
Raytraced Shadows
in
Call of Duty: Modern Warfare
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Agenda

- Agenda:
  - Background
  - Acceleration structures
  - Raytracing
  - Denoising
- All timings for NVIDIA RTX 2070 @ 1440p

- Here is our agenda for today.
- We will start by describing the motivation behind raytracing, and why we chose shadows.
- Next, we want to walk you through some problems we encountered during development. Some of those are specific to our title, but we mostly want to focus on general problems that most people will encounter when doing raytracing, and give you solutions that worked for us and that hopefully will work for you as well.
- Those topics include raytracing in general (from shader perspective), how to feed it with optimal data and how to denoise multiple lights per pixel at the same time.
- Any timings given during this presentation were collected on NVIDIA RTX 2070 at 1440p.

Background

Background

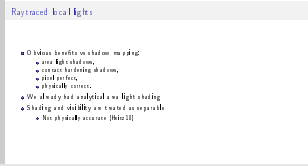
Background

- Beginning of our raytracing R&D
- Let's start with basics!
- Visibility only
- Shadows for local lights - easiest?
- Separate acceleration structures per light
  - keeps performance problems local

- For the start of our DXR adventure, we wanted to keep things simple.
- We felt that sticking to visibility only algorithms will save us a lot of time, since we don't have to care about shading.
- This left 3 main candidates: ambient occlusion, sun shadows and local light shadows.
- We picked local lights, since we thought using per-light acceleration structures will help us deliver better performance, by keeping acceleration structures small, and any problems will be easier to contain. As it later turned out, this greatly helped with achieving high raytrace performance.

Raytraced local lights

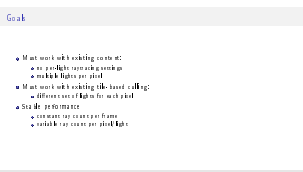
- Obvious benefits vs shadow mapping:
  - area light shadows,
  - contact hardening shadows,
  - pixel perfect,
  - physically correct.
- We already had analytical area light shading
- Shading and visibility are treated as separable
  - Not physically accurate [Heitz18]



- Unlike a hacky approximation provided by shadow maps, raytraced shadows are physically correct and give multiple immediately visible improvements.
- Since we already had proper shading for area lights, inconsistencies with shadow maps were even more obvious.
- Unfortunately, to keeps things managable, we had to operate under assumption that visibility and shading are separable, which isn't true. However, raytraced shadows still provide vastly improved visuals.

Goals

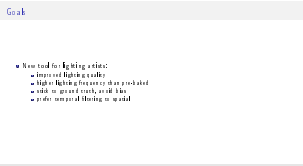
- Must work with existing content:
  - no per-light raytracing settings
  - multiple lights per pixel
- Must work with existing tile-based culling:
  - different set of lights for each pixel
- Stable performance
  - constant ray count per frame
  - variable ray count per pixel/light



- We started our work after most maps were created, so we had to make sure raytracing will work without having to redo lighting for those maps.
- That meant no specific raytracing settings in editor, just use exisiting physical lights sizes.
- We also had to make sure that we handle multiple lights - we have a limit of 256 lights per frame, and each pixel can have different set of lights. Even if there are many overlapping, they cannot flicker or disappear.
- We care about predictability of the frame time, so we want to keep raytracing execution time constant, while allowing for picture quality to scale depending on load.

Goals

- New tool for lighting artists:
  - improved lighting quality
  - higher lighting frequency than pre-baked
  - stick to ground truth, avoid bias
  - prefer temporal filtering to spatial



- We wanted to evaluate quality improvements given by area shadows. Evaluating them at real-time gives much higher frequency detail than what we can store in lightmaps (due to storage concerns).
- For this purpose we wanted to avoid aggressive spatial filters, because they usually need to have a big radius, which adds bias (especially when traycing in lower than native resolution) - we chose to rely mainly on temporal accumulation.

Raytraced Shadows in Call of Duty: Modern Warfare

So how do we go from this...

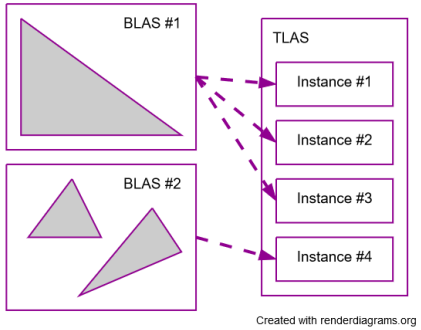
to this - without killing performance?

Acceleration structures

Acceleration structures

Acceleration structures

- Bottom/top level (BLAS/TLAS)
- Separation necessary to amortize build times
- TLAS sees BLAS only as it's top-level bounding box

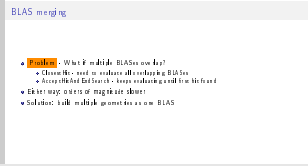


Acceleration structures
- Bottom/top level (BLAS/TLAS)
- Separation necessary to amortize build times
- TLAS sees BLAS only as it's top-level bounding box

- There are two levels of acceleration structures in DirectX Raytracing API.
- Ideally, we would build one AS for the whole scene. However, for real-time purposes AS build times are non-negligible.
- So we usually build individual surfaces as separate BLASes and join them together in one big TLAS (or in our case, multiple TLASes).
- This way we have reasonable granularity - individual BLAS build times and sizes are managable, they can be amortized between frames and removed after source meshes are streamed out.
- However, too naive approach can have significant performance implications. During TLAS building, the TLAS does not have access to insides of BLAS, it just sees its bounding box.
- This degree of separation is necessary, TLAS build times have to be kept on the low side, since they are rebuild every frame.

BLAS merging

- Problem - What if multiple BLASes overlap?
  - ClosestHit - need to evaluate all overlapping BLASes
  - AcceptHitAndEndSearch - keeps evaluating until first hit found
- Either way: orders of magnitude slower
- Solution: build multiple geometries as one BLAS

