Advancements in Tiled-Based Compute Rendering

Gareth Thomas
Developer Technology Engineer, AMD

GAME DEVELOPERS CONFERENCE®
MOSCONE CENTER · SAN FRANCISCO, CA
MARCH 2-6, 2015 · EXPO: MARCH 4-6, 2015

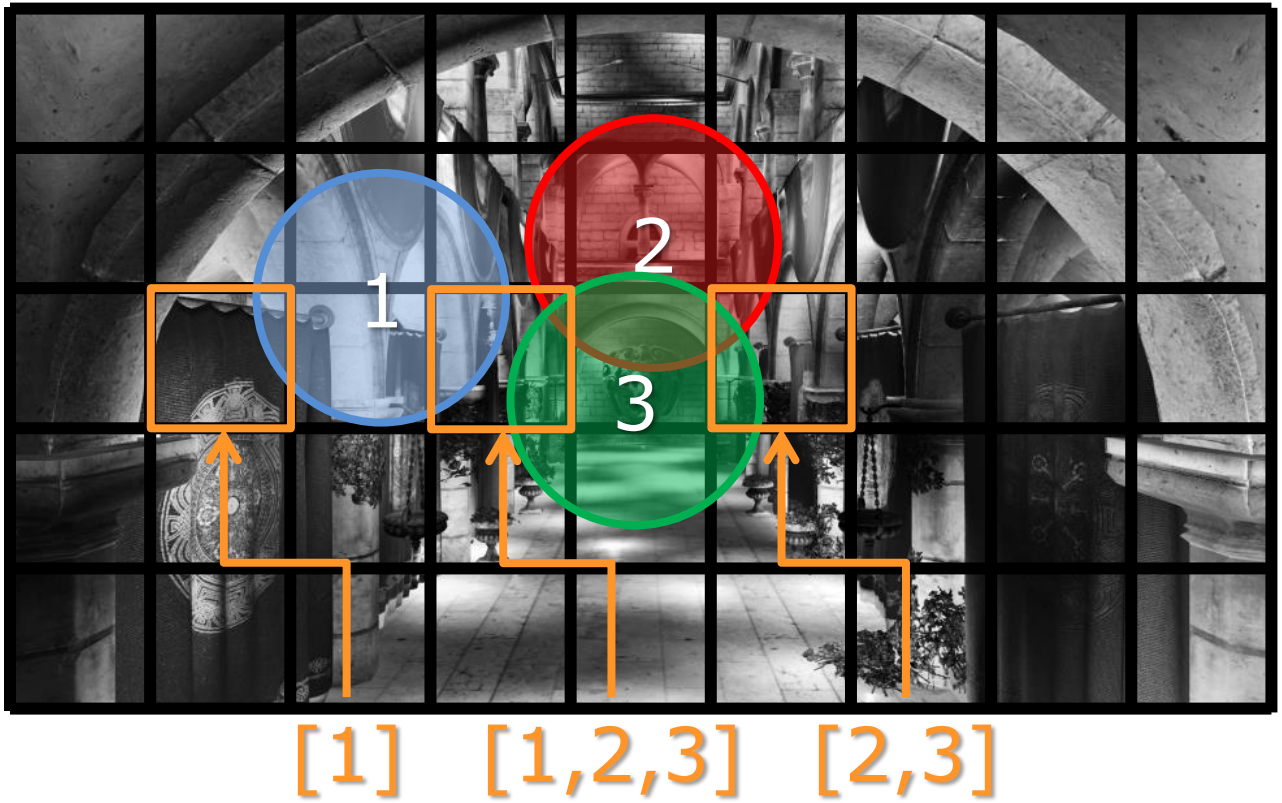
Agenda

- Current Tech
- Culling Improvements
- Clustered Rendering
- Summary

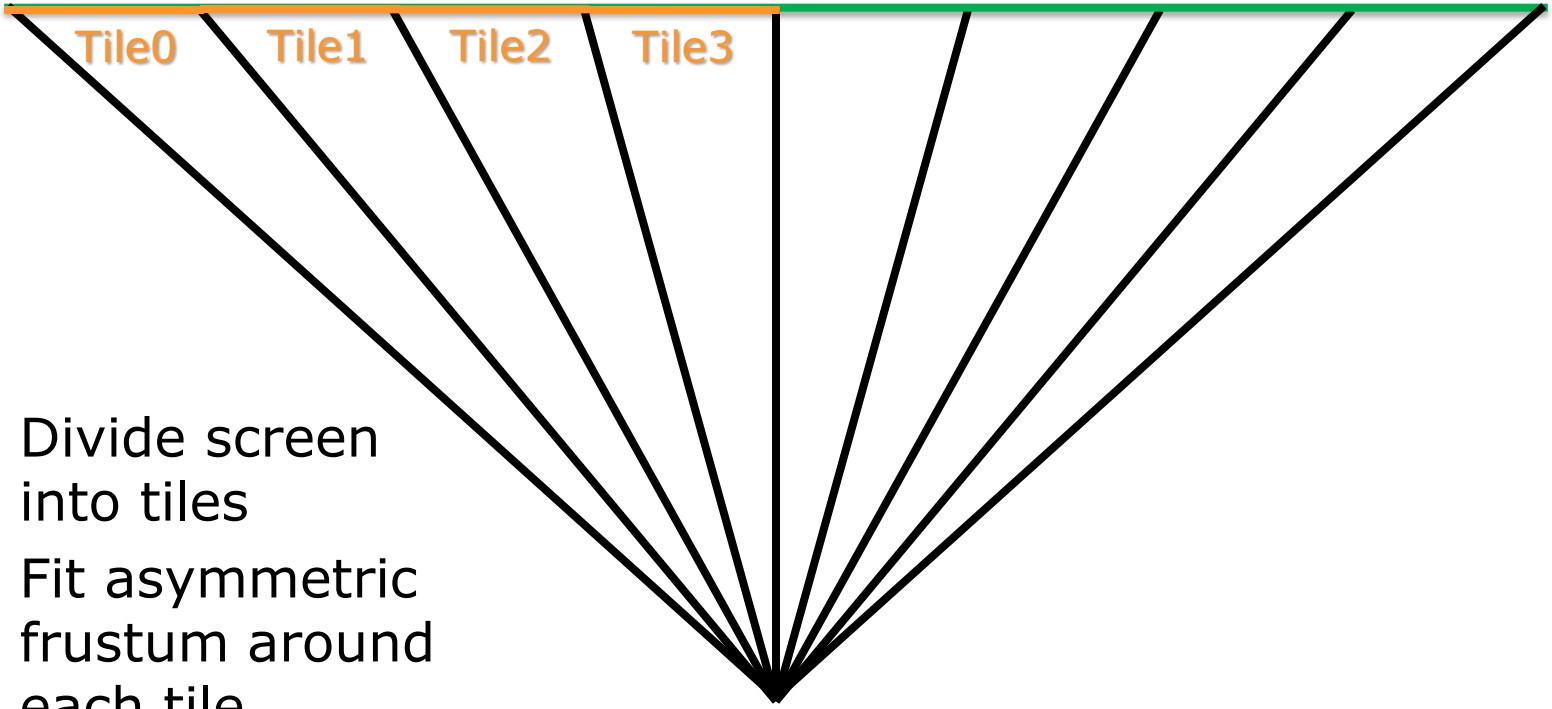
Proven Tech – Out in the Wild

- Tiled Deferred [Andersson09]
  - Frostbite
  - UE4
  - Ryse
- Forward+ [Harada et al 12]
  - DiRT & GRID Series
  - The Order: 1886
  - Ryse

Tiled Rendering 101

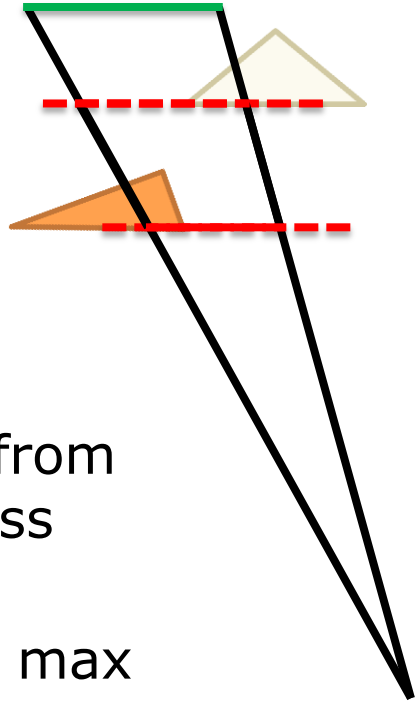


Tiled Rendering 101



- Divide screen into tiles
- Fit asymmetric frustum around each tile

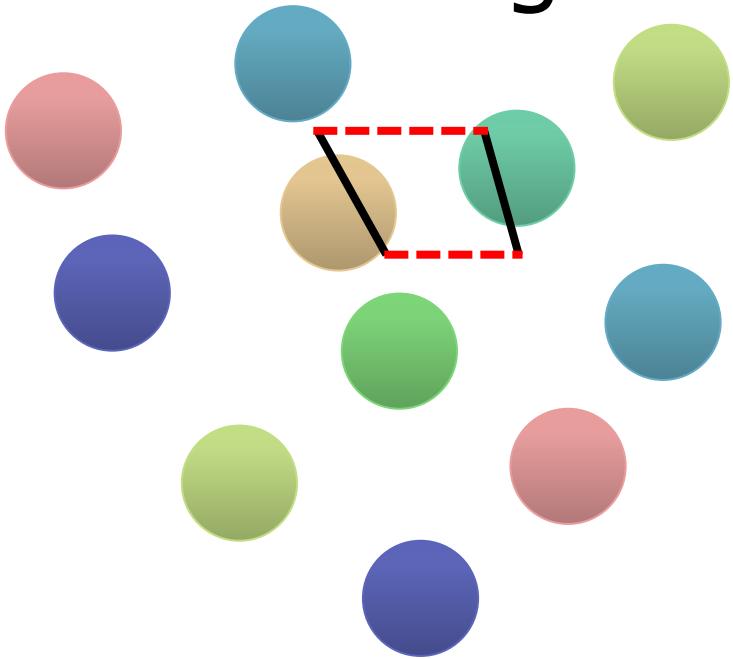
Tiled Rendering 101



- Use z buffer from depth pre-pass as input
- Find min and max depth per tile

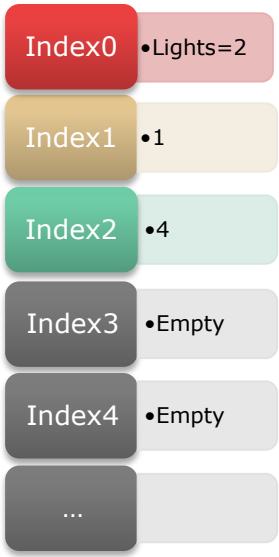
- Use this frustum for intersection testing

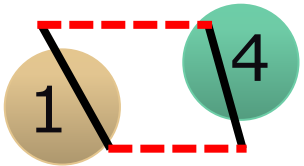
Tiled Rendering 101

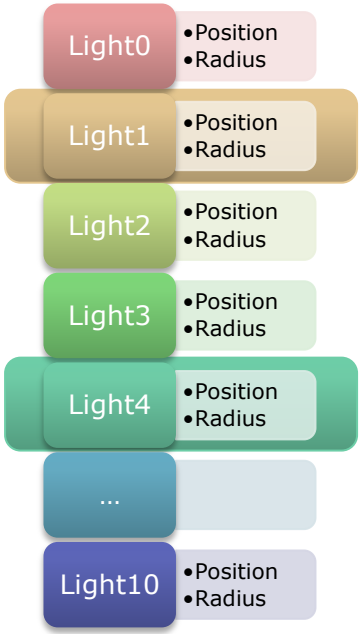


Light0	•Position •Radius
Light1	•Position •Radius
Light2	•Position •Radius
Light3	•Position •Radius
Light4	•Position •Radius
...	
Light10	•Position •Radius

