XBox One / Playstation 4
  - 30 fps
  - Up to 4k dynamic resolution
- PC
  - DirectX 11 and Vulkan

Agenda

- Saber Engine render pipeline
  - High-level GPU workflow
  - Shading overview
  - Vulkan optimizations

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- Saber Engine render pipeline
  - High-level GPU workflow
  - Shading overview
  - Vulkan optimizations
- Zombies rendering
  - Close-up and mid-range characters
  - Far-plane swarm
  - Decals and gibbing

Saber Engine

WORLD WAR Z

QUAKE CHAMPIONS

HALO: THE MASTER CHIEF COLLECTION

HALO CE ANNIVERSARY

GOD MODE

R.I.P.D.

INVERSION

BATTLE LA

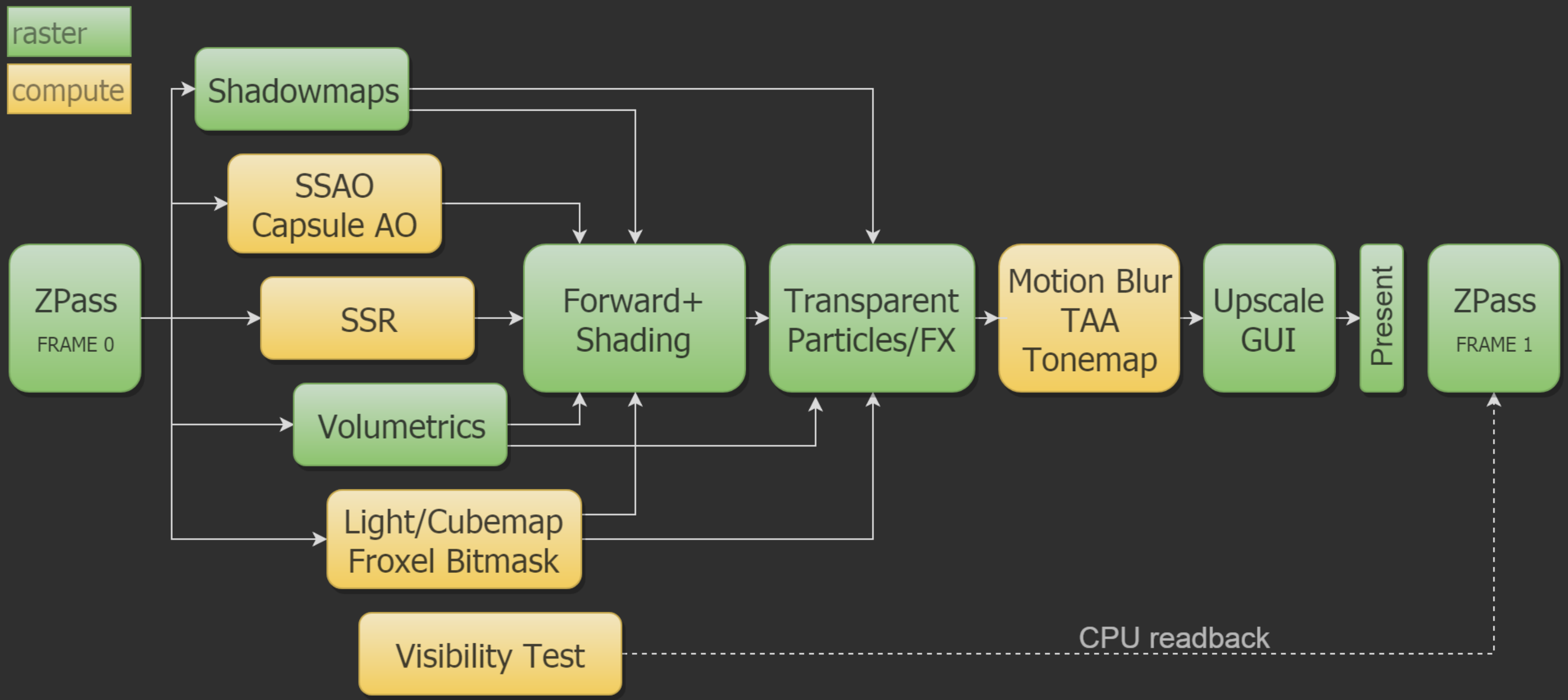
TIMESHIFT

WILL ROCK

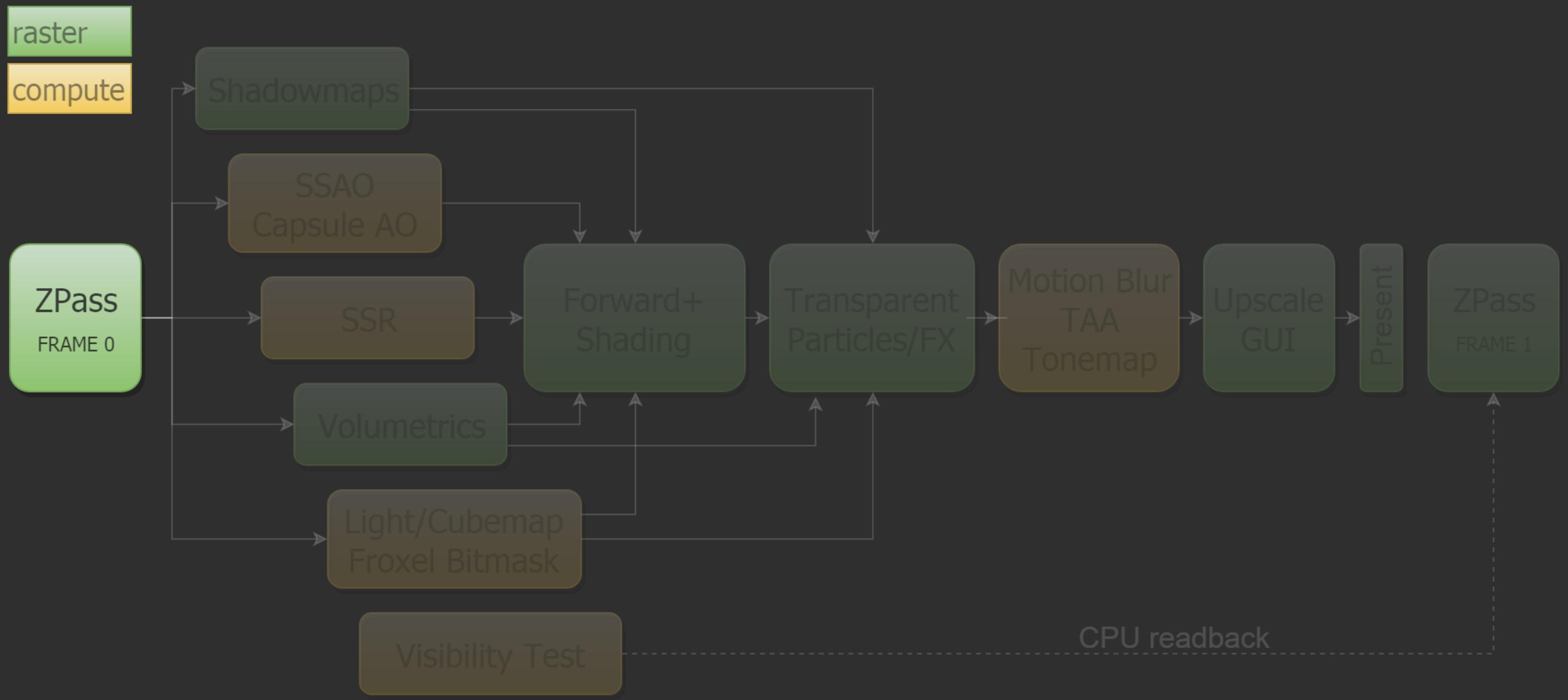
Saber Engine render pipeline

- GPU-driven visibility system
- Full depth prepass
- Forward+ PBR shading
- Baked GI: RNM + dominant direction
- 2 frames of latency
- Multithreaded command buffer recording