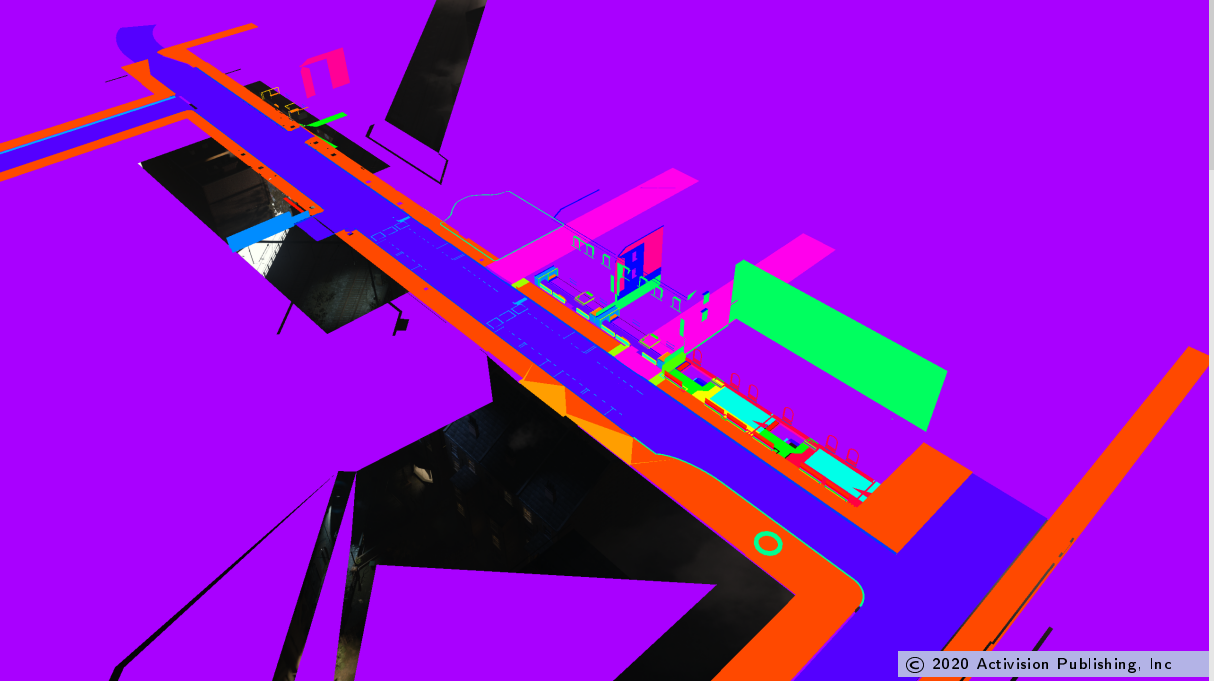


- The problems materializes when multiple BLASes have overlapping bounding boxes.
- Regardless whether you need closest or any hit, what usually happens is that ray traversal has to test against multiple BLASes, so performance degredates extremely fast.
- Fortunately, DXR API allows for providing a list of multiple index/vertex buffers during build, so we can build multiple surfaces as one BLAS.

Here is a worst-case scenario from our game. A light with not much geometry around.

Raytraced Shadows in Call of Duty: Modern Warfare

Here it is zoomed out. How many objects do you think fall into this light's influence?

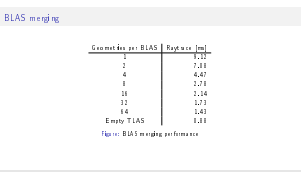


- Here you can see color-coded surfaces. Probably a bit more than you expected.
- What you see is geometry brushes used by level designers.
- Map compiler aggressively merges those surfaces for more efficient work submission.
- In most cases this means 1 drawcall for all triangles with the same material.
- Which means large bounding boxes and a lot of overlap.
- For DXR that is less than ideal.

BLAS merging

Geometries per BLAS	Raytrace [ms]
1	9.12
2	7.08
4	4.47
8	2.78
16	2.14
32	1.73
64	1.43
Empty TLAS	0.88

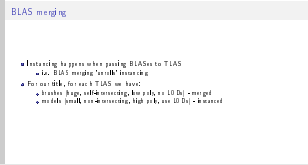
Figure: BLAS merging performance



Here you can see actual performance for different number of surfaces per BLAS. And it would be even worse without AcceptHitAndEndSearch.

BLAS merging

- Instancing happens when passing BLASes to TLAS
  - i.e. BLAS merging 'unrolls' instancing
- For our title, for each TLAS we have:
  - brushes (huge, self-intersecting, low poly, no LODs) - merged
  - models (small, non-intersecting, high poly, use LODs) - instanced



- The downside of BLAS merging is that you can't reuse geometries as instances.
- For us, especially since we have separte TLASes per light, the solution was rather clear.

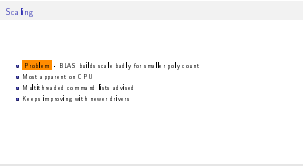
BLAS merging

- At the moment we pay the cost of brush+model trace
  - Acceptable compromise
- Naive merging won't scale for global TLAS:
  - Need for constants rebuilds due to streaming
- Solution:
  - Enforce non-overlapping surfaces between streamed chunks
  - Merge surfaces for each chunk separately

- We did not fully get rid of overlap. In the case shown on screenshots, we will have one big brush BLAS covering almost entire map, so it will overlap every model inside it. This is an accepable performance trade-off.
- This approach won't scale when doing whole-scene TLAS.
- Fortunately, our streamer divides world into non-overlapping chunks, which we will be able to use for BLAS merging in the future.

Scaling

- Problem - BLAS builds scale badly for smaller poly count
- Most apparent on CPU
- Multithreaded command lists advised
- Keeps improving with newer drivers

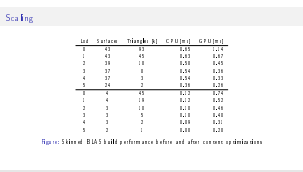


- It's important to note that CPU cost is not trivial. Consider recording multiple command lists in parallel when calling BuildRaytracingAccelerationStructure.
- This is something that keeps improving with newer drivers, so hopefully it will soon be a non-issue.

Scaling

Lod	Surfaces	Triangles [k]	CPU [ms]	GPU [ms]
0	43	93	0.65	1.14
1	43	45	0.63	0.67
2	39	18	0.58	0.45
3	37	8	0.54	0.36
4	37	3	0.54	0.33
5	24	2	0.36	0.26
0	4	45	0.12	0.74
1	4	19	0.12	0.52
2	3	10	0.10	0.46
3	3	5	0.10	0.40
4	3	2	0.09	0.31
5	2	1	0.08	0.28

Figure: Skinned BLAS build performance before and after content optimizations



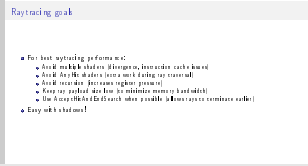
- Here you have CPU and GPU timings for BLAS building of different LODs for one of our character models. This is both before and after content optimizations.
- As you can see, performance does not scale linearly with vertex/surface count. Tiny surfaces are quite heavy.

Raytracing

Raytracing

Raytracing goals

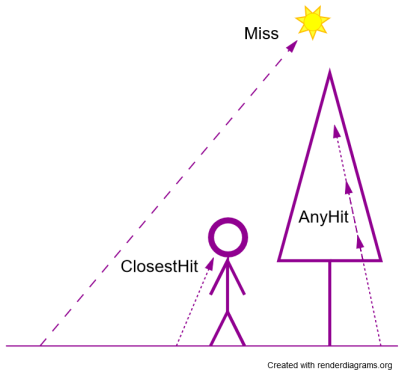
- For best raytracing performance:
  - Avoid multiple shaders (divergence, instruction cache issues)
  - Avoid AnyHit shaders (extra work during ray traversal)
  - Avoid recursion (increases register pressure)
  - Keep ray payload size low (to minimize memory bandwidth)
  - Use AcceptHitAndEndSearch when possible (allows rays to terminate earlier)
- Easy with shadows!