Tiled Rendering 101







Targets for Improvement

- Z Prepass (on Forward+)
- Depth bounds
- Light Culling
- Color Pass

Depth Bounds

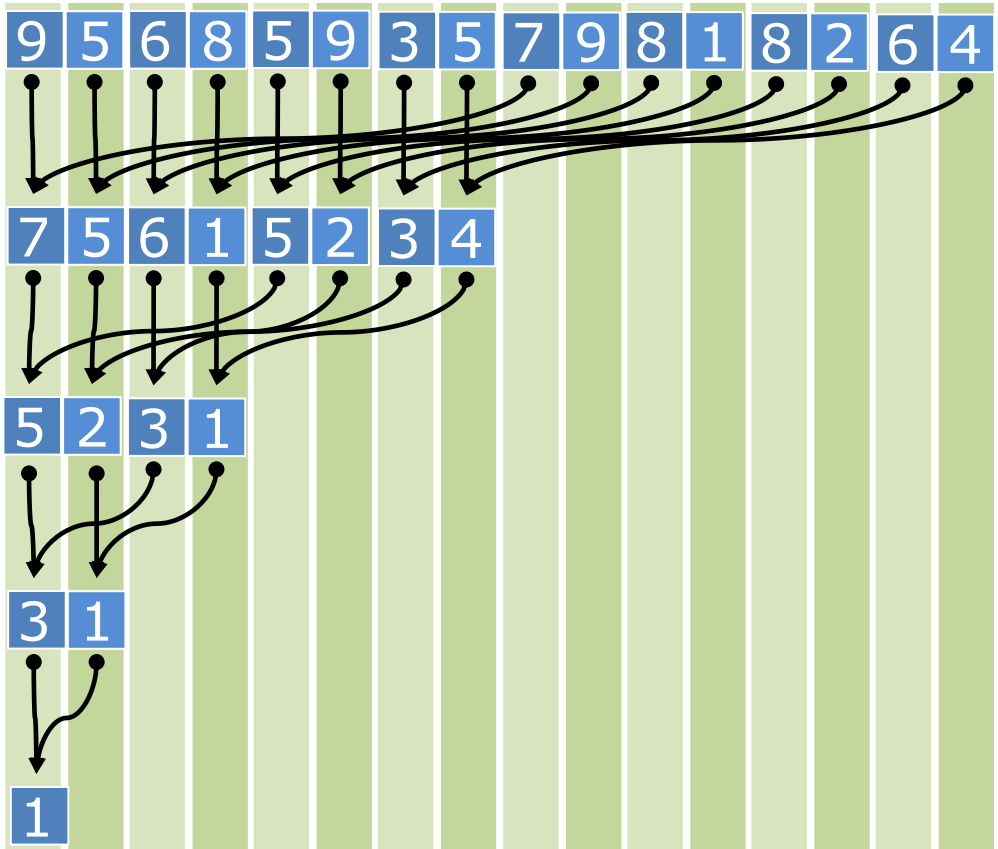
- Determine min and max bounds of the depth buffer on a per tile basis
- Atomic Min Max [Andersson09]

```
groupshared uint ldsZMin;
groupshared uint ldsZMax;

[numthreads(16, 16, 1)]
void CalculateDepthBoundsCS( uint3 globalIdx : SV_DispatchThreadID, uint3 localIdx : SV_GroupThreadID )
{
    uint localIdxFlattened = localIdx.x + localIdx.y*16;

    if( localIdxFlattened == 0 )
    {
        ldsZMin = 0x7f7fffff;  // FLT_MAX as a uint
        ldsZMax = 0;
    }

    GroupMemoryBarrierWithGroupSync();

    float depth = g_DepthTexture.Load( uint3(globalIdx.x,globalIdx.y,0) ).x;  // read one depth sample per thread

    uint z = asuint( ConvertProjDepthToView( depth ) );                       // reinterpret as uint

    if( depth != 0.0 )
    {
        InterlockedMax( ldsZMax, z );                                         // atomic min & max
        InterlockedMin( ldsZMin, z );
    }

    GroupMemoryBarrierWithGroupSync();

    float maxZ = asfloat( ldsZMax );                                          // reinterpret back to float
    float minZ = asfloat( ldsZMin );
}
```

Parallel Reduction

- Atomics are useful but not efficient
- Compute-friendly algorithm
- Great material already available:
  - "Optimizing Parallel Reduction in CUDA" [Harris07]
  - "Compute Shader Optimizations for AMD GPUs: Parallel Reduction" [Engel14]

```
depth[tid] = min(depth[tid],depth[tid+8])
depth[tid] = min(depth[tid],depth[tid+4])
depth[tid] = min(depth[tid],depth[tid+2])
depth[tid] = min(depth[tid],depth[tid+1])
```



Implementation details

- First pass reads 4 depth samples
- Needs to be separate pass
- Write bounds to UAV
  - Maybe useful for other things too

```
groupshared float ldsZMin[64];
groupshared float ldsZMax[64];

[numthreads(8,8,1)]
void CalculateDepthBoundsCS( uint3 globalIdx : SV_DispatchThreadID, uint3 localIdx : SV_GroupThreadID, uint3 groupIdx : SV_GroupID )
{
    uint2 sampleIdx = globalIdx.xy*2;

    float depth00 = g_SceneDepthBuffer.Load(uint3(sampleIdx.x,  sampleIdx.y,  0)).x;        float viewPosZ00 = ConvertProjDepthToView(depth00);
    float depth01 = g_SceneDepthBuffer.Load(uint3(sampleIdx.x,  sampleIdx.y+1,0)).x;        float viewPosZ01 = ConvertProjDepthToView(depth01);
    float depth10 = g_SceneDepthBuffer.Load(uint3(sampleIdx.x+1,sampleIdx.y,  0)).x;        float viewPosZ10 = ConvertProjDepthToView(depth10);
    float depth11 = g_SceneDepthBuffer.Load(uint3(sampleIdx.x+1,sampleIdx.y+1,0)).x;        float viewPosZ11 = ConvertProjDepthToView(depth11);

    float minZ00 = (depth00 != 0.f) ? viewPosZ00 : FLT_MAX;                                 float maxZ00 = (depth00 != 0.f) ? viewPosZ00 : 0.0f;
    float minZ01 = (depth01 != 0.f) ? viewPosZ01 : FLT_MAX;                                 float maxZ01 = (depth01 != 0.f) ? viewPosZ01 : 0.0f;
    float minZ10 = (depth10 != 0.f) ? viewPosZ10 : FLT_MAX;                                 float maxZ10 = (depth10 != 0.f) ? viewPosZ10 : 0.0f;
    float minZ11 = (depth11 != 0.f) ? viewPosZ11 : FLT_MAX;                                 float maxZ11 = (depth11 != 0.f) ? viewPosZ11 : 0.0f;

    uint threadNum = localIdx.x + localIdx.y*8;

    ldsZMin[threadNum] = min(minZ00,min(minZ01,min(minZ10,minZ11)));
    ldsZMax[threadNum] = max(maxZ00,max(maxZ01,max(maxZ10,maxZ11)));

    GroupMemoryBarrierWithGroupSync();

    if (threadNum < 32)
    {
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+32]);              ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+32]);
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+16]);              ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+16]);
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+8]);               ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+8]);
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+4]);               ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+4]);
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+2]);               ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+2]);
        ldsZMin[threadNum] = min(ldsZMin[threadNum],ldsZMin[threadNum+1]);               ldsZMax[threadNum] = max(ldsZMax[threadNum],ldsZMax[threadNum+1]);
    }

    GroupMemoryBarrierWithGroupSync();

    if(threadNum == 0)
    {
        g_DepthBounds[groupIdx.xy] = float2(ldsZMin[0],ldsZMax[0]);
    }
}
```

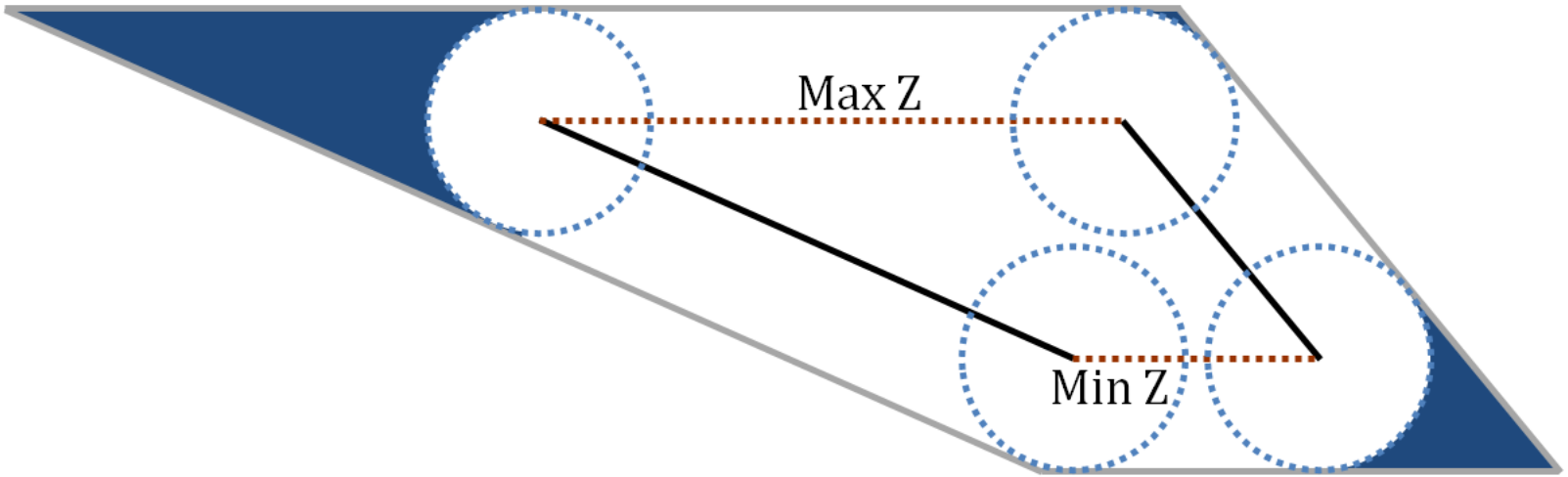
Parallel Reduction - Performance

	Atomic Min/Max	Parallel Reduction
AMD R9 290X	1.8ms	1.60ms
NVIDIA GTX 980	1.8ms	1.54ms