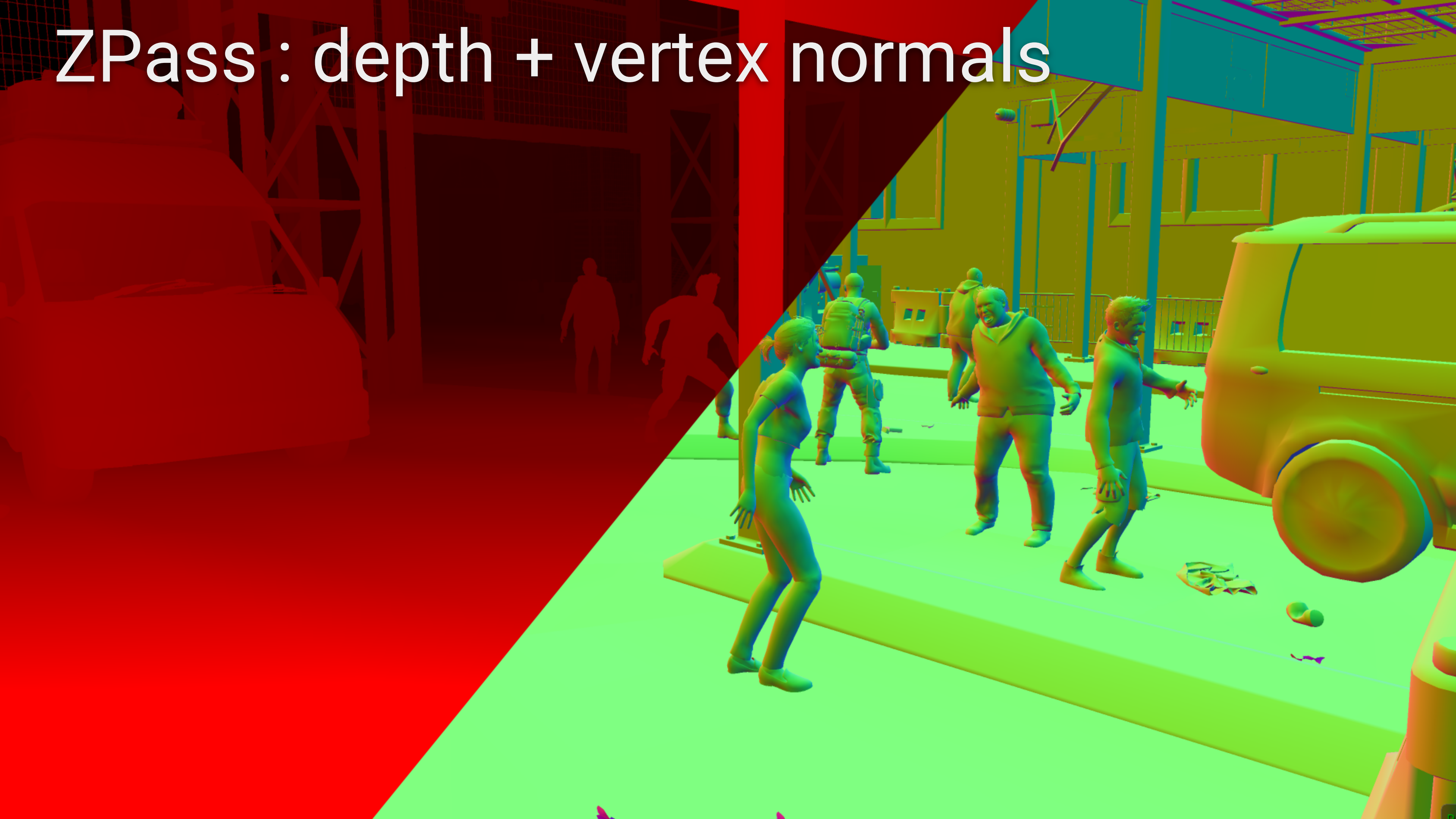
GPU Workflow



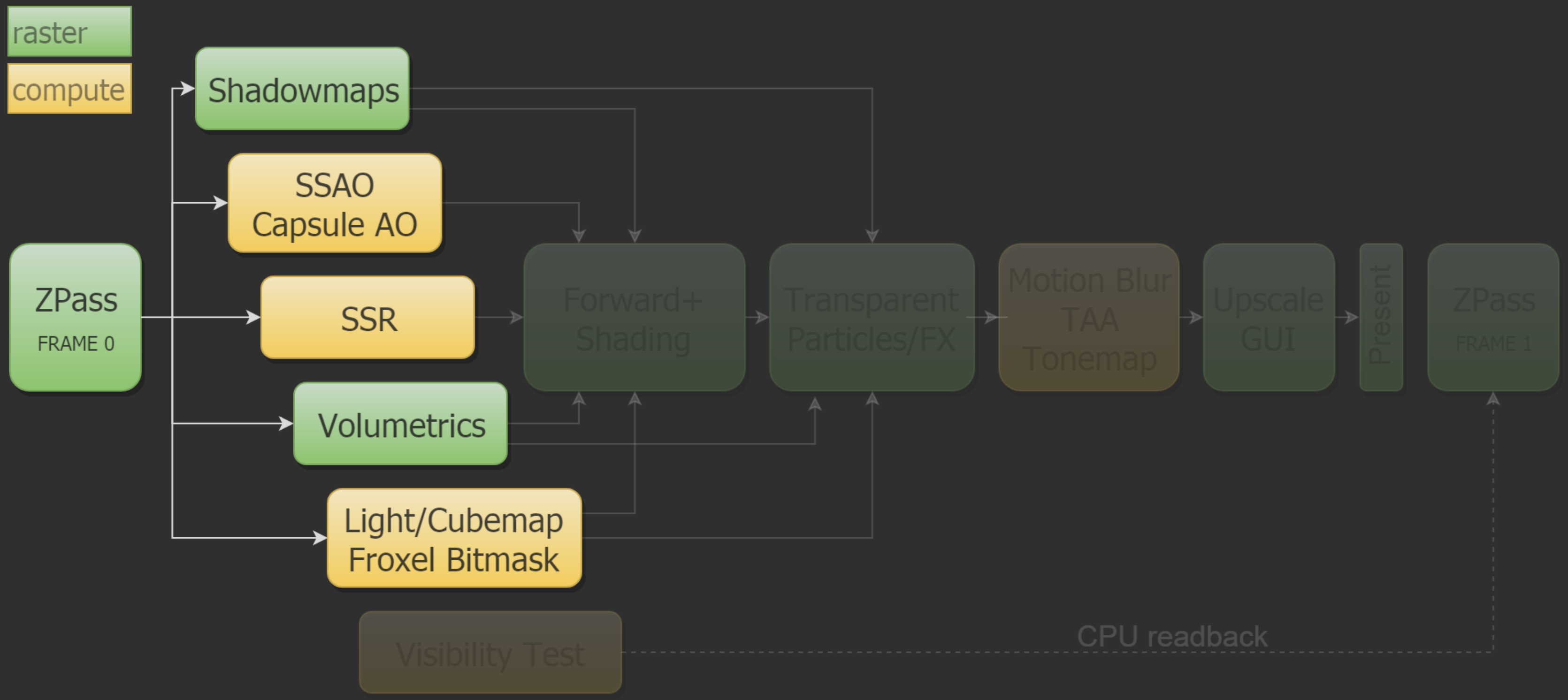
GPU: ZPass


raster
compute
ZPass
FRAME 0
Shadowmaps
SSAO
Capsule AO
SSR
Volumetrics
Light/Cubemap
Froxel Bitmask
Visibility Test
Forward+
Shading
Transparent
Particles/FX
Motion Blur
TAA
Tonemap
Upscale
GUI
Present
ZPass
FRAME 1
CPU readback