- To achieve high raytracing performance, we should avoid using expensive features unless necessary.
- Which is precisely where raytraced shadows shine: we do not need per-material shaders, recursion, and we don't need closest occluder - any occluder will do.

Raytracing in practice

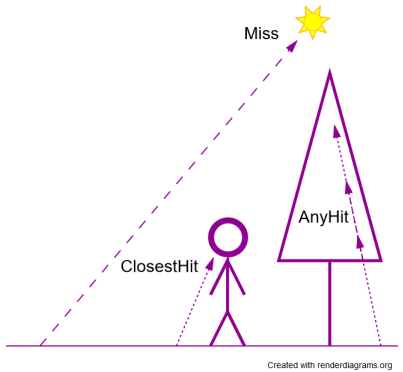
- 1x Raygen
- 1x Miss
- 1x ClosestHit
- 2x AnyHit:
  - alpha testing
  - ray bias for mismatched geometry



- Keeping divergence low is easy, since we only need a very specific set of shaders.
- There two caveats though: we need to handle alpha tested geometry, which necessitates use of not-so-performant AnyHit shader.
- Same type of shader is also used to introduce ray bias for acceleration structures which geometries do not exactly match positions reconstructed from rasterized depth. But more on that later.

Raytracing in practice

- Raycast from pixel to light
  - no recursion
- Max trace distance = distance to light
  - no need for light geometry

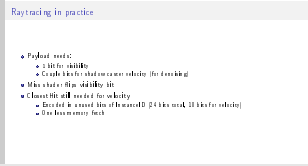


Raytracing in practice
- Raycast from pixel to light
  - no recursion
- Max trace distance = distance to light
  - no need for light geometry

- Assuming we have acceleration structures built, raycast is easy - using reconstructed world space position we cast rays towards the light, by importance sampling a capsule shape.
- We do not need to build BLAS for light shape, since we can simply set max trace distance to distance to our importance sampled point on light - the miss shader will be called if no intersection between two points is found.

Raytracing in practice

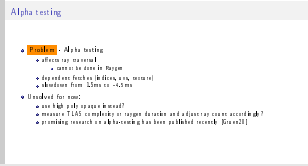
- Payload needs:
  - 1 bit for visibility
  - Couple bits for shadow caster velocity (for denoising)
- Miss shader flips visibility bit
- ClosestHit still needed for velocity
  - Encoded in unused bits of InstanceID (24 bits total, 10 bits for velocity)
  - One less memory fetch



- In simplest case, we would only need 1 bit in ray payload and a miss shader to determine visibility, since DXR API allows for not providing a ClosestHit shader at all.
- However, our denoiser uses shadow caster velocity for tuning temporal convergence (more on that later).
- To avoid any extra memory fetches, we encode compressed velocity in unused bits of InstanceID.
- Note that we use AcceptHitAndEndSearch so we aren't guaranteed to get velocity of actual shadow caster, but we haven't encountered any cases in practice where this would be an issue. Usually, a moving object does not have an overlapping bounding box with static geometry, so we get an actual closest hit even if didn't specif that we wanted to.

Alpha testing

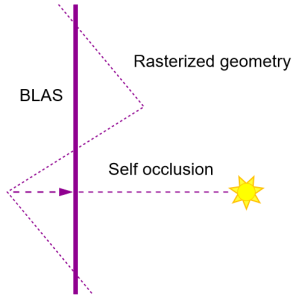
- **Problem** - Alpha testing
  - affects ray traversal
    - cannot be done in Raygen
  - dependent fetches (indices, uvs, texture)
  - slowdown from 1.5ms to ~4.5ms
- Unsolved for now:
  - use high poly opaque instead?
  - measure TLAS complexity or raygen duration and adjust ray count accordingly?
  - promising research on alpha-testing has been published recently [Gruen20]



- Unfortunately, we were unable to solve performance issues with alpha testing.
- There is no easy solution here - alpha testing requires dependent memory fetches, and even if it is able to be properly amortized by other threads on GPU, it's still a substantial amount of additional work.
- Using high-poly opaques has been an object of research, however there is no guarantee of it being faster, and it is going to take more storage.
- We have also thought of detecting if given TLAS has any alpha tested geometry, and adjusting ray count accordingly, but this is more of a workaround than solution and it won't work with global TLAS.
- In similar manner, we could adjust ray count based on previous frame raygen execution time.
- Fortunately, since we shipped, some promising research on potential alpha-testing hardware support has been published.

Mismatched geometry

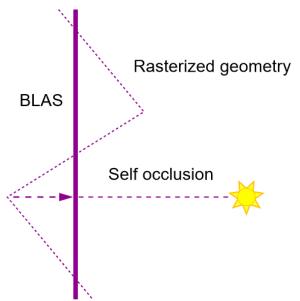
- **Problem** - Mismatched geometry
  - e.g.: vertex animation, tesselation, subdiv
- no indirect builds in API
  - need to know index/vertex count on CPU



- As previously mentioned, we have cases where geometries in accelerations structures do not match the geometries used with rasterizer.
- This concerns geometries generated using vertex and geometry shaders, but even after porting them to compute it still would be impossible to build them.
- DXR API lacks indirect builds, so we would need to know index and vertex count on CPU, which is not possible for GPU driven data.

Mismatched geometry

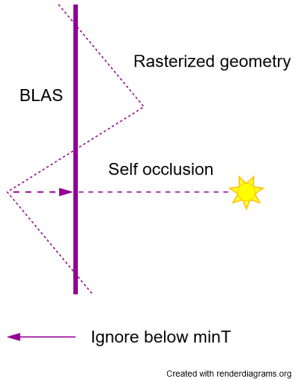
- Workaround - ray bias
  - could bias minT in Raygen, based on a stencil bit...
  - ... but what if we need to set bias per object?
  - not enough bits!
- Solution: ray bias in AnyHit shader

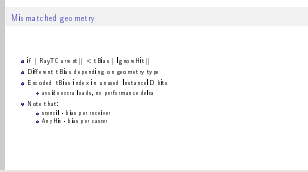


- We thought of biasing minimum trace distance, if we only could determine object type per-pixel, like e.g. from stencil.
- However, we did not have enough stencil bits left for our needs, so we came up with different solution.
- By using bias in AnyHit shader, we can have different biases on even per object basis.

Mismatched geometry

- if (RayTCurrent() < tBias) IgnoreHit()
- Different tBias depending on geometry type
- Encoded tBias index in unused InstanceID bits
  - avoids extra loads, no performance delta
- Note that:
  - stencil - bias per receiver
  - AnyHit - bias per caster





- We previously scrutinized performance of AnyHit shaders in relation to alpha testing, however they are not that slow if you don't do too much work in them.
- We use AnyHit shader to reject hits below certain threshold.
- There are couple different hardcoded thresholds for different types of features (subdiv, tesselation etc.), and we encode index to them in unused bits of InstanceID to avoid any extra memory indirections.
- Of course, the two approaches described are a bit different, since once biases by receiver, the other by caster.
- In our case it was mostly used to avoid self-shadowing issues on subdiv character faces and tesselated terrain, so the AnyHit method was actually preferable.