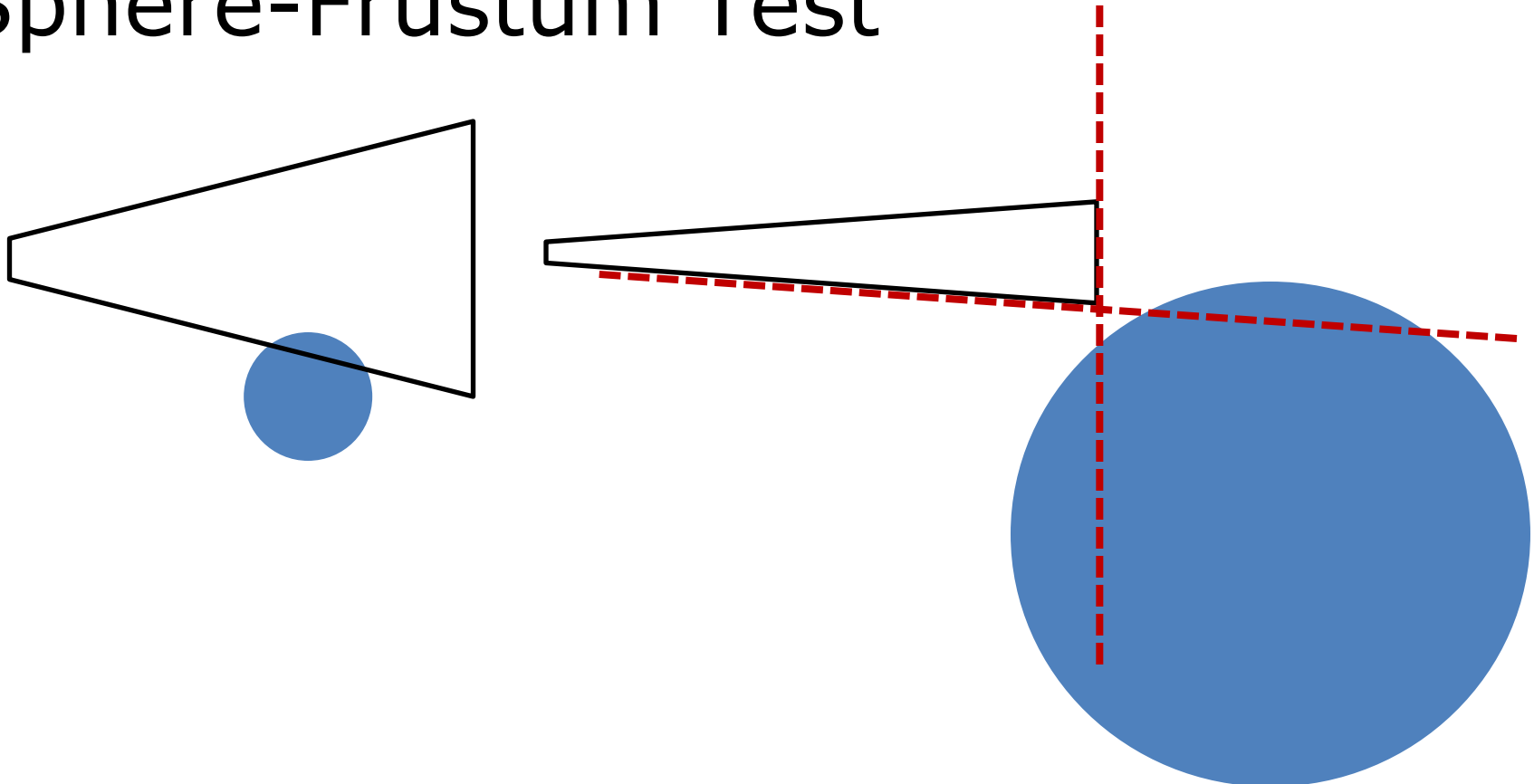
- Combined cost of depth bounds and light culling of 2048 lights at 3840x2160
- Parallel reduction pass takes ~0.35ms
- Faster than Atomic Min/Max on the GPUs tested