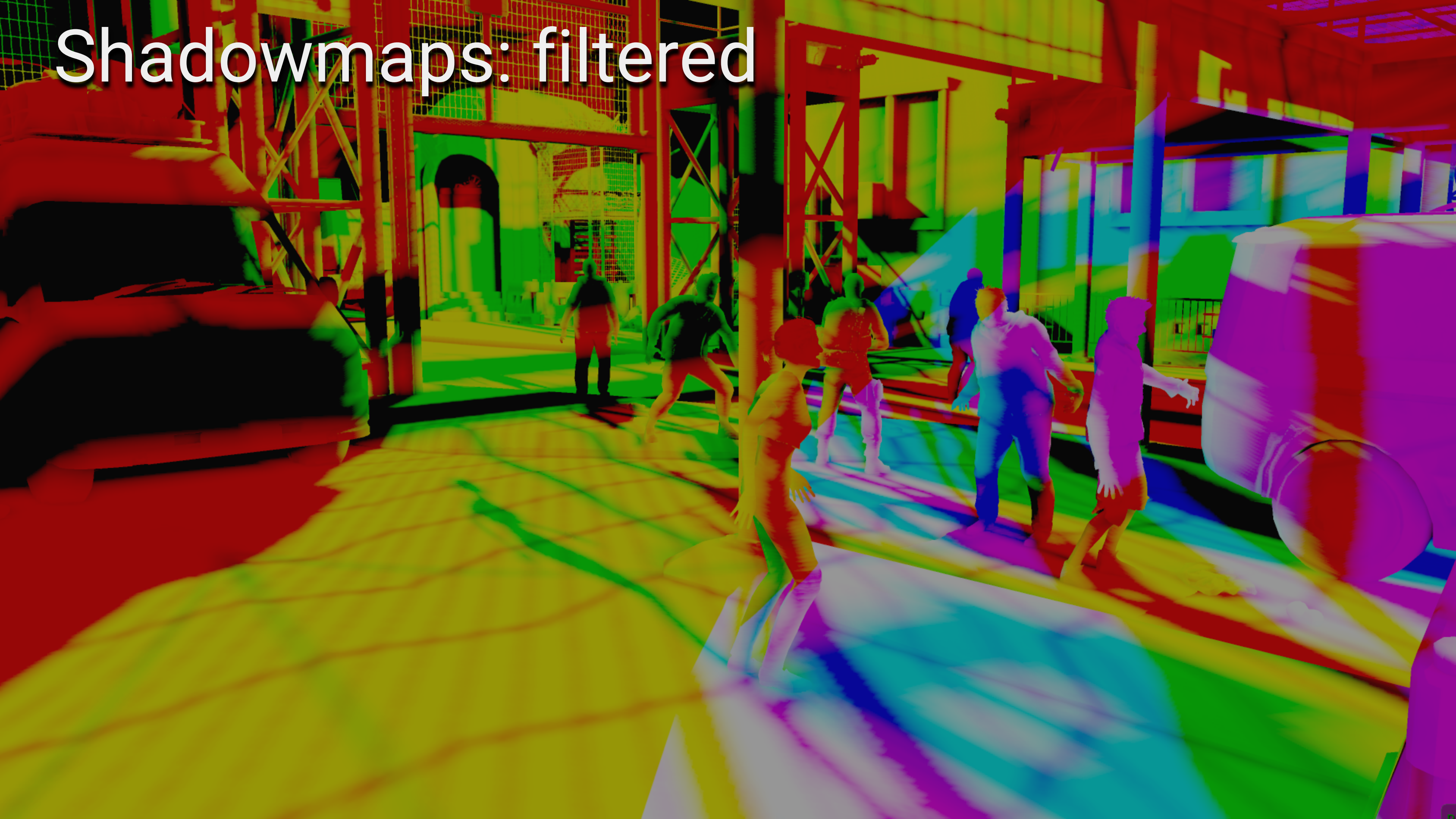
ZPass : depth + vertex normals



GPU: Pre-Shading



Shadowmaps: PCF only


Shadowmaps: filtered

Lighting: indirect

Lighting: indirect + direct

Occlusion: pre-baked with GI (stat scene)

Occlusion: SSAO

Occlusion: capsule AO + shadows [Iwanicki13]