Here we can see tesselated terrain with black spots due to mismatched geometry.

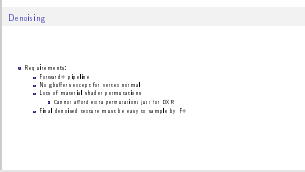
And here it is after applying bias.

Denoising

Denoising

Denoising

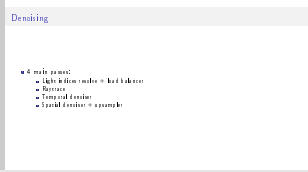
- Requirements:
  - Forward+ pipeline
  - No gbuffers except for vertex normal
  - Lots of material shader permutations
    - Cannot afford extra permutations just for DXR
  - Final denoised texture must be easy to sample by F+



- Call of Duty: Modern Warfare uses forward+ shading, which means we have a lot of specialized material shader permutations.
- Shaders require recompiling after each driver or game update, so we didn't want to bloat game with even more permutations.
- Any new code added to F+ shaders would be present everywhere - even if inactive - including our min spec, so we had to make sure it won't add extra register pressure.
- We aimed to have a simple texture that can be point sampled, with each texel containing floating point visibility for multiple lights.

Denoising

- 4 main passes:
  - Light indices resolve + load balancer
  - Raytrace
  - Temporal denoiser
  - Spatial denoiser + upsampler



- Here you can see the high-level outline of our whole gpu-side implementation.
- Before we go into details, let's see what it looks like in practice.

2020-09-07

Raytraced Shadows in Call of Duty: Modern Warfare

Exponential shadow maps - leaking, missed details.

2020-09-07

Raytraced Shadows in Call of Duty: Modern Warfare

Raytraced pointlight.

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Raytraced Shadows in Call of Duty: Modern Warfare

Raytraced sphere light - raw input, before denoising.

Raytraced Shadows in Call of Duty: Modern Warfare

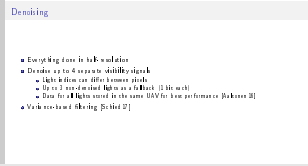
Without denoising, but with TAA. Pretty good...

... but dedicated shadow temporal denoiser is better.

Adding delicate spatial blur and TAA completes the final look.

Denoising

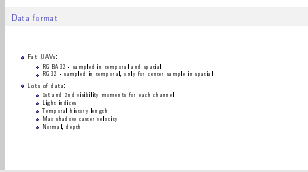
- Everything done in half-resolution
- Denoise up to 4 separate visibility signals
  - Light indices can differ between pixels
  - Up to 3 non-denoised lights as a fallback (1 bit each)
  - Data for all lights stored in the same UAV for best performance [Aaltonen16]
- Variance-based filtering [Schied17]



- Note that all UAVs and compute dispatch sizes are half-resolution (25% pixel count).
- For each texel, we store 4 separate channels containing light visibility, which means we can denoise up to 4 lights per pixel.
- 4 lights per pixel are plenty, but in rare cases there can be more.
- We didn't want to force our lighting artists to redo lighting for DXR, so we added a fallback that stores not-denoised visibility for extra 3 lights (7 in total).
- Thankfully, our temporal anti-aliasing is pretty good at denoising by itself, so those places are not too jarring.
- We wanted to keep all our data in the same UAV - according to multiple benchmarks one fetch of 4x wider texture is faster than sampling 4 textures separately.
- We use variance-based filtering, based on the ASVGF paper, which is also used in Quake 2 RTX.

Data format

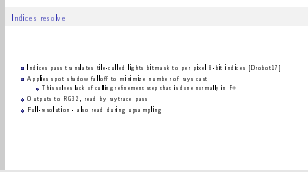
- Fat UAVs:
  - RGBA32 - sampled in temporal and spatial
  - RG32 - sampled in temporal, only for center sample in spatial
- Lots of data:
  - 1st and 2nd visibility moments for each channel
  - Light indices
  - Temporal history length
  - Max shadow caster velocity
  - Normal, depth



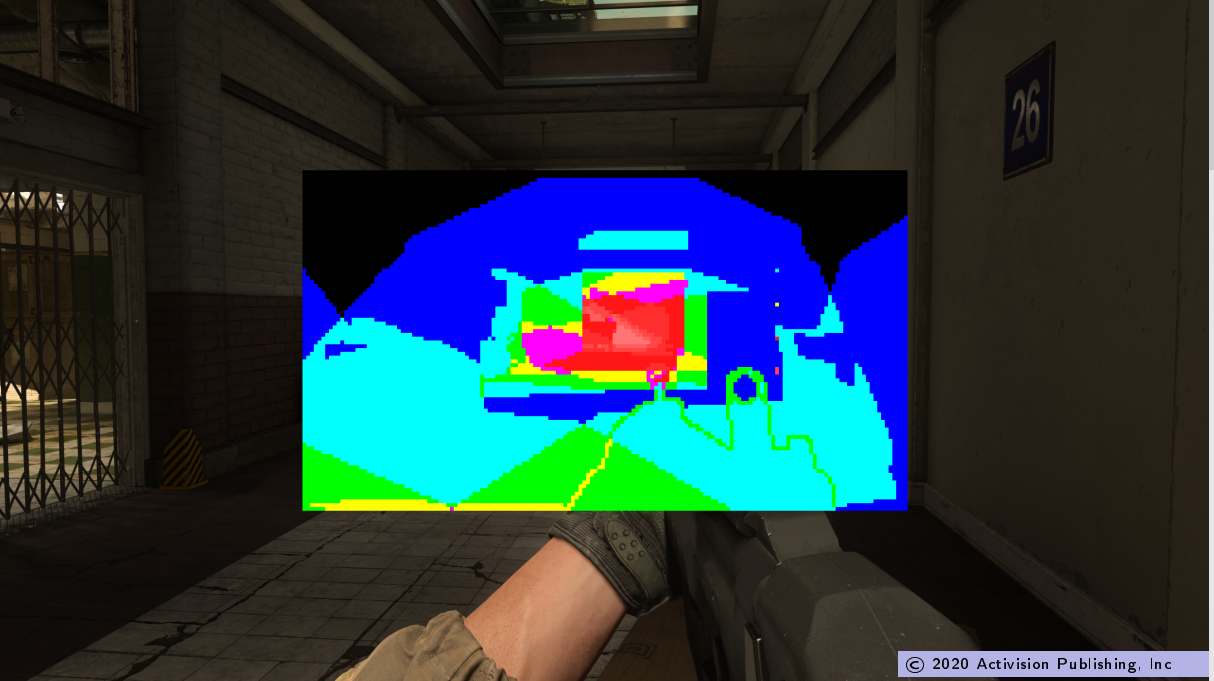
- 4 lights per pixel requires a lot of storage, so our UAVs are quite fat.
- Fortunately, we were able to avoid sampling all data at all times, i.e. spatial denoiser does not have to sample auxiliary RG32 texture when sampling neighbourhood.
- To compute variance, we need to store 1st and 2nd visibility moments for each channel separately.
- After first pass, we also keep per-pixel normals and depth in the same UAV - that way we don't have to do extra memory fetches.
- Other data is needed for various heuristics that determine temporal and spatial filters' strengths.