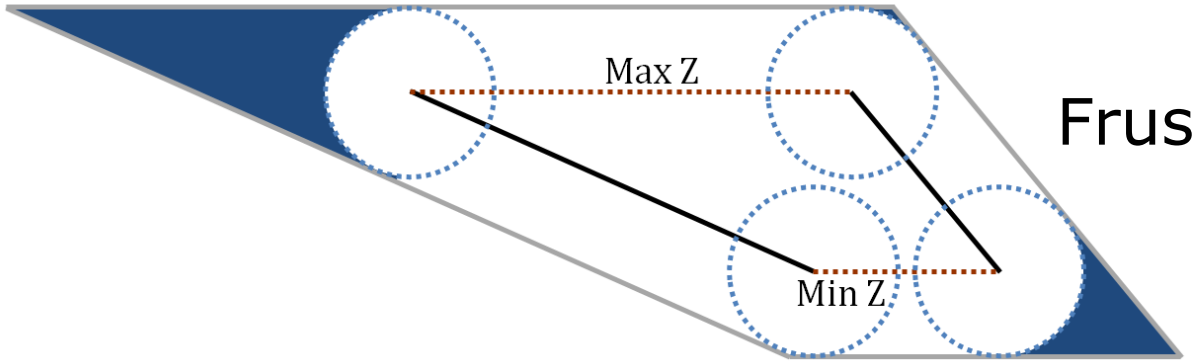
Light Culling:
The Intersection Test

Sphere-Frustum Test



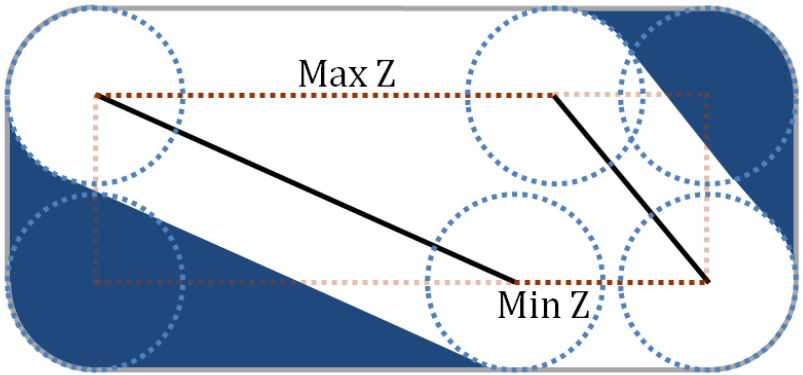
Sphere-Frustum Test

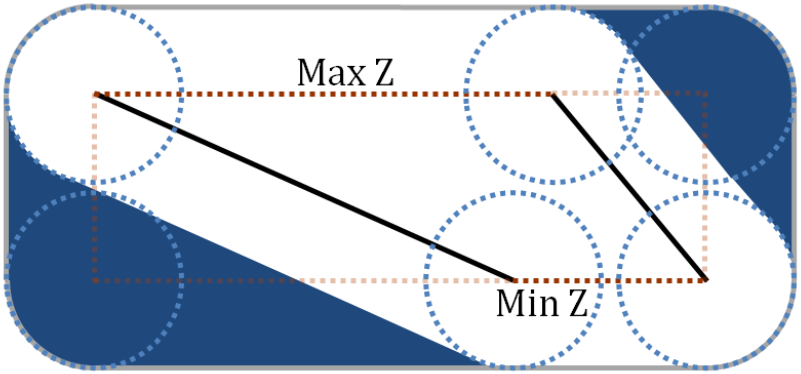




Frustum planes

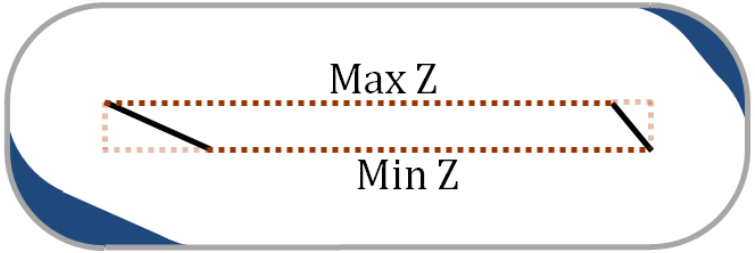
AABB around Frustum





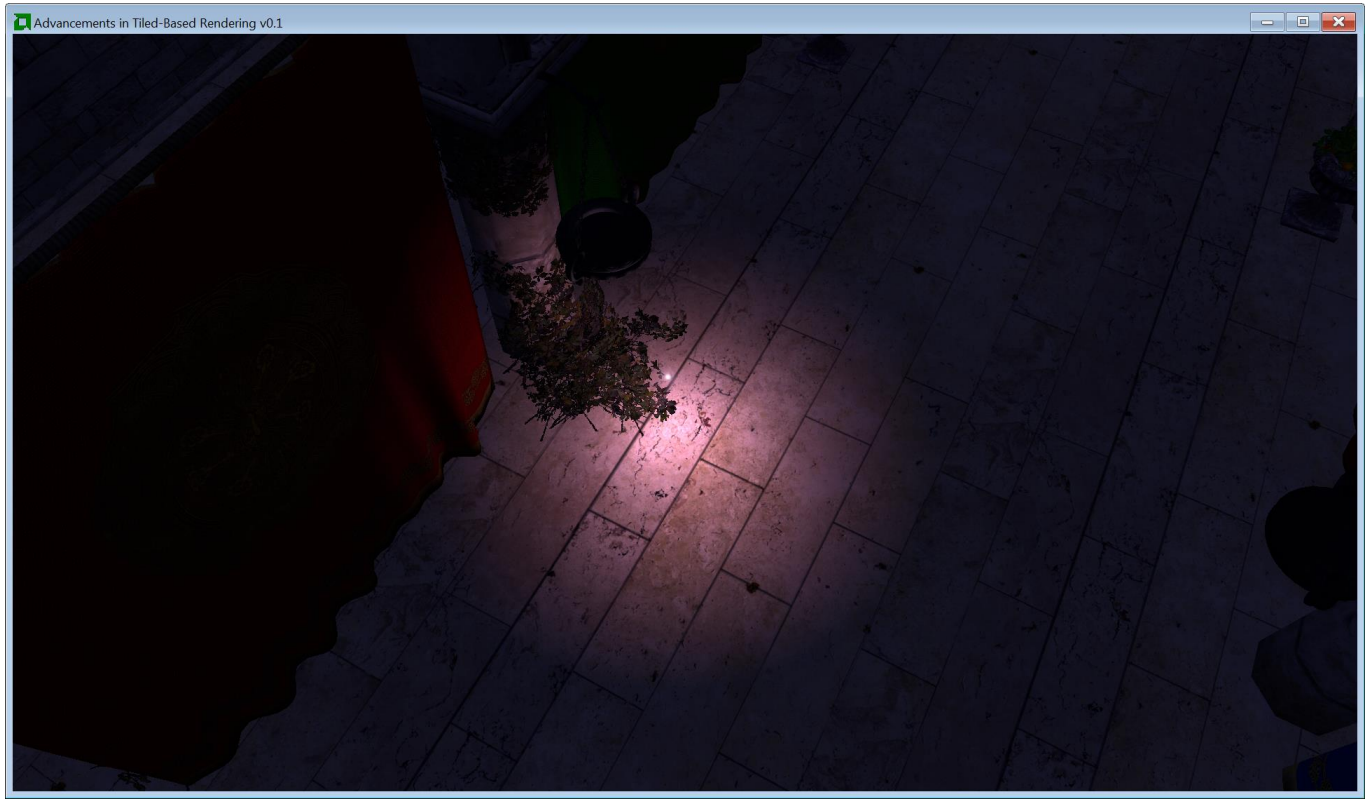
AABB around long frustum

AABB around short frustum

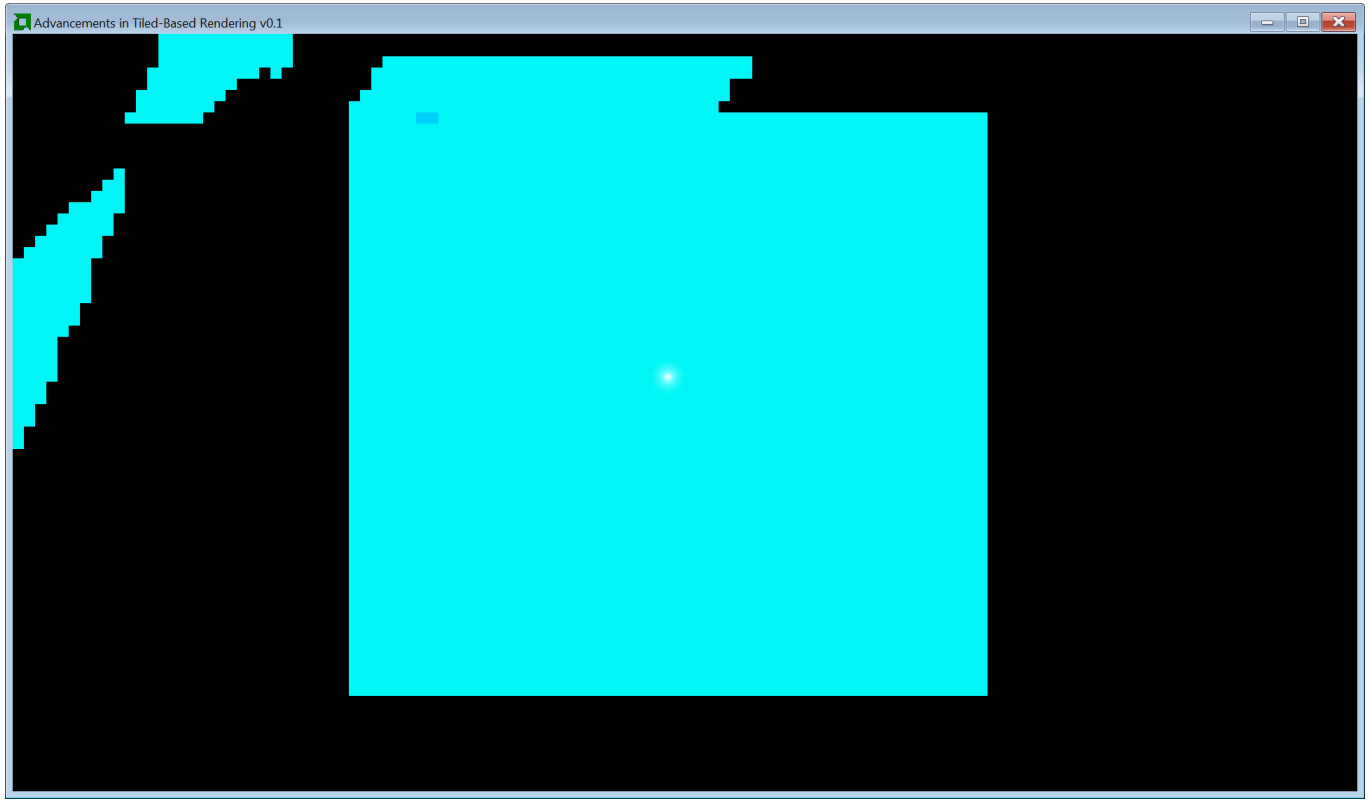


Arvo Intersection Test [Arvo90]

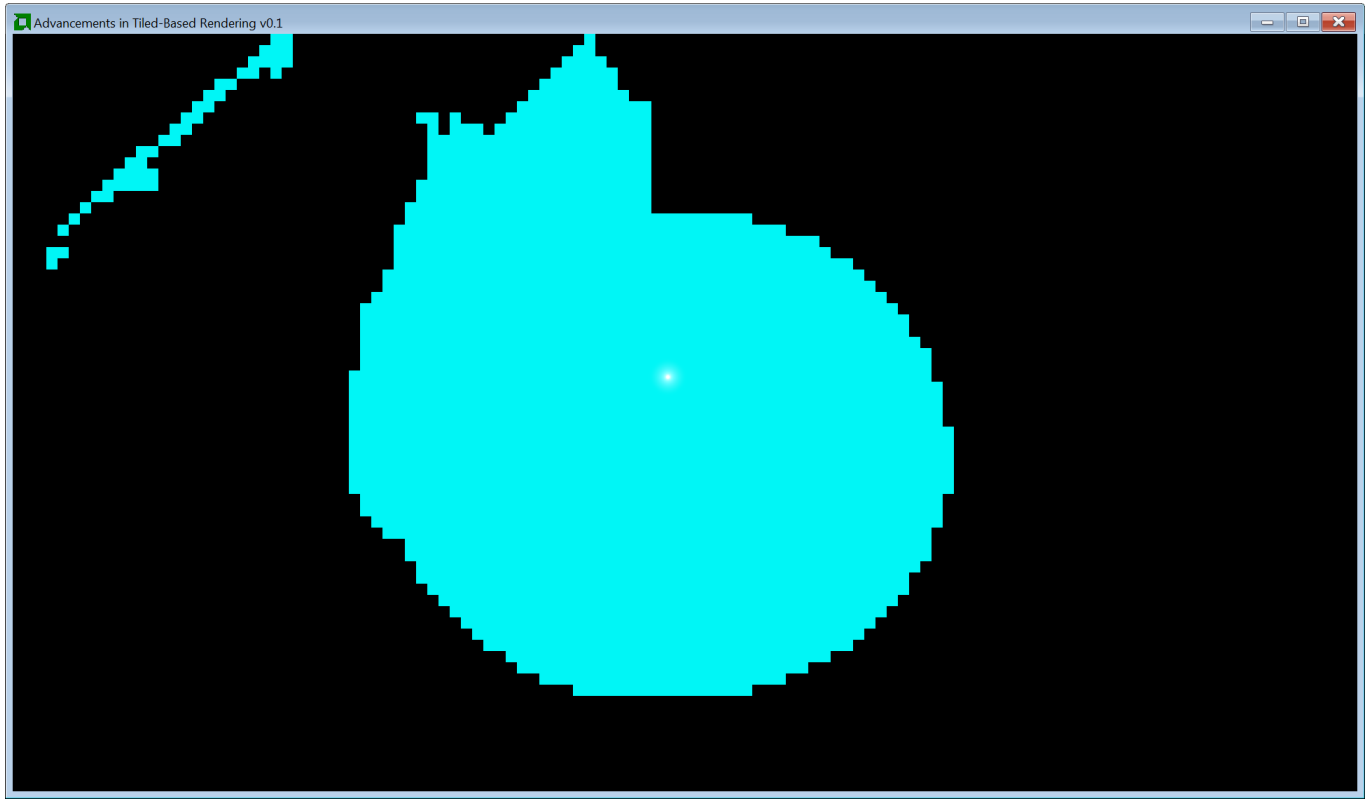
```
bool TestSphereVsAABB(float3 sphereCenter, float sphereRadius, float3 AABBCenter, float3 AABBHalfSize)
{
    float3 delta = max(0, abs(AABBCenter - sphereCenter) - AABBHalfSize);

    float distSq = dot(delta, delta);

    return distSq <= sphereRadius * sphereRadius;
}
```