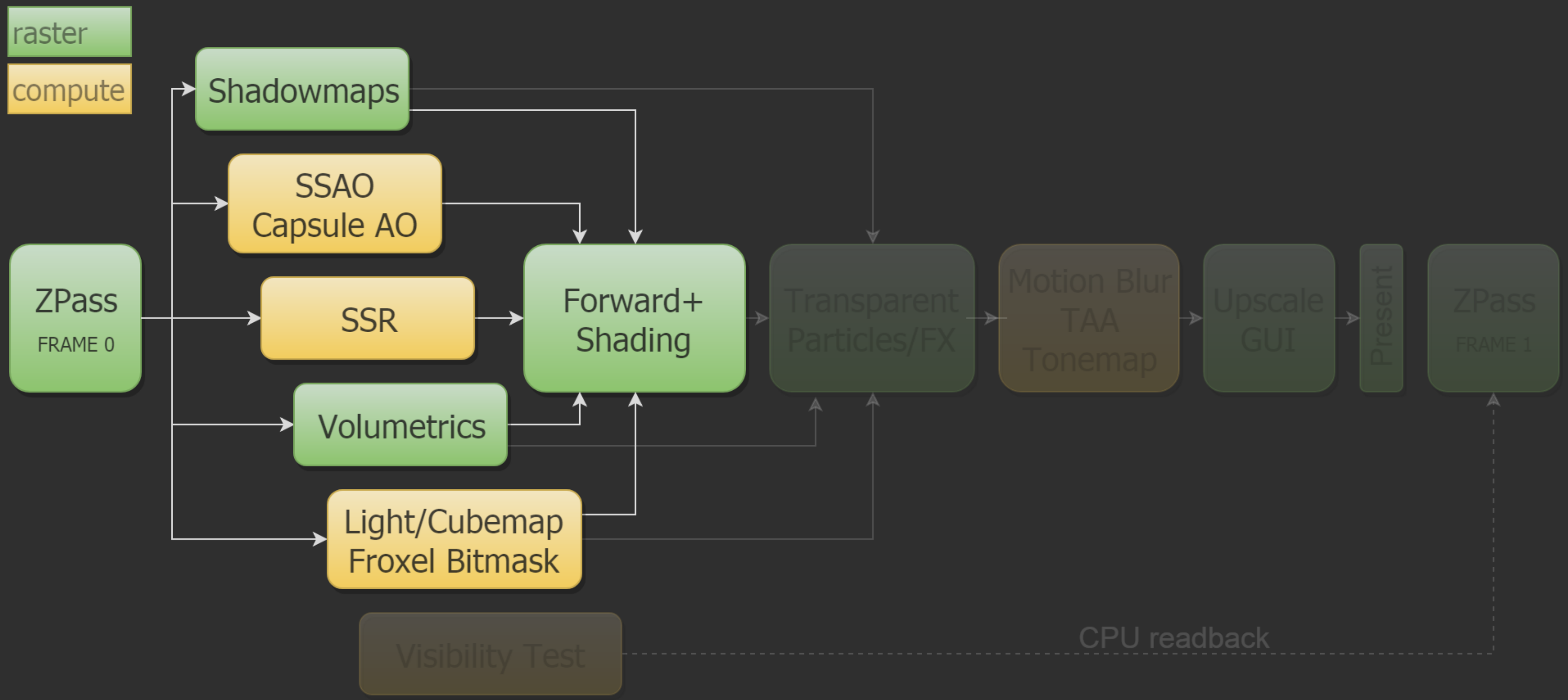
Reflections: off

Reflections: Cubemaps + SSR

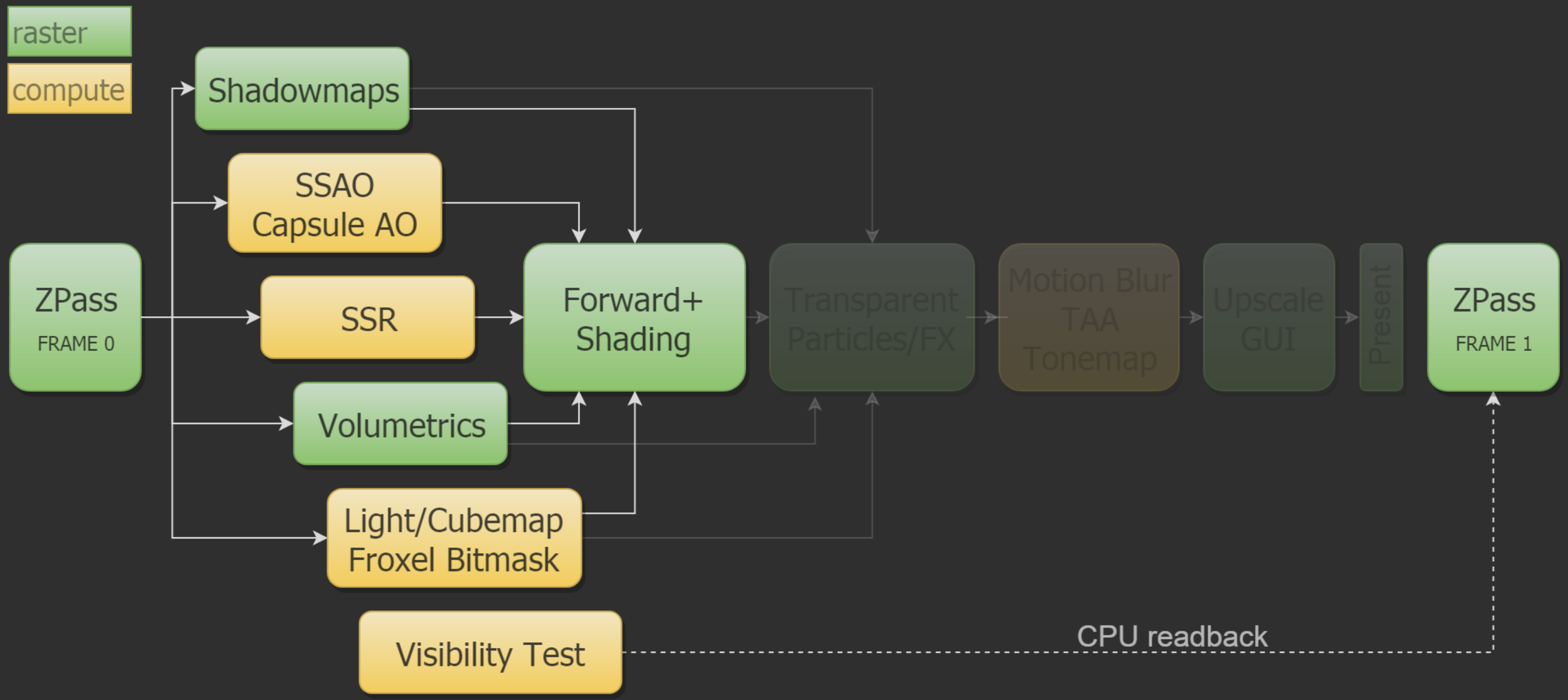
Volumetrics: off

Volumetrics: shadow light tracing [Glatzel14]

GPU: Forward+ Shading



GPU: Visibility Test



GPU Visibility system

- Based on “Practical, Dynamic Visibility for Games” [Hill11]
- Simple and efficient, no need for PVS/portals etc.
- Main camera: HZB occlusion culling with handmade occluders
- PSSM splits: frustum culling only
- 0.7ms (XBox One) GPU budget for scene with 100k+ objects
- Requires 1 frame of latency for CPU readback