Indices resolve

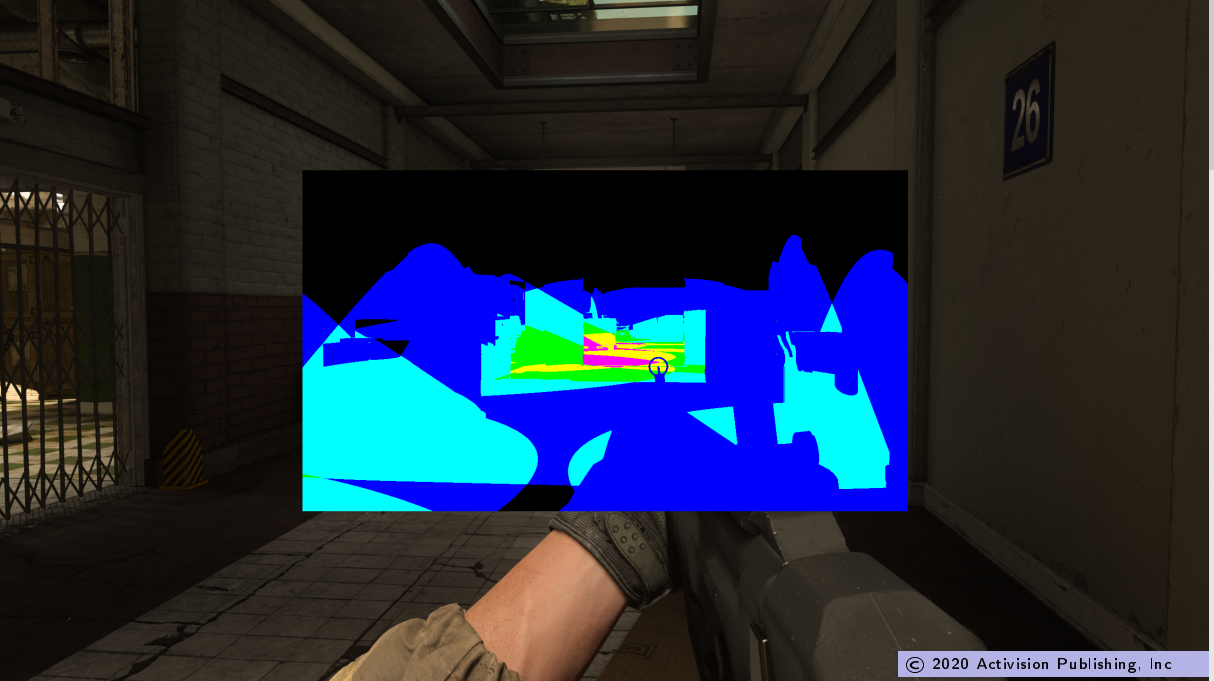
- Indices pass translates tile-culled lights bitmask to per pixel 8-bit indices [Drobot17]
- Applies spot shadow falloff to minimize number of rays cast
  - This solves lack of culling refinement step that is done normally in F+
- Outputs to RG32, read by raytrace pass
- Full-resolution - also read during upsampling



- We have a highly optimized light culling scheme for F+.
- However, it does not check for spot shadow falloff during culling itself to avoid fetching light descriptors - falloff is applied during F+ which is faster overall.
- But with DXR we want to skip any unnecessary rays, so we want to apply falloff before raycast.
- Indices resolve pass reads light culling bitmask, applies falloff and writes to an intermediate RG32 UAV, which is later read by raytrace pass and upsampling pass.
- We output indices in full-resolution to use later during upsampling.



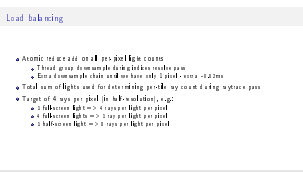
Heatmap of tile-culled lights.



Heatmap after spot shadow falloff.

Load balancing

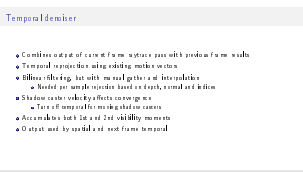
- Atomic reduce add on all per-pixel light counts
  - Thread group downsample during indices resolve pass
  - Extra downsample chain until we have only 1 pixel - extra ~0.02ms
- Total sum of lights used for determining per-tile ray count during raytrace pass
- Target of 4 rays per pixel (in half-resolution), e.g.:
  - 1 full-screen light => 4 rays per light per pixel
  - 4 full-screen lights => 1 ray per light per pixel
  - 1 half-screen light => 8 rays per light per pixel



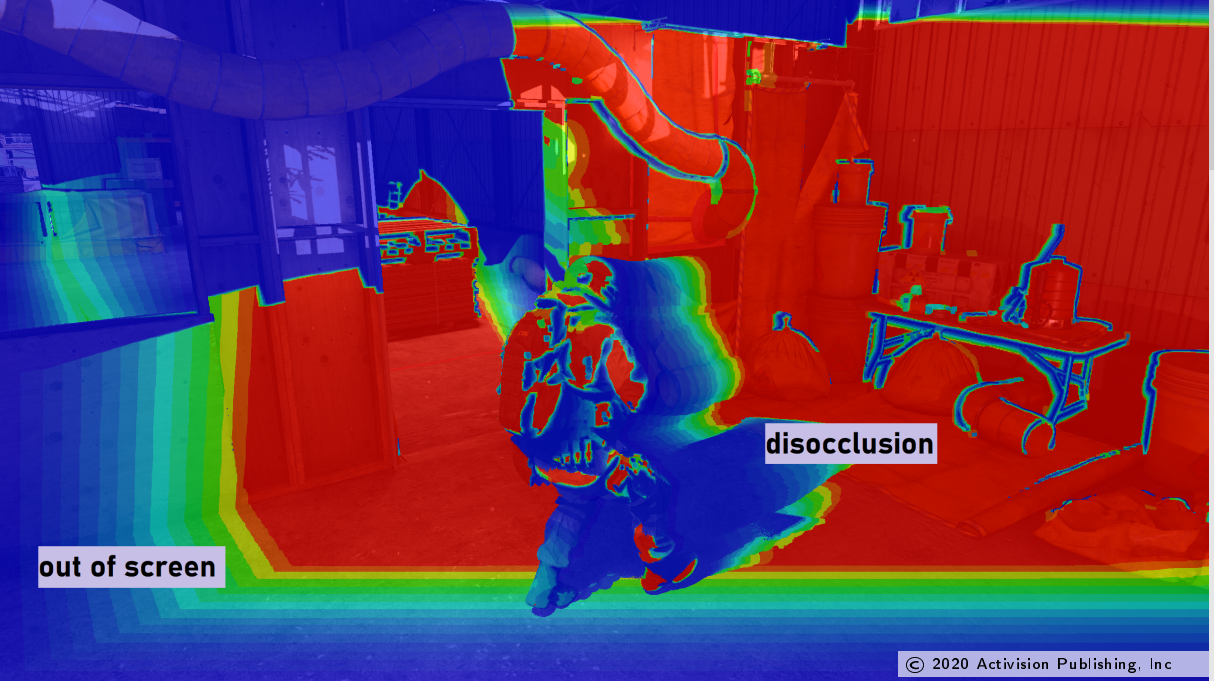
- We also do an atomic add reduction to count all lights on screen
- This is used to dynamically adjust ray count per pixel to maintain constant raytracing performance.