Single Point Light



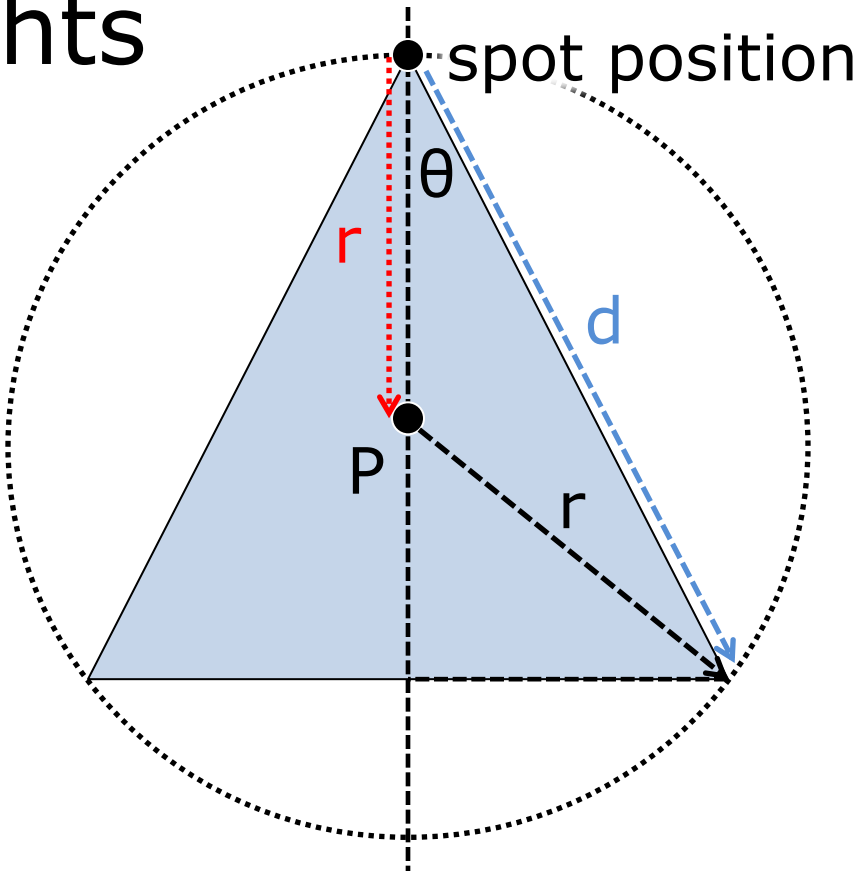
Frustum/Sphere Test



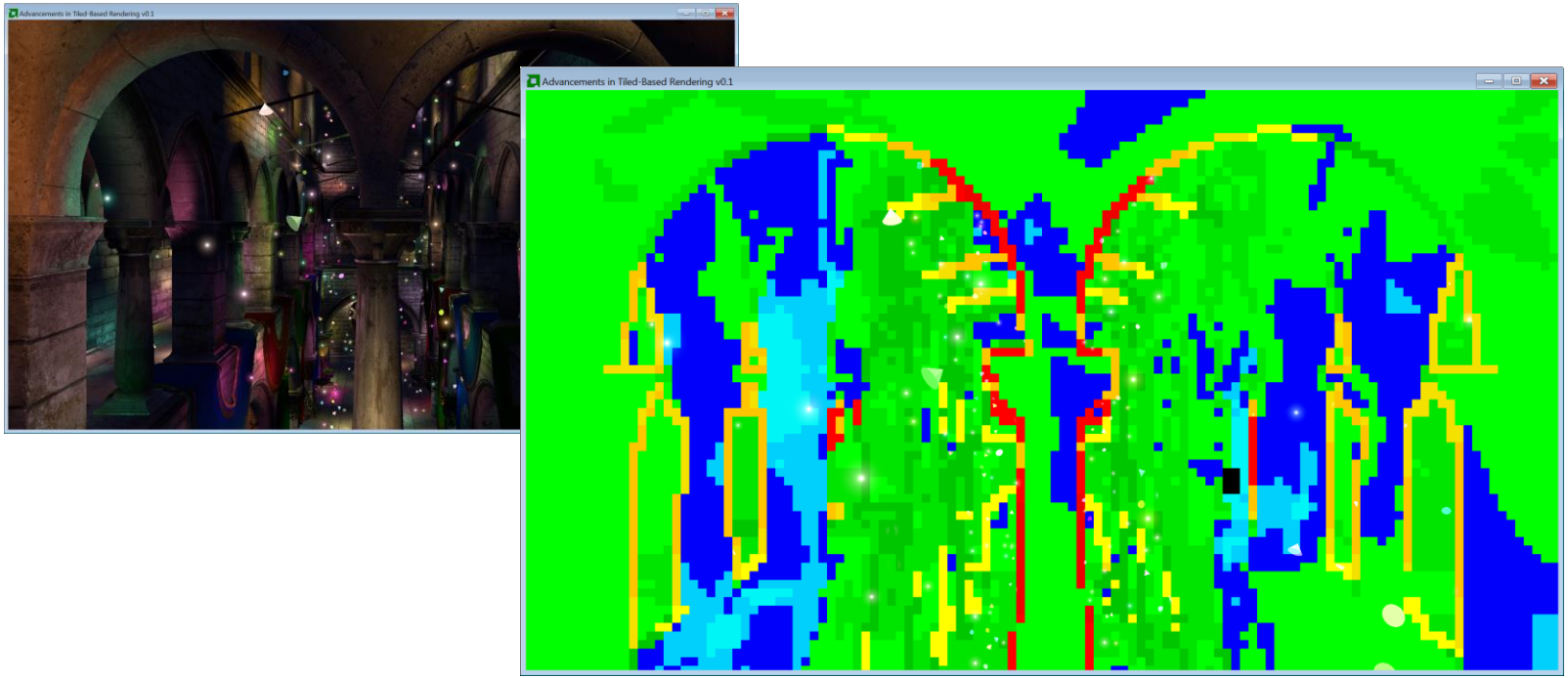
Arvo AABB/Sphere Test

Culling Spot Lights

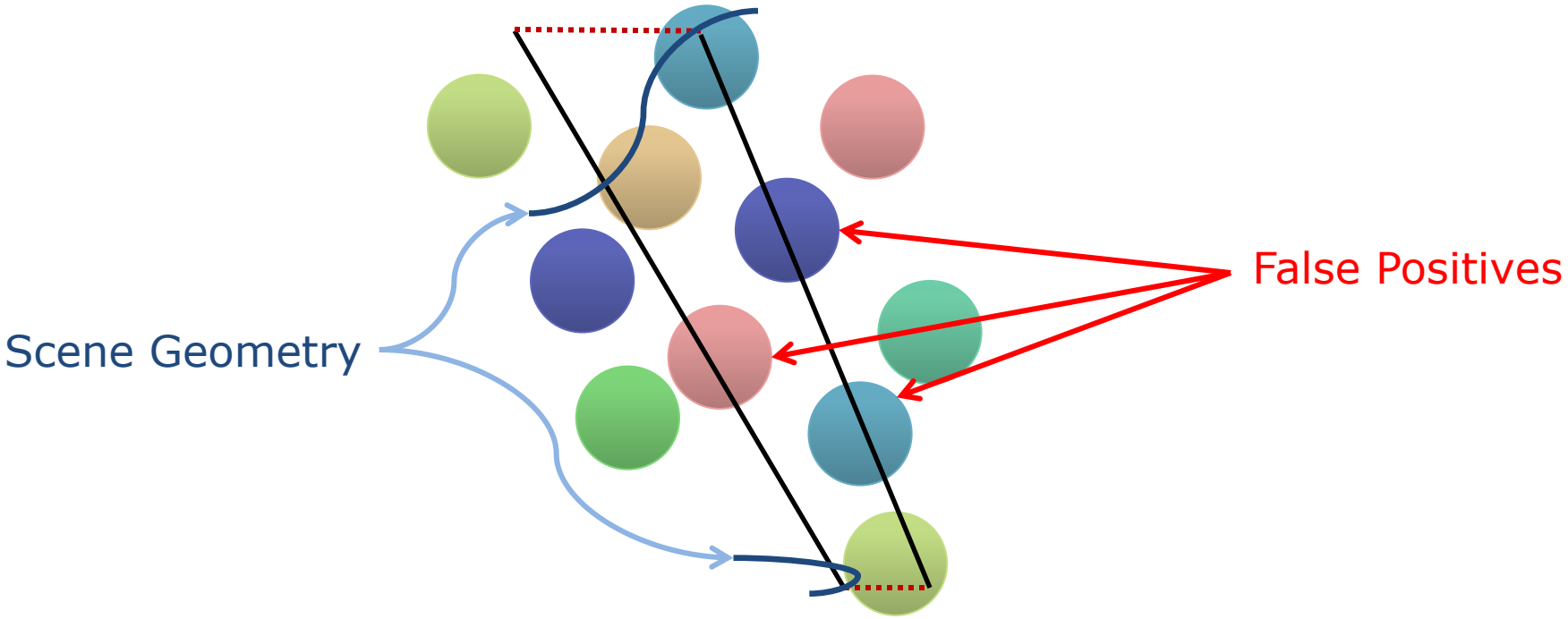
- Don’t put bounding sphere around spot light origin
- Tightly bound spot light inside sphere at P with radius r



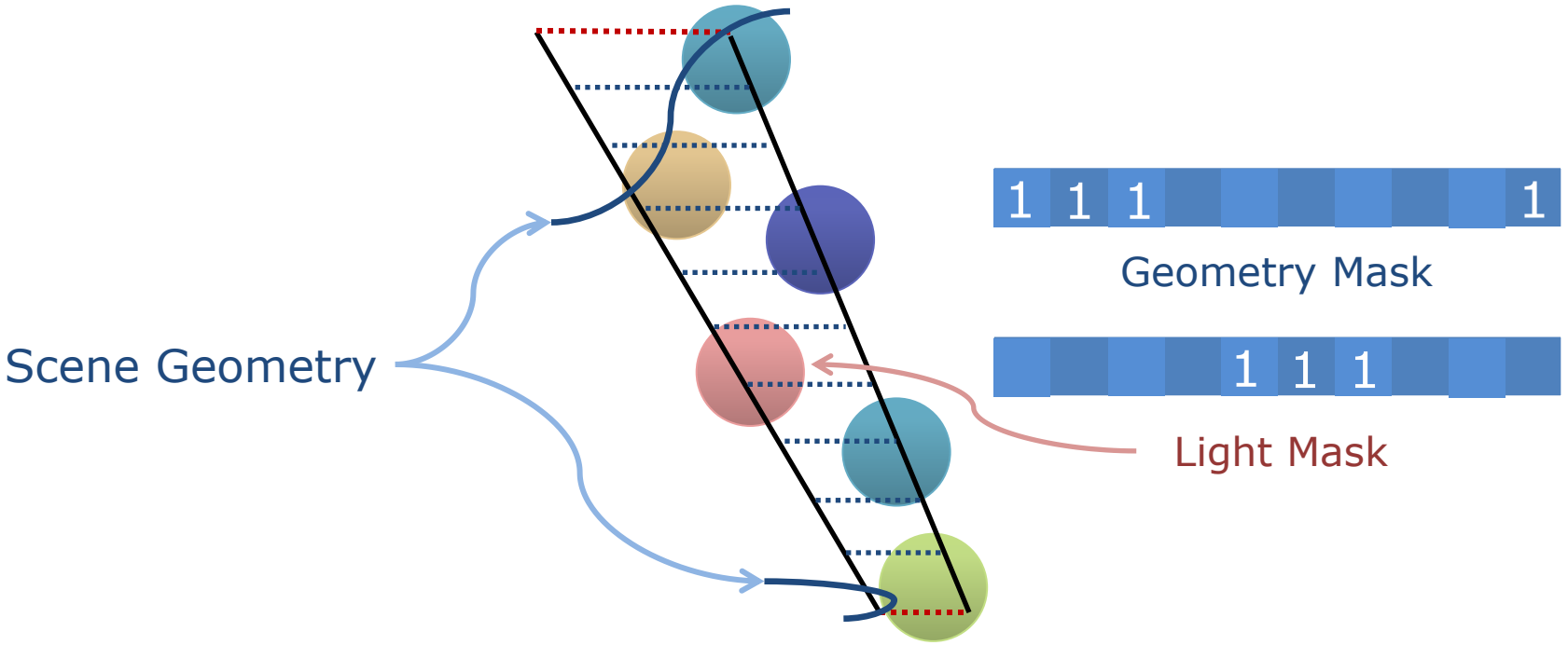
Depth Discontinuities



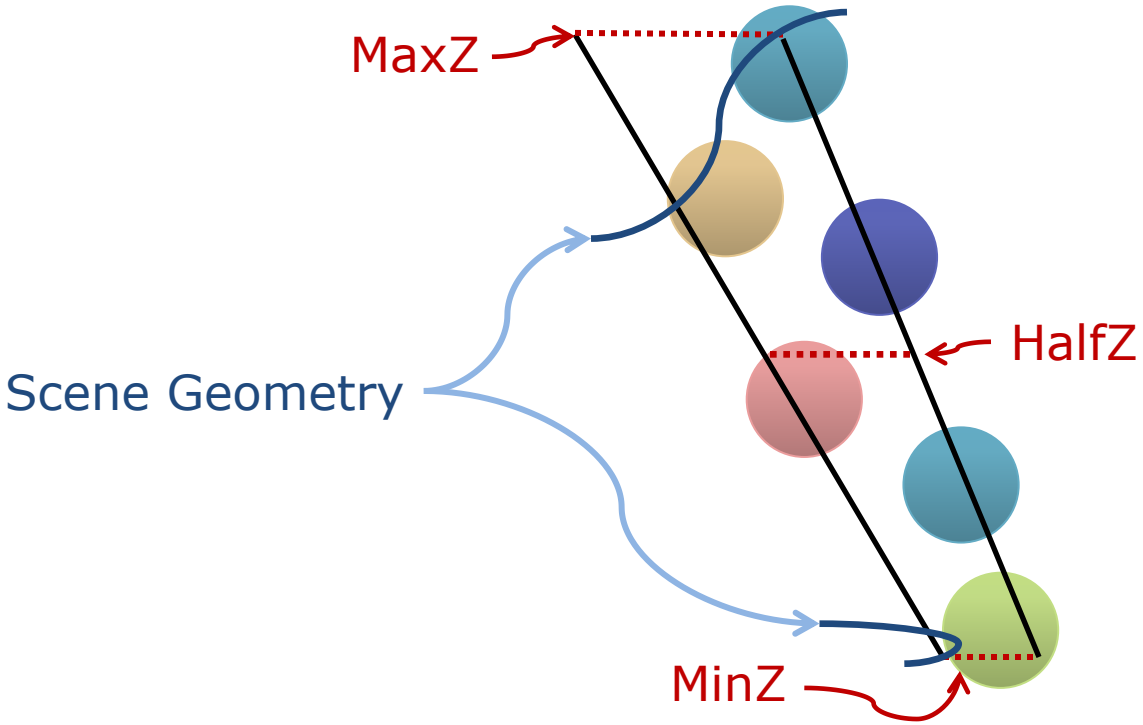
Depth Discontinuities



2.5D Culling [Harada et al 12]