GPU Visibility

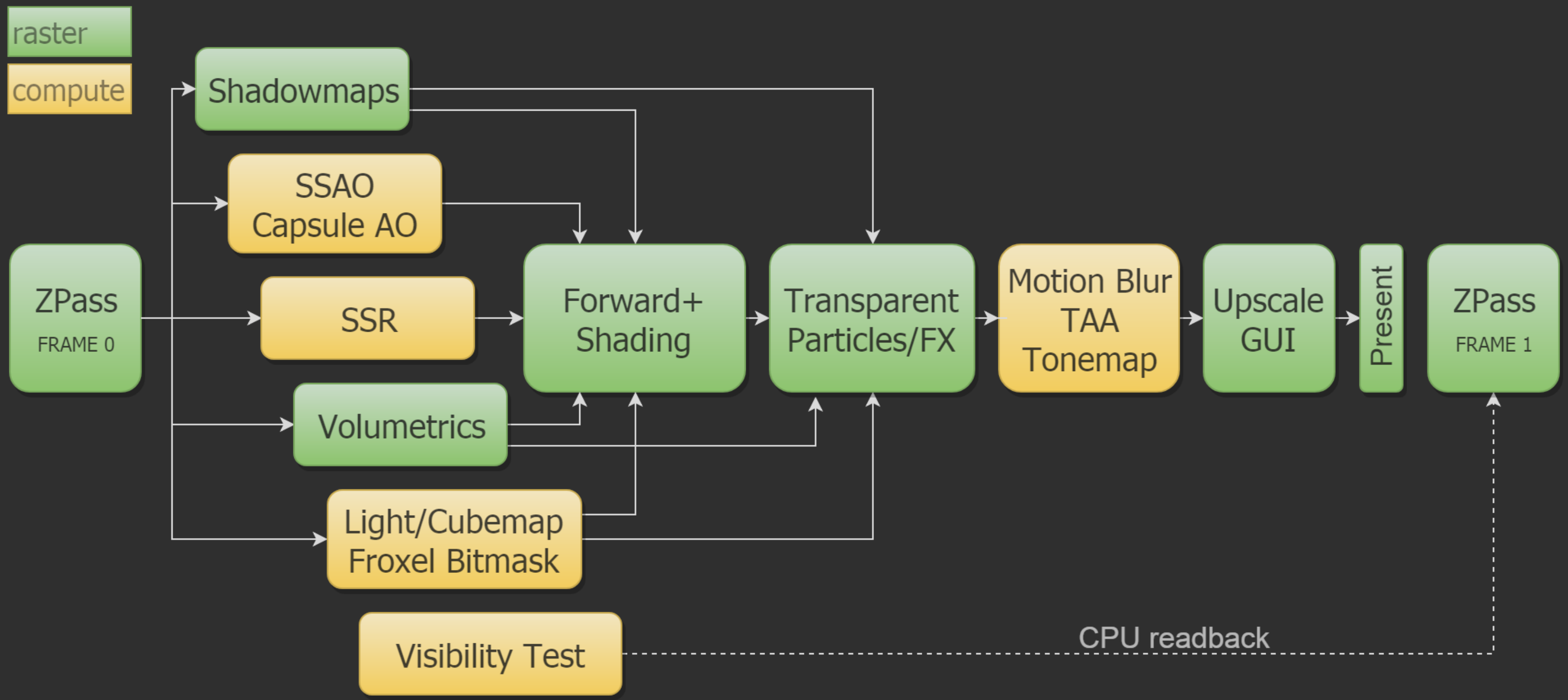

render_frame/__render_frame [time] : current: 12.024 peak: 13.334 average: 11.732
fps/fps [time] : current: 53.411 peak: 64.324 average: 55.838
GPU/IDLE (%) [time] : current: 51.919 peak: 56.285 average: 40.205
GPU/visibility HZB [time] : current: 0.009 peak: 0.551 average: 0.071
GPU/visibility Test [time] : current: 0.250 peak: 0.798 average: 0.307
GPU/visibility Test Camera [time] : current: 0.032 peak: 0.573 average: 0.090
GPU/visibility Test Copy Result [time] : current: 0.070 peak: 0.147 average: 0.033
GPU/visibility Downsample [time] : current: 0.020 peak: 0.020 average: 0.017
GPU Visibility: occluders

GPU Visibility: culling efficiency

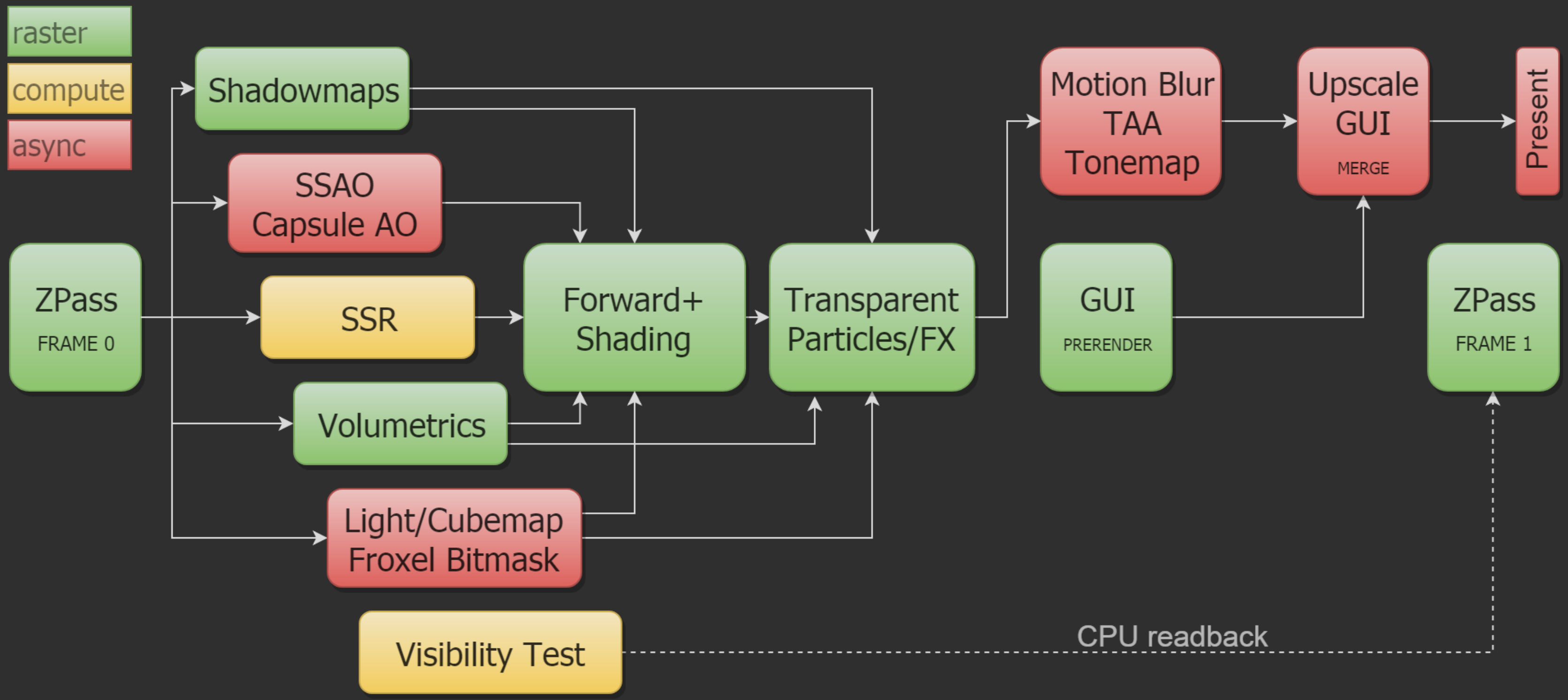
[redacted]

GPU Visibility: culling efficiency

GPU: Direct3D11



GPU: Vulkan Async Compute



Vulkan vs D3D11

- Up to 10% less GPU time
  - Wave intrinsics (GL_KHR_shader_subgroup)
    - Forward+ lighting / reflection loops scalarization in shading pass
  - Async compute
  - Half-precision math
- No helper driver thread: 40% less total rendering CPU load
- 20% reduction of CPU critical path due to MT command buffers
- Render target memory aliasing
  - 30% less memory
  - Dynamic resolution

Zombies rendering

Zombies rendering

- Over 5k visible zombies per-frame
- Most are non-interactive background swarm
- 300+ foreground “real” ingame entities/characters
- Only 50 have fully developed zombie brains
- Instancing was used to reduce draw call pressure
- Flexible per-instance visual customization system
  - Inspired by “Shading a bigger, better sequel” [Grimes10]

300+ foreground characters

Customization: meshes

- 3 base archetypes / skeletons
  - Male / Female / ‘Big’ male
  - ~50 bones per skeleton
- 4 mesh regions per archetype
  - Legs / Torso / Head / Hair
  - 2-5k tris per region
- 4-8 mesh variations for each region
- 70+ unique mesh combinations total
  - Plus ~10 additional unique zombie models (chemical, screamer, etc...)