Temporal denoiser

- Combines output of current frame raytrace pass with previous frame results
- Temporal reprojection using existing motion vectors
- Bilinear filtering, but with manual gather and interpolation
  - Needed per sample rejection based on depth, normal and indices
- Shadow caster velocity affects convergence
  - Turn off temporal for moving shadow casters
- Accumulates both 1st and 2nd visibility moments
- Output used by spatial and next frame temporal



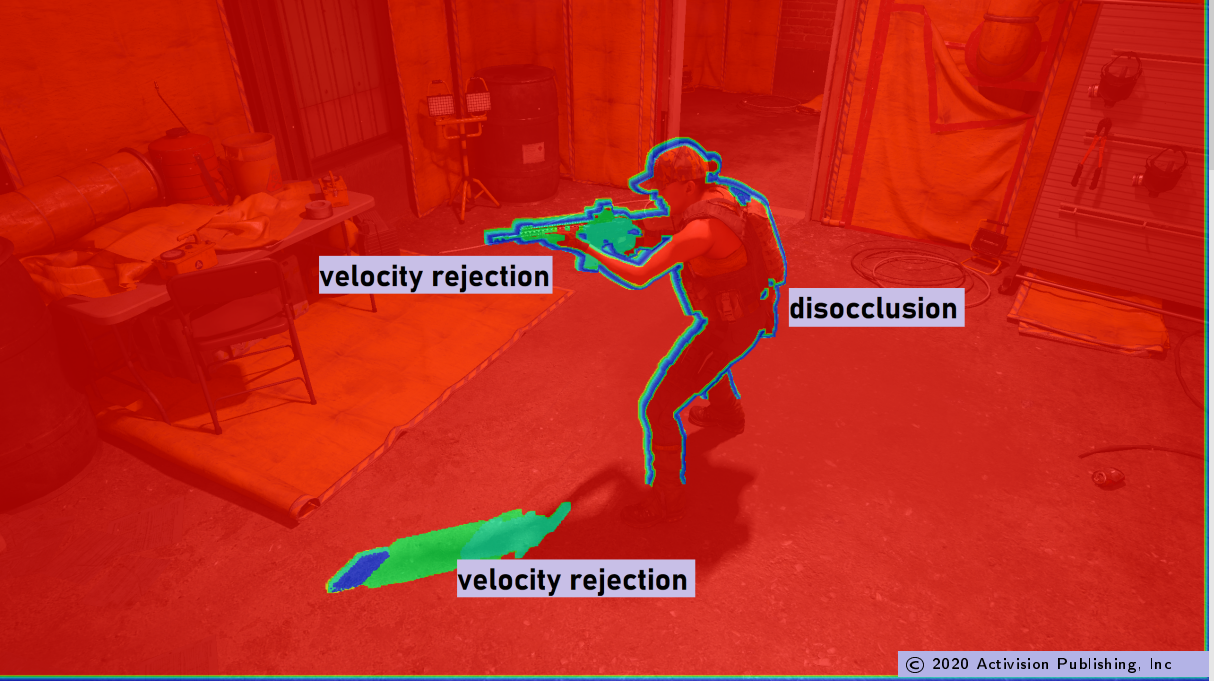
- Raytrace pass uses indices to determine light visibility and passes this information to temporal denoiser.
- It's a pretty standard temporal accumulation scheme with feedback loop. There are couple caveats though.
- We want to apply rejection per each bilinear sample - e.g. we do not want to reject based on depth after bilinear filtering - so we have to implement bilinear filter ourselves.
- To avoid ghosting on moving shadows, we tune out temporal filtering when shadow caster velocity is non-zero.
- We accumulate both 1st and 2nd moments so that spatial denoiser can estimate variance over time.



2020-09-07

Raytraced Shadows in Call of Duty: Modern Warfare

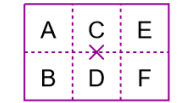
Heatmap of temporal history length, with character and camera in motion.



Heatmap of temporal history length, with idling character and static camera.

Temporal denoiser

- **Problem** - can't query for texels touched by hardware Gather
  - May result in being off by 1 pixel - using weights for different texels
  - Temporal accumulation completely explodes
  - Avoid Gather, load each sample separately



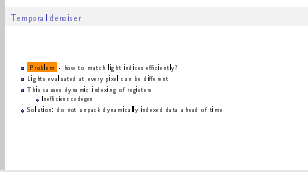
ABCD or CDEF?

Created with renderdiagrams.org

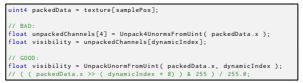
- One extra issue we ran into is that we can't make assumption about exact math done by hardware when picking samples for Gather.
- We can't query hardware for texels touched during Gather with given uv - we have to choose them ourselves.
- We have 2 UAVs with 6 channels, so instead of doing 6 gathers we ended up doing 8 loads, which lowered performance a bit.

Temporal denoiser

- Problem - how to match light indices efficiently?
- Lights evaluated at every pixel can be different
- This causes dynamic indexing of registers
  - Inefficient codegen
- Solution: do not unpack dynamically indexed data ahead of time



- One interesting performance caveat is how to match light indices between samples. This applies both to temporal and spatial denoisers.
- Each pixel can have a different set of light affecting it, so even if two pixels share same lights, it's not guaranteed they will be in the same order.
- This isn't something that can be precomputed, so we ended up with dynamic register indexing.
- This is something that is supported neither by DXC nor actual hardware. DXC ended up producing code that either forced data to go through memory, or a lot of inefficient ALU magic involving conditional masks and swaps.
- This is usually easily remedied by manually using LDS, but in this case we can do even better.



```
uint4 packedData = texture[samplePos];

// BAD:
float unpackedChannels[4] = Unpack4UnormsFromUint( packedData.x );
float visibility = unpackedChannels[dynamicIndex];

// GOOD:
float visibility = UnpackUnormFromUint( packedData.x, dynamicIndex );
// ( ( packedData.x >> ( dynamicIndex * 8) ) & 255 ) / 255.0;
```

- Thankfully, our visibility for 4 channels in stored in one dword.
- Instead of unpacking it ahead of time, we can unpack it 'on demand'.
- Unpacking 1 byte float from a dword involves a bit-shift by 0, 8, 16, or 24. We can simply make the bitshift amount dependent on the matched light index.
- This avoid dynamic indexing and reduces register pressure.

Spatial denoiser

- Spatial poisson disk blur
- Fixed-radius pattern, sample weights depend on variance:
  - Variance computed from 1st and 2nd moment (temporal estimate only)
  - Longer temporal history => lower variance => lower filter strength
  - Penumbra => high variance => strong filter
  - Contact shadows or point light shadows => zero variance => no filter

Spatial denoiser
Spatial poisson disk blur
Fixed-radius pattern, sample weights depend on variance:
Variance computed from 1st and 2nd moment (temporal estimate only)
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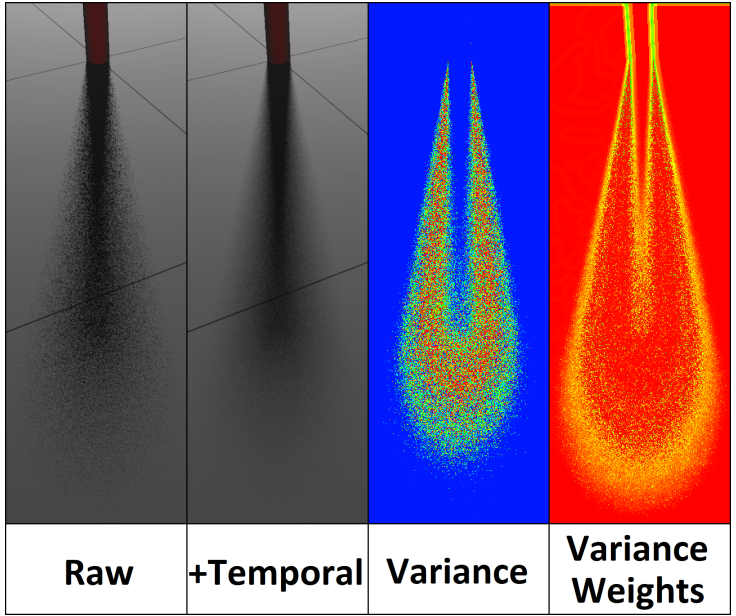
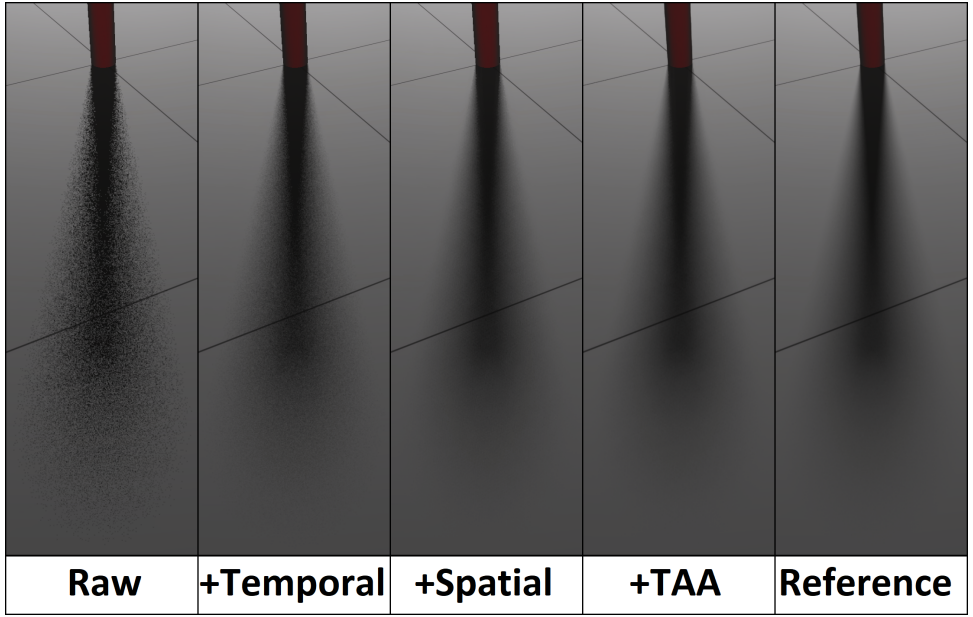
Contact shadows or point light shadows => zero variance => no filter

- Our spatial denoiser is a simple, non-separable, poisson disk blur.
- We apply weighting heuristics that include depths, normals and variance.
- Since we denoise multiple lights at the same time, we do not use variance to scale sampling radius.
- Instead, we modify sample weights based on variance.
- Spatial filtering introduces bias to our shadows so we want to keep it's strength low if it is not needed.
- As temporal accumulation collects more frames, variance goes down, so we fade out the strength of spatial filter.
- Outside of that, variance filtering allows us to avoid overblurring of contacts shadows or point light shadows.



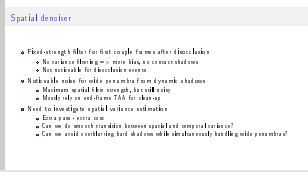
Here is a heat map of variance (noisy, because variance estimation is only temporal) and resulting heatmap of variance weights during spatial filter.



Whole denoising process - if temporal denoiser has time to converge, spatial blur and TAA will only add minor refinement.

Spatial denoiser

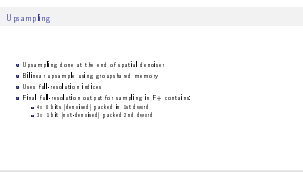
- Fixed-strength filter for first couple frames after disocclusion
  - No variance filtering => more bias, no contact shadows
  - Not noticeable for disocclusion events
- Noticeable noise for wide penumbra from dynamic shadows
  - Maximum spatial filter strength, but still noisy
  - Mostly rely on end-frame TAA for clean-up
- Need to investigate spatial variance estimation
  - Extra pass - extra cost
  - Can we do smooth transition between spatial and temporal variance?
  - Can we avoid overblurring hard shadows while simultaneously handling wide penumbras?



- Our variance estimation is temporal only, so we are left without variance knowledge if disocclusion occurs.
- In such cases, we simply turn off variance filtering and employ a fixed filter.
- This results in very arbitrary filtering, so artifacts can be visible.
- Fortunately, our temporal anti-aliasing is very good at denoising, so you won't notice that in motion, unless you encounter an extremely big light with dynamic occluders around.
- We considered an extra spatial variance estimation pass, but to truly make it worth the cost we would need to ensure high quality without sacrificing performance.