HalfZ



HalfZ low bits

HalfZ high bits

numLights near side

numLights far side

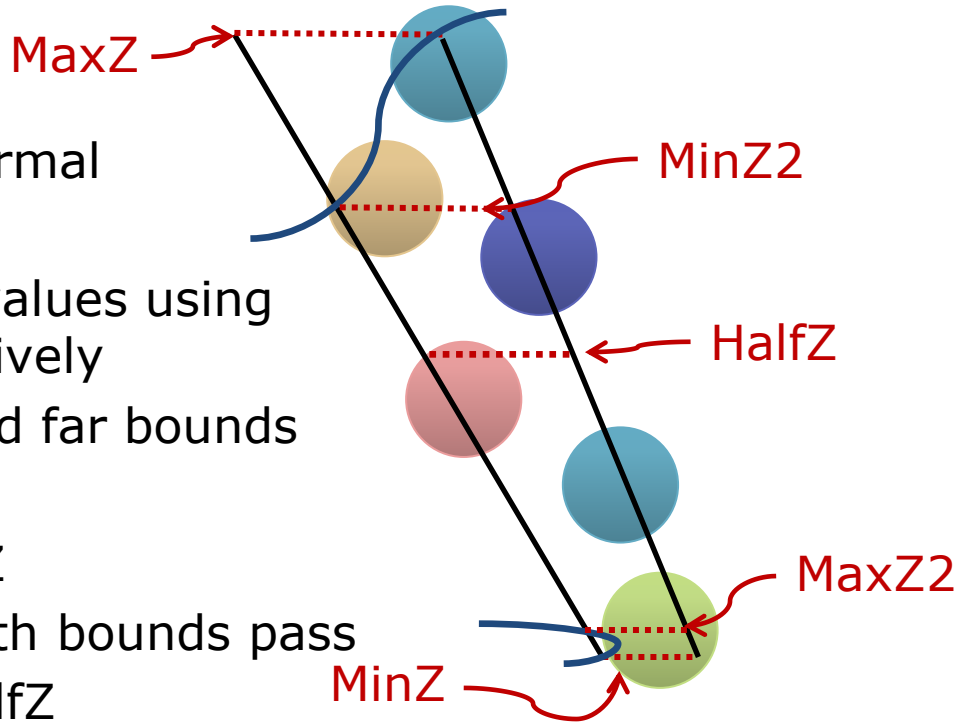
light indices…

16 bit light index buffer

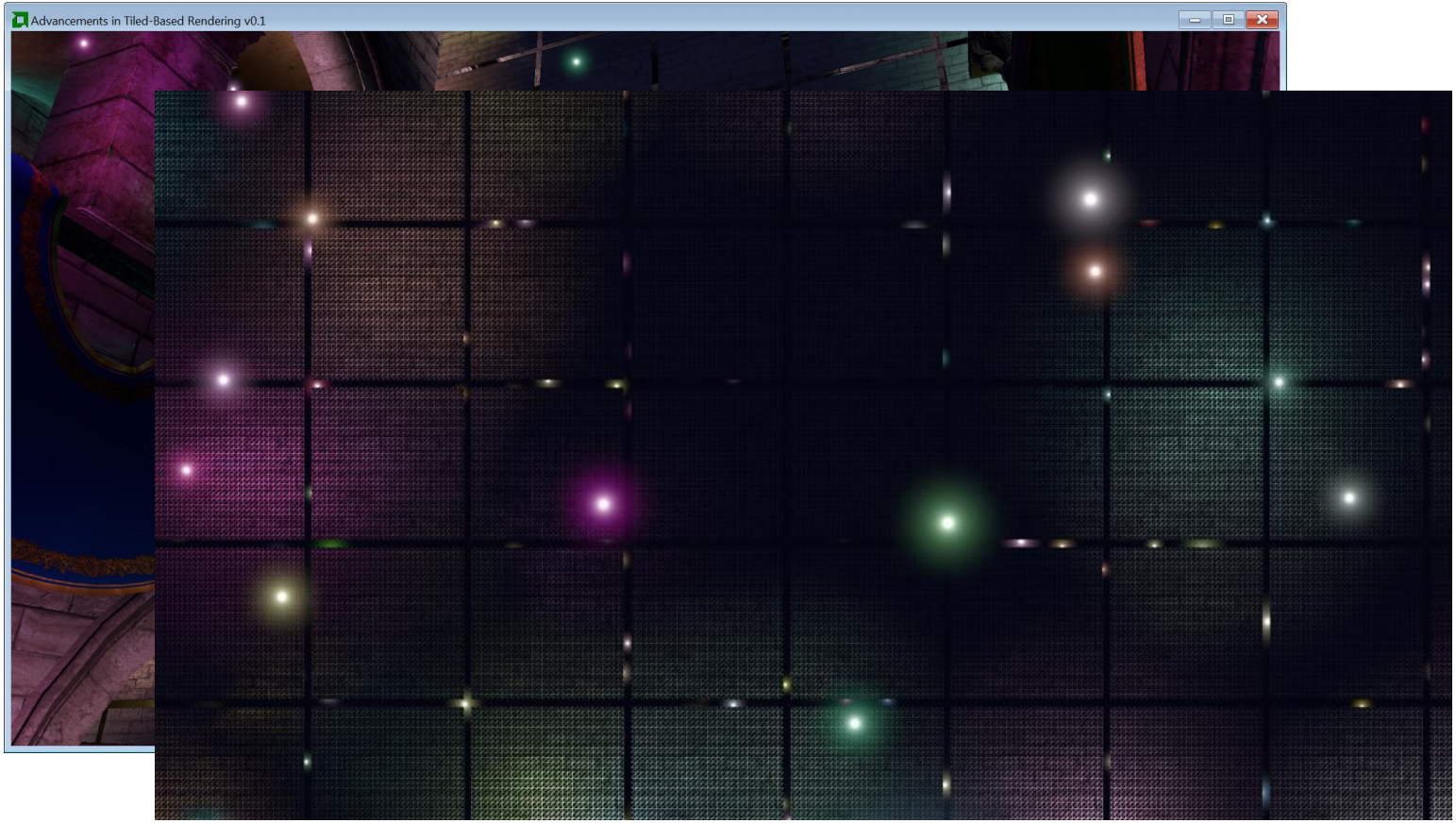
size: maxLightsPerTile x 2 + 4

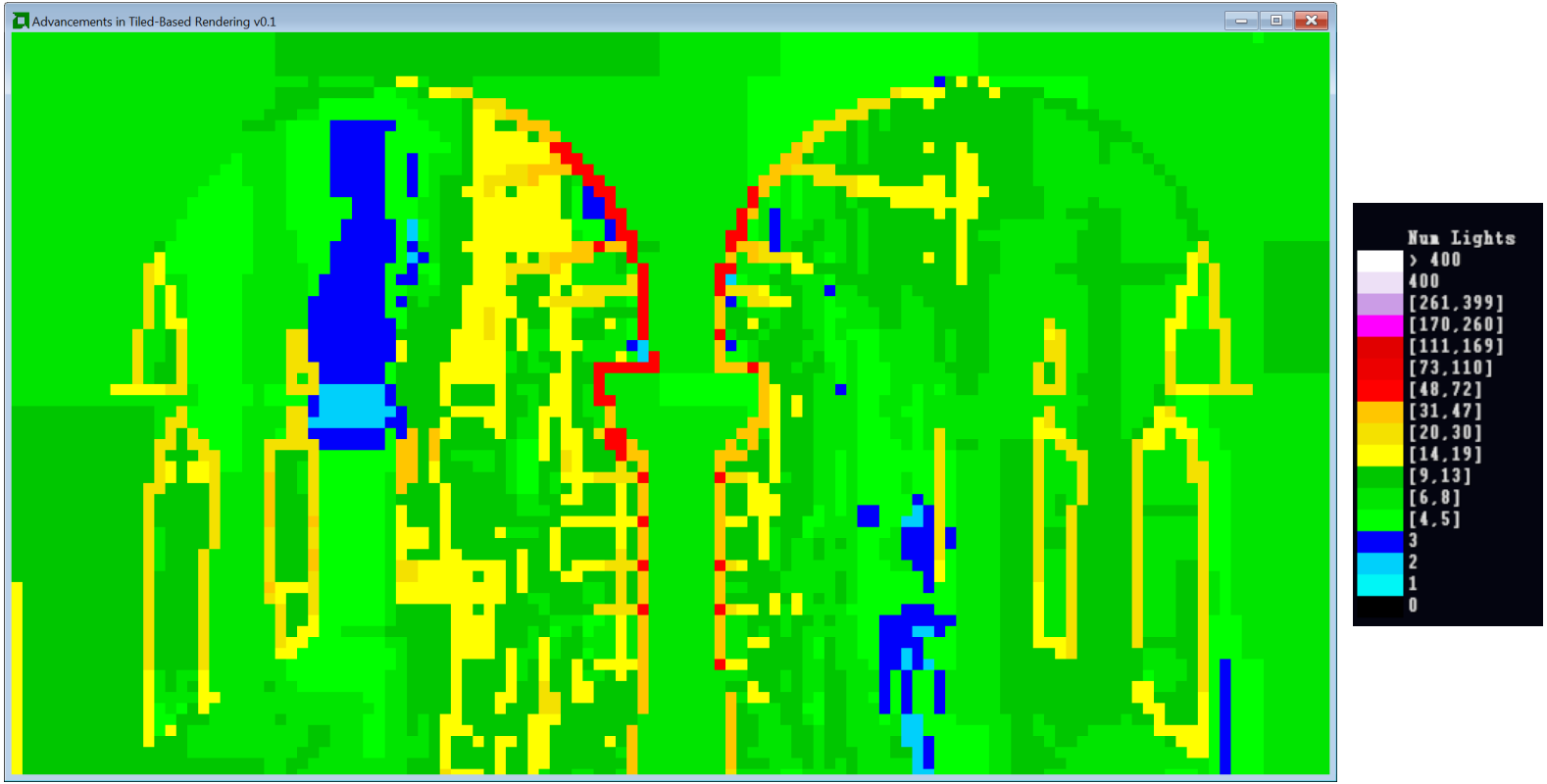
Modified HalfZ

- Calculate Min & Max Z as normal
- Calculate HalfZ
- Second set of Min and Max values using HalfZ and max & min respectively
- Test against near bounds and far bounds
- Write to either one list
- Or write to two lists *cf.* HalfZ
- Doubles the work in the depth bounds pass
- Worst case converges on HalfZ

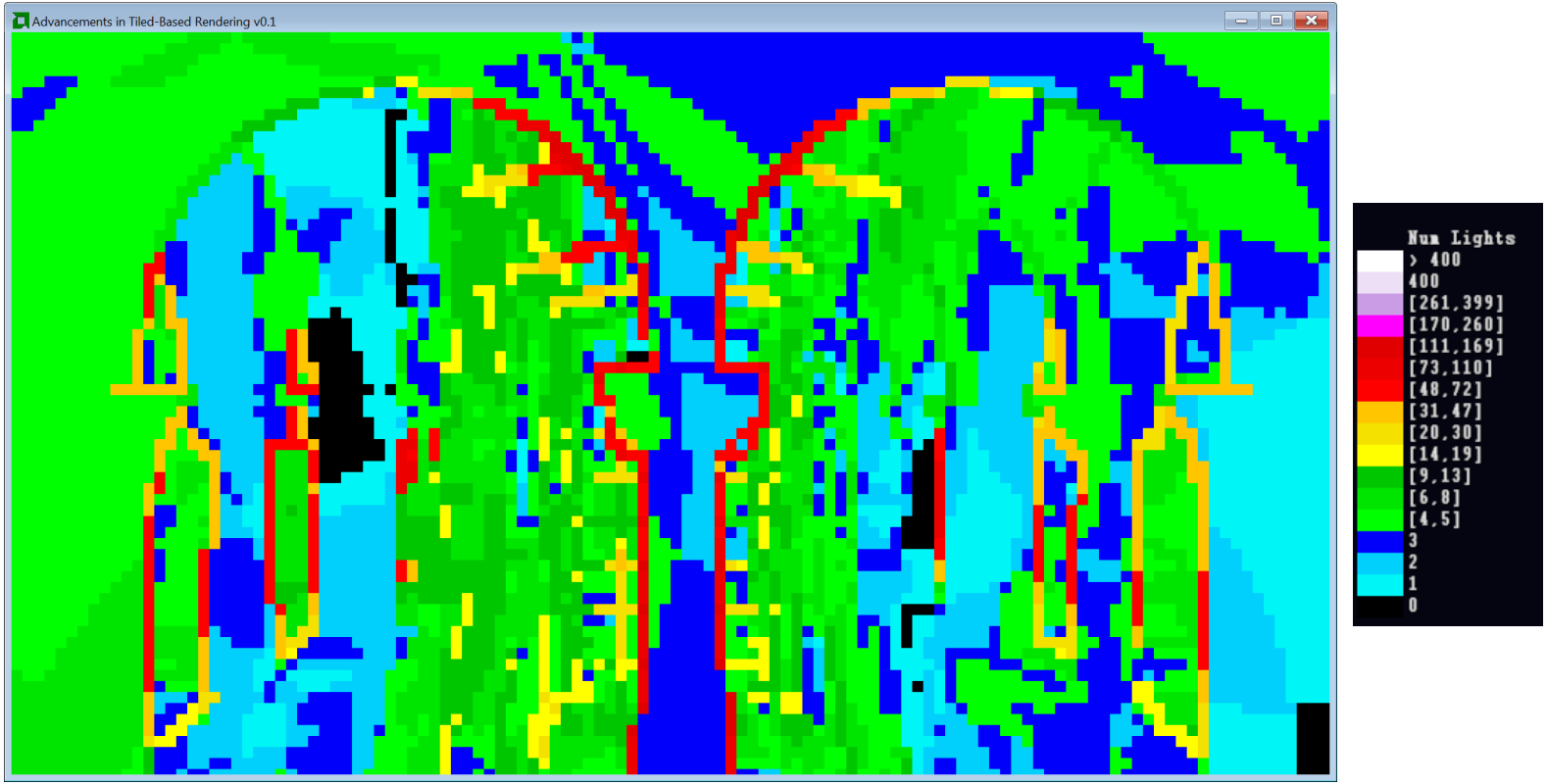


Sponza Atrium + 1 million sub pixel triangles

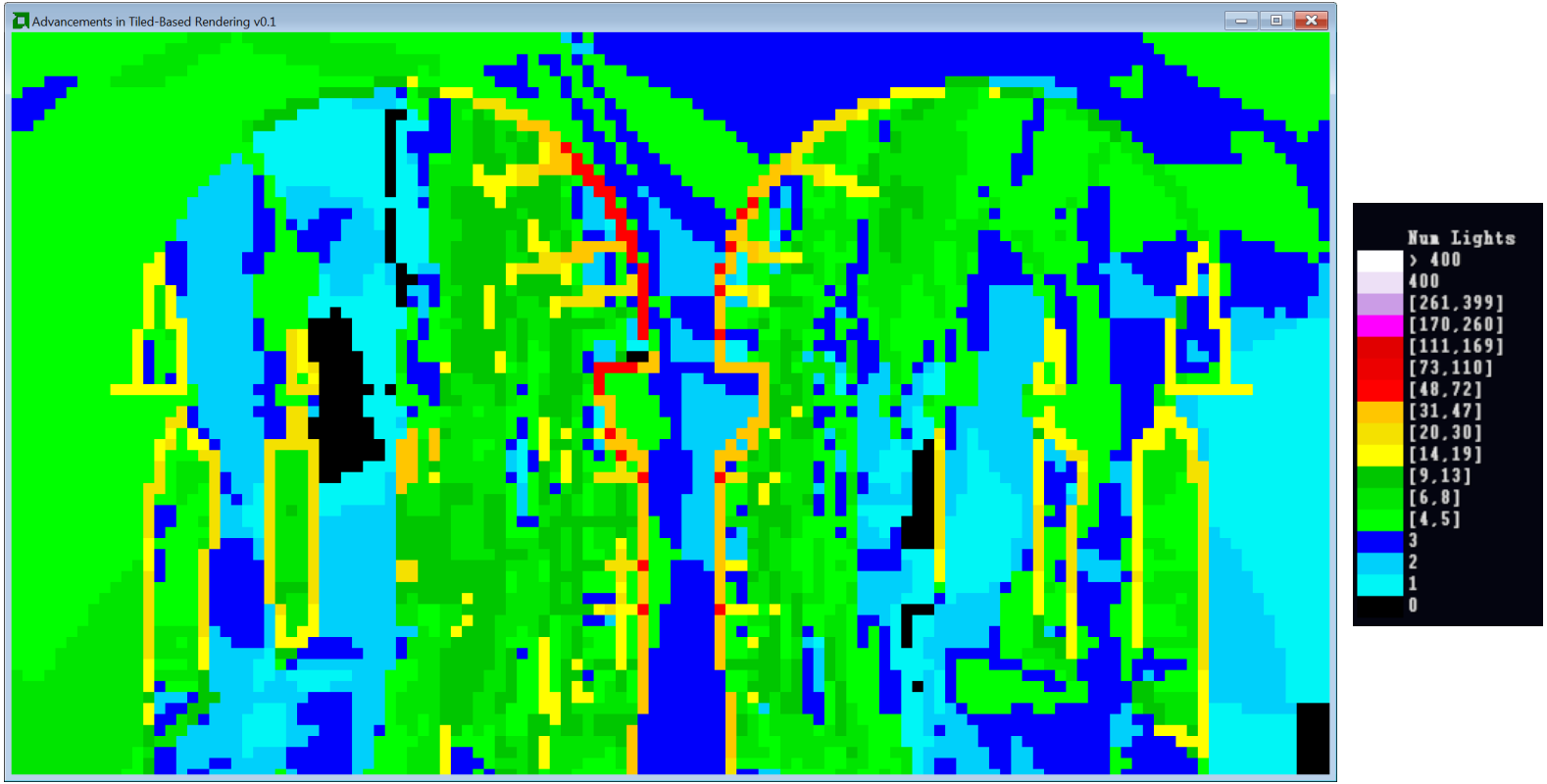

Advancements in Tiled-Based Rendering v0.1



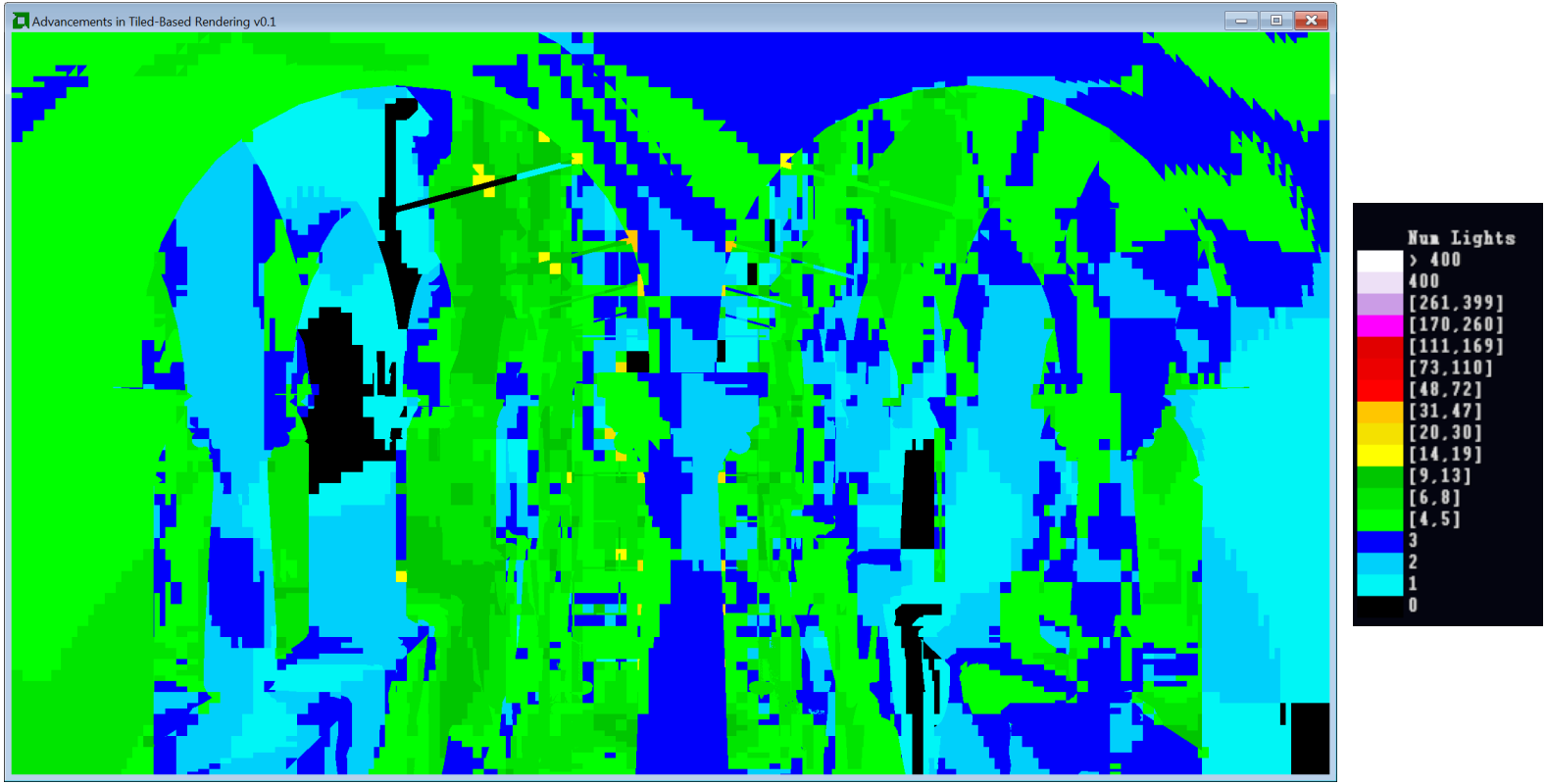
MinMax depth bounds, Frustum culling



MinMax depth bounds, AABB culling



MinMax depth bounds, Hybrid culling (AABB + Frustum sides)

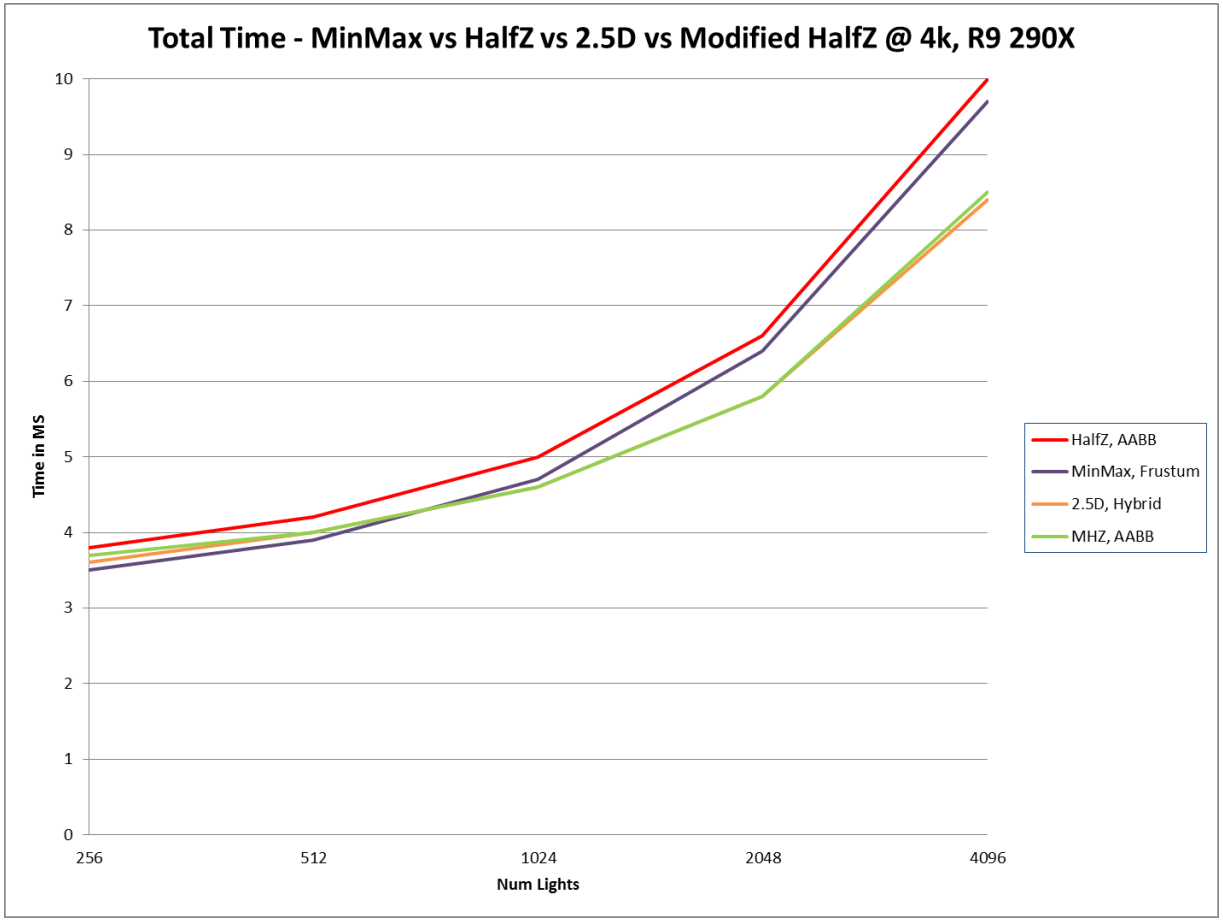


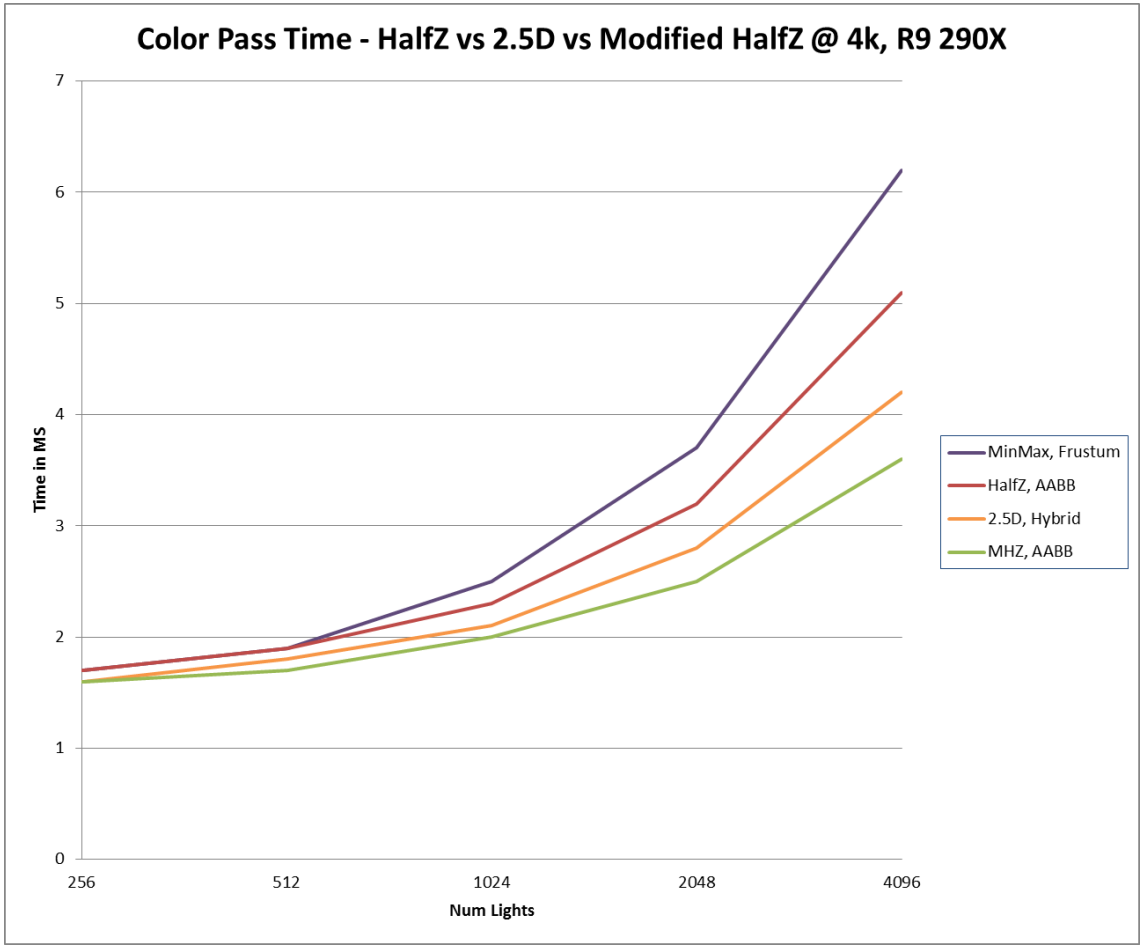
Modified HalfZ depth bounds, AABB culling

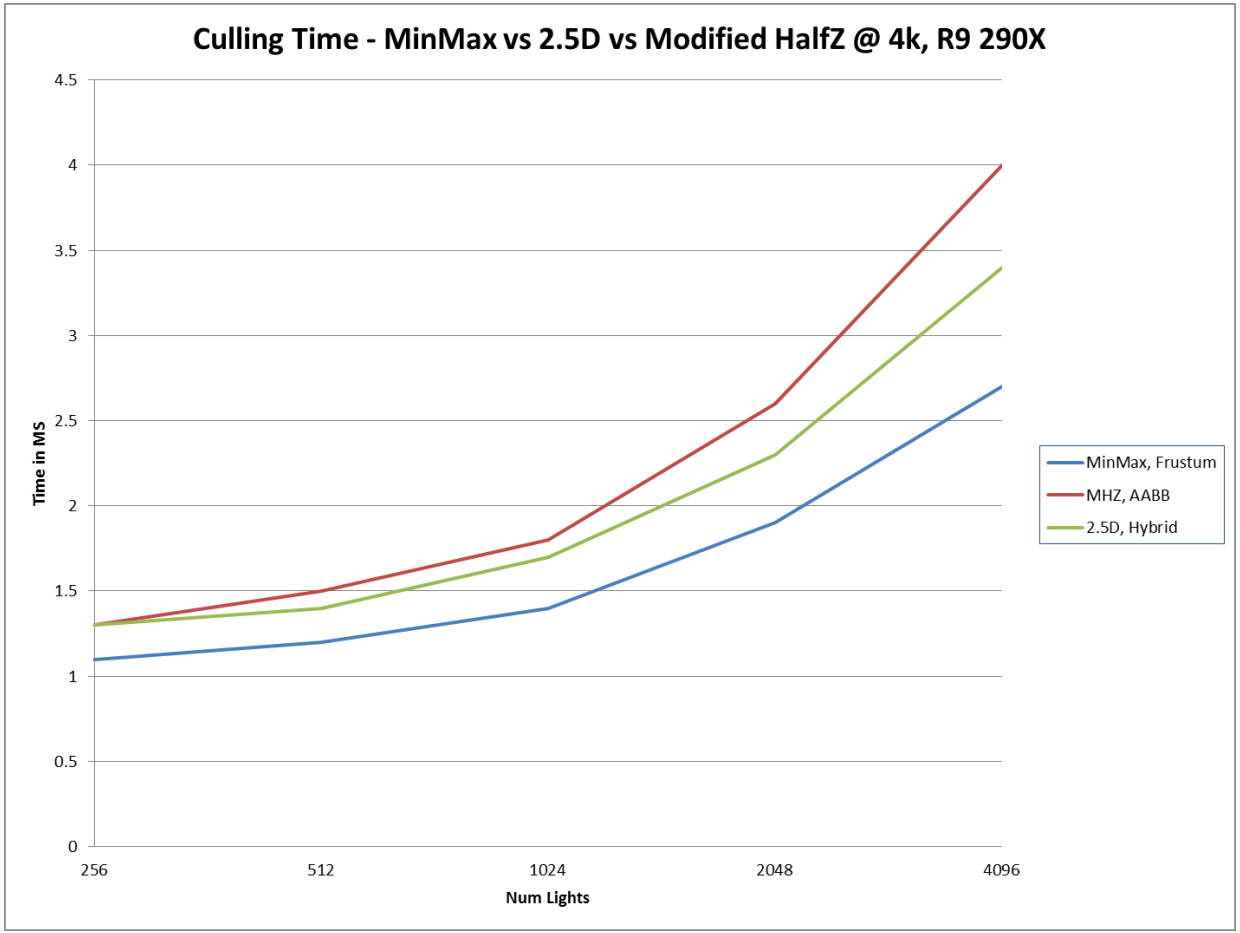
Unreal Engine 4, Infiltrator Demo

MinMax Depth Bounds

Modified HalfZ in one light list

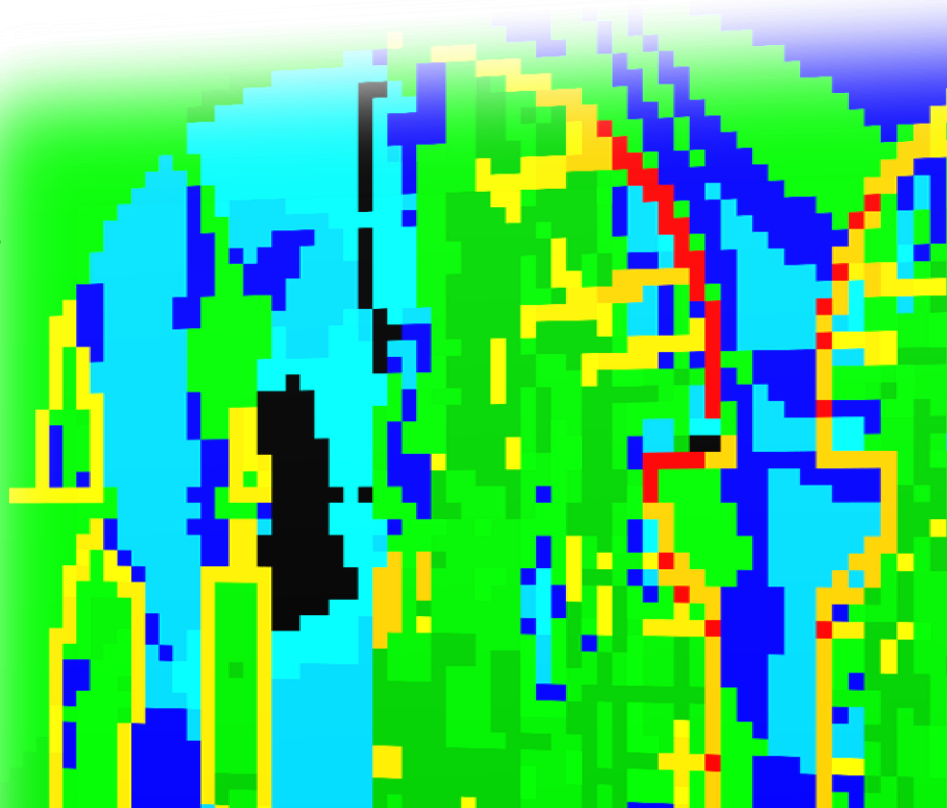

Total Time - MinMax vs HalfZ vs 2.5D vs Modified HalfZ @ 4k, R9 290X
Time in MS
0
1
2
3
4
5
6
7
8
9
10
256
512
1024
2048
4096
Num Lights
HalfZ, AABB
MinMax, Frustum
2.5D, Hybrid
MHZ, AABB