Customization: male archetype meshes

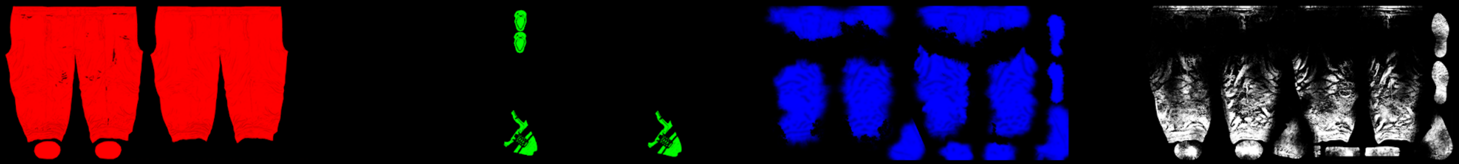
Customization: color and stain masks

- For each mesh region (shirts / jeans / shoes / hair)
  - Color masking texture (ARGB8 texture, low-res)
  - Stain masking texture (ARGB8 texture, low-res)
- Shared stain texture set (bloodstains / snow / dust)
  - Albedo / normals / roughness textures
  - All textures are tiled
  - Stored as texture array
- Per-instance constants
  - Color : Channel mask + solid color
  - Stain : Channel mask + texture array index

Customization: color and stain masks

TORSO MASK :

LEGS MASK :



Customization: hundreds distinct looks

Zombie rendering: instancing

- Get individual zombies from visibility system
- Gather identical meshes into instancing buckets
  - Same mesh variation for one region going into one bucket
  - Different LOD models going to separate buckets
- Process accumulated buckets into render queue
  - Sort bucket by visibility mask (each active camera has it’s own bit)
  - Gather meshes with the same visibility mask into batches (30 meshes max)
  - For each batch fill continuous constant buffer with per-instance data
  - Generate 1 draw call per batch for every pass/camera (Z, SM, shading)

Zombie rendering: sample workload

- LOD 0 (8 meters): 10 zombies, ~130k tris, 500 bones, 26 dp, 140k cb
  - 6 unique heads, 8 torsos, 6 legs, 6 hairs = 26 draw prims calls (vs 40)
  - 50 bones x 2 frames + customization = 100kb of per-instance consts
  - Per-draw call material constants: 40kb
- LOD 1 (14 m): 30 zombies, ~180k tris, 1500 bones, 38 dp, 520k cb
- LOD 2 (25 m): 70 zombies, ~175k tris, 2800 bones, 46 dp, 1120k cb
- LOD 3 (35 m): 100 zombies, ~115k tris, 2600 bones, 61 dp, 1250k cb
- LOD 4 (>35m): 100 zombies, ~25k tris, 2600 bones, 52 dp, 1130k cb
- Total: 223 draw calls (vs 1240), 625k tris, ~4mb of const buffer data
- 2.5ms x 6 threads CPU to generate ~1000 draw calls (Z, SM, Shading)

Zombie rendering: background swarm

Zombie rendering: background swarm

- Over 5k zombies
  - Non-interactive: essentially just a GPU-driven animation
  - 8 pre-baked variations total: 2 mesh types x 4 unique appearances
  - ~400 triangles per mesh
- Inspired by “The Technical Art of Uncharted 4” [Maximov16]
- Utilize existing grass rendering solution
- Add texture-baked vertex animation
- Move alongside pre-modeled tracks

Swarm: grass rendering solution

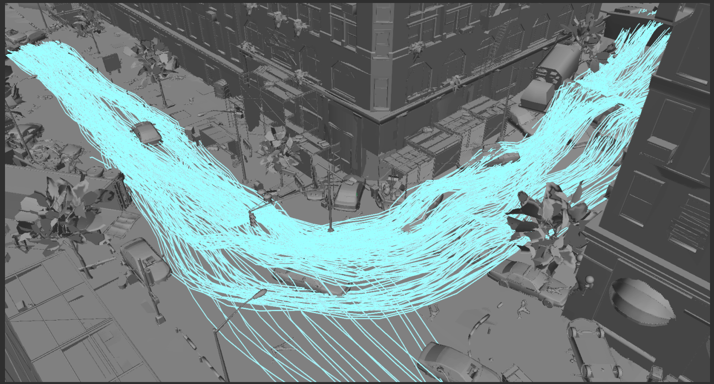
- Zombies are authored as grass blades
- Blades are distributed with ‘seed brush’ over level geometry
- Same blades spatially merged into ‘containers’
- Each container has
  - Per-blade instancing data
    - Position + orientation
    - Indirect lighting (sampled from underlying LM)
    - Seed for procedural animation and track selection
  - OBB for visibility culling / LOD calculations
  - Single draw call to render all blades

Swarm: baked vertex animation

- Just a single ‘running’ animation for each of 2 zombie types
- Stored as per-frame per-vertex offset + normal
- Baked in two 32-bit textures:
    - Offsets from default model - quantized to 8 bit using model’s AABB
    - Object-space normals stored as is
- VS: Sampled with UV = (vertex_id, frame_number)

Swarm: movement tracks

- Designers lay tracks for a running swarm
- Each track is authored as a spline
- Each track converted to an array of 16 bit fixed point positions
- Whole set of tracks stored as single 2D INT16 texture
- VS: Sampled with UV = (elapsed_time, track_index)




HELP!