Upsampling

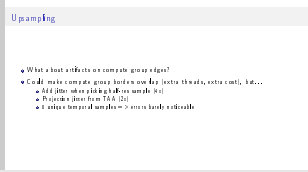
- Upsampling done at the end of spatial denoiser
- Bilinear upsample using groupshared memory
- Uses full-resolution indices
- Final full-resolution output for sampling in F+ contains:
  - 4x 8 bits (denoised) packed in 1st dword
  - 3x 1 bit (not-denoised) packed 2nd dword



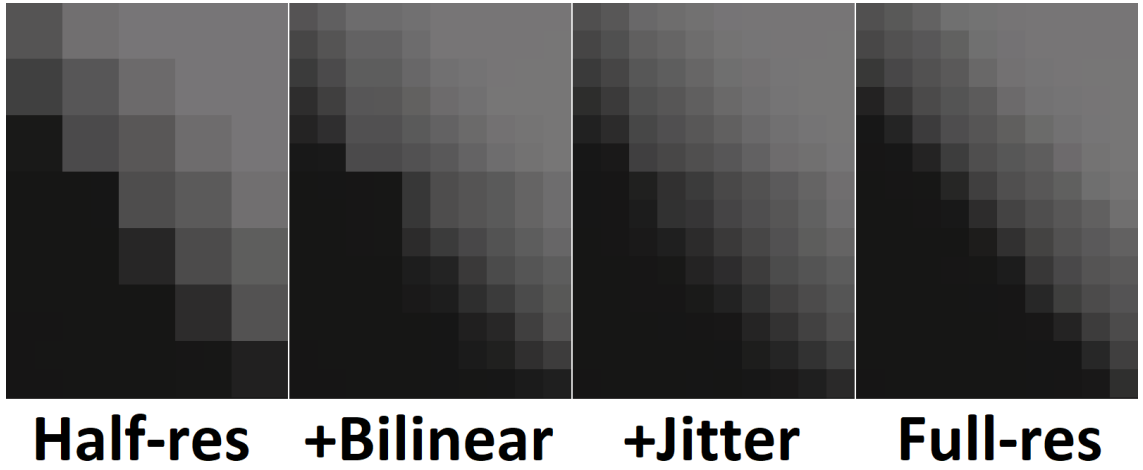
- To amortize denoising cost, we do upsampling in the same pass as spatial denoiser.
- We use groushared memory to share visibility values between neighbours and do bilinear filtering for missing texeles.
- Full resolution indices from the first compute pass are used, to avoid any artifacts.
- The final texture sampled by F+ is in full-resolution, and contains visibility for both denoised and non-denoised channels.

Upsampling

- What about artifacts on compute group edges?
- Could make compute group borders overlap (extra threads, extra cost), but...
  - Add jitter when picking half-res sample (4x)
  - Projection jitter from TAA (2x)
  - 8 unique temporal samples => errors barely noticeable



- Since we cannot access visibility from different compute groups, we have to guess values for border texels.
- We could make compute groups overlap by duplicating work of border threads, but in practice we found it to be an overkill.
- We already jittered in time which sample of 2x2 neighbourhood we pick for our half-res textures, and with 2x TAA jitter we have 8 unique samples in 8 consecutive frames, which makes all errors imperceptible.



Note the doubled pixels on compute group edges before adding jitter. This can be a visibly distracting pattern, though only on flat surfaces spanning multiple tiles.

Summary

Summary

Summary

- Open problems:
  - Alpha testing performance
  - Mismatched geometry
  - Better spatial denoiser

- During the talk we outlined couple problems that we still need to solve.
- Alpha testing will most likely have to be replaced with high poly opaque BLASes, but actual performance/mesh complexity balance is yet to be measured.
- Mismatched geometry is the biggest concern, since modern vertex shading pipeline seems to evolve in orthogonal way to raytracing with advent of mesh shaders.
- And finally, we need to improve our spatial denosing scheme. NVIDIA Raytracing Gameworks provides a good spatial denoiser, but it is not suited to denoising multiple lights. It's worth investigating how it could be integrated with our framework in performant way.

Summary

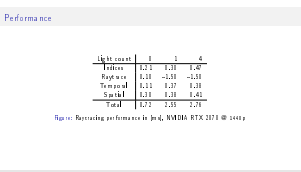
- Achievements:
  - High performance thanks to local TLASes
  - Constant performance regardless of light count
  - No content adjustments needed
    - All lights are raytraced

- However, many things did went well for us. Barring alpha testing, our raytracing is very performant and it scales well with content.
- The execution cost is more or less constant regardless of light count.
- Most importantly it works well for all lights, our artists did not have to redo lighting or turn off raytracing for individual lights.

Performance

Light count	0	1	4
Indices	0.21	0.30	0.47
Raytrace	0.10	~1.50	~1.50
Temporal	0.11	0.37	0.38
Spatial	0.30	0.38	0.41
Total	0.72	2.55	2.76

Figure: Raytracing performance in [ms], NVIDIA RTX 2070 @ 1440p



- Here you can see average raytracing performance.
- Load balancing maintains constant cost.
- Raytrace is usually about 1.5ms, rarely goes above 2ms, except for locations with heavy use of alpha testing.

Here are some in-game examples of our denoiser in action. Proper area light shadows give desired soft look.

Raytraced Shadows in Call of Duty: Modern Warfare

Here are some in-game examples of our denoiser in action. Proper area light shadows give desired soft look.

Raytraced Shadows in Call of Duty: Modern Warfare

They help to ground objects in their surroundings.

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They do not experience leaking and ensure penumbra widening with distance from shadowcaster.

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Raytraced Shadows in Call of Duty: Modern Warfare

Summary

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  - molejnik@infinityward.com, Twitter: @olej3d
  - pkozlowski@nvidia.com
- Thanks!

- We wanted to thank Oleg and Tim from NVIDIA for their help with our work.
- If you have any questions, feel free to contacts us.
- Thank you for your time!

Bibliography

[Heitz18] Eric Heitz, Stephen Hill and Morgan McGuire
Combining Analytic Direct Illumination and Stochastic Shadows
https://eheitzresearch.wordpress.com/705-2/

[Gruen20] Holger Gruen, Carsten Benthin, Sven Woop
Sub-Triangle Opacity Masks for Faster Ray Tracing of Transparent Objects
https://youtu.be/prZJ8FBG9BI?t=11416

[Aaltonen16] Sebastian Aaltonen
PerfTest
https://github.com/sebbbi/perftest#nvidia-turing-rtx-2080-ti

[Schied17] Christoph Schied et al.
Spatiotemporal Variance-Guided Filtering
https://research.nvidia.com/publication/2017-07_Spatiotemporal-Variance-Guided-Filtering%3A

[Drobot17] Michał Drobot
Improved Culling for Tiled and Clustered Rendering
http://advances.realtimerendering.com/s2017/2017_Sig_Improved_Culling_final.pdf