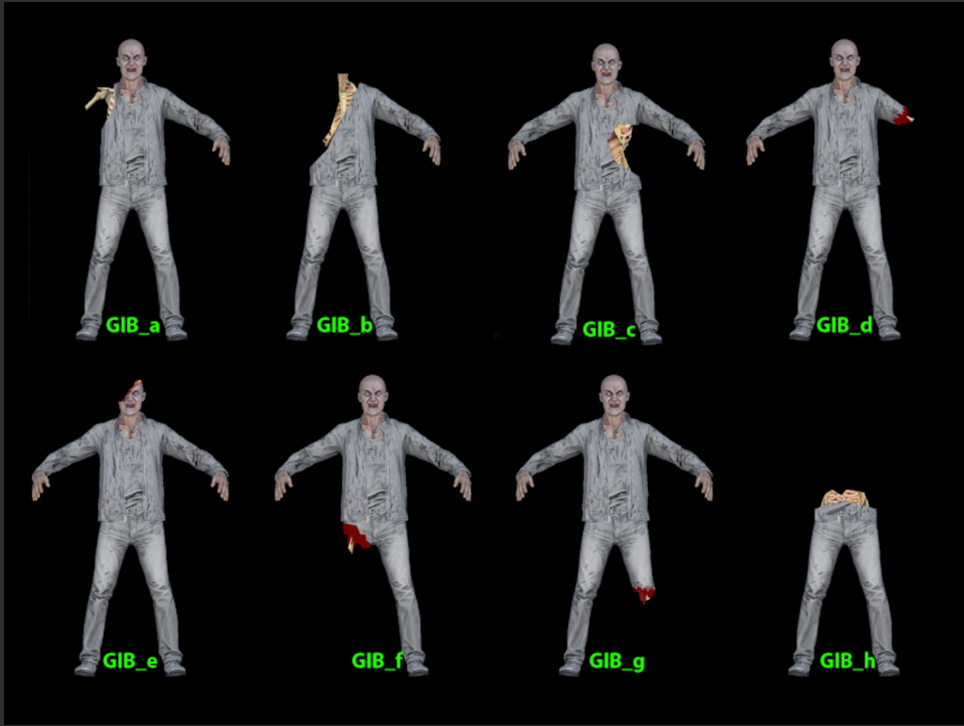
Gibbing & decals

Gibbing & decals

- Hide triangles in wounded regions using vertex masks
- Unhide parts of pre-modeled gore meshes
- Add decals for better mesh - gore mesh stitching
- Based on “Rendering wounds in Left 4 Dead 2” [Vlachos10]

Gibbing: region vertex masking

- Define mesh regions to be hidden during gibbing
  - Use original mesh tessellation
- Store per-vertex 32-bit mask
  - 1 bit per region, 32 regions max
- Split the edges on region's border
- Define per-instance 32-bit mask
  - Zero bits for gibbed regions
- VS: hide masked triangles
  - M_{vert} & M_{inst} == 0 -> zero-area tri




Gib meshes

Decal system

- Transform damage origin to model bind pose (inverse skinning) and store it
- Pass bind pose vertices from VS to PS
- PS: loop and apply decals before lighting
  - Planar projection with angle fade-factor
  - Simple blend mode
  - Albedo + normal + roughness / metalness
  - 16 decals max

References

[Grimes10] “Shading a bigger, better sequel”, Bronwen Grimes, GDC 2010

[Vlachos10] “Rendering wounds in Left 4 Dead 2”, Alex Vlachos, GDC 2010

[Hill11] “Dynamic Visibility for Games”, Stephen Hill and Daniel Collin, GPU Pro 2

[Iwanicki13] “Lighting Technology of The Last of Us”, Michal Iwanicki, Siggraph 2013

[Glatzel14] “Volumetric Lighting for Many Lights in Lords of the Fallen”, Benjamin Glatzel, Digital Dragons, 2014

[Maximov16] “The Technical Art of Uncharted 4”, Andrew Maximov and Waylon Brinck, Siggraph 2016

Thanks

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- Dmitry Zaborovsky
- Ivan Shostak
- Ivan Popov
- Timur Popov
- Anton Vasilev

Questions?

krupkin@saber3d.com

sladkoff@saber3d.com

Bonus slides

GPU Visibility system : input

- Immutable UAV buffer for stat scene
  - 2-level world space OBB hierarchy
- Semi-dynamic UAV buffer for moveable objects
  - Allocated on-demand via free list
  - Occasional per-element OBB update
  - Used for any type of objects: characters/lights/volumetrics etc.
- List of cameras
  - Frustum + set of control / filter flags
  - Includes main camera and any number of dependent cameras (SM)

GPU Visibility system : HZB

- Render occluders to fixed resolution depth (512x256)
  - About 10k triangles total - really low res occluders
  - Several dozen draw calls - occluders merged and frustum-culled on CPU
- Build HZB - conservative depth mip hierarchy down to 2x2
- OBB occlusion test
  - Calculate bbox screen-space extents
  - Choose appropriate HZB level (2x2 pixels bbox coverage)
  - Cull by OBB min depth
  - Subpixel culling

GPU Visibility system : tests

- Camera specific set of tests
- Frustum vs OBB (all cameras)
- Occlusion (main camera only)
- Distance / screen-space area (SM cameras)
- Object state vs camera state (LoDs, reflection camera)

GPU Visibility system : output

- Per-object cam mask & distance list
- Hierarchical merge stage (2-level hierarchy for stat scene)
- Per-camera, per-object type append buffer with object IDs
- CPU readback
- Object ID list used as direct input for CPU render jobs
    - ZPass / Shadowmap
    - Volumetrics / Dynamic lights / Reflection probes

GPU Visibility: drawbacks

- 1 frame of latency for CPU readback
- Manual occluder authoring
- 2 frames of latency for SM tests in case of light culling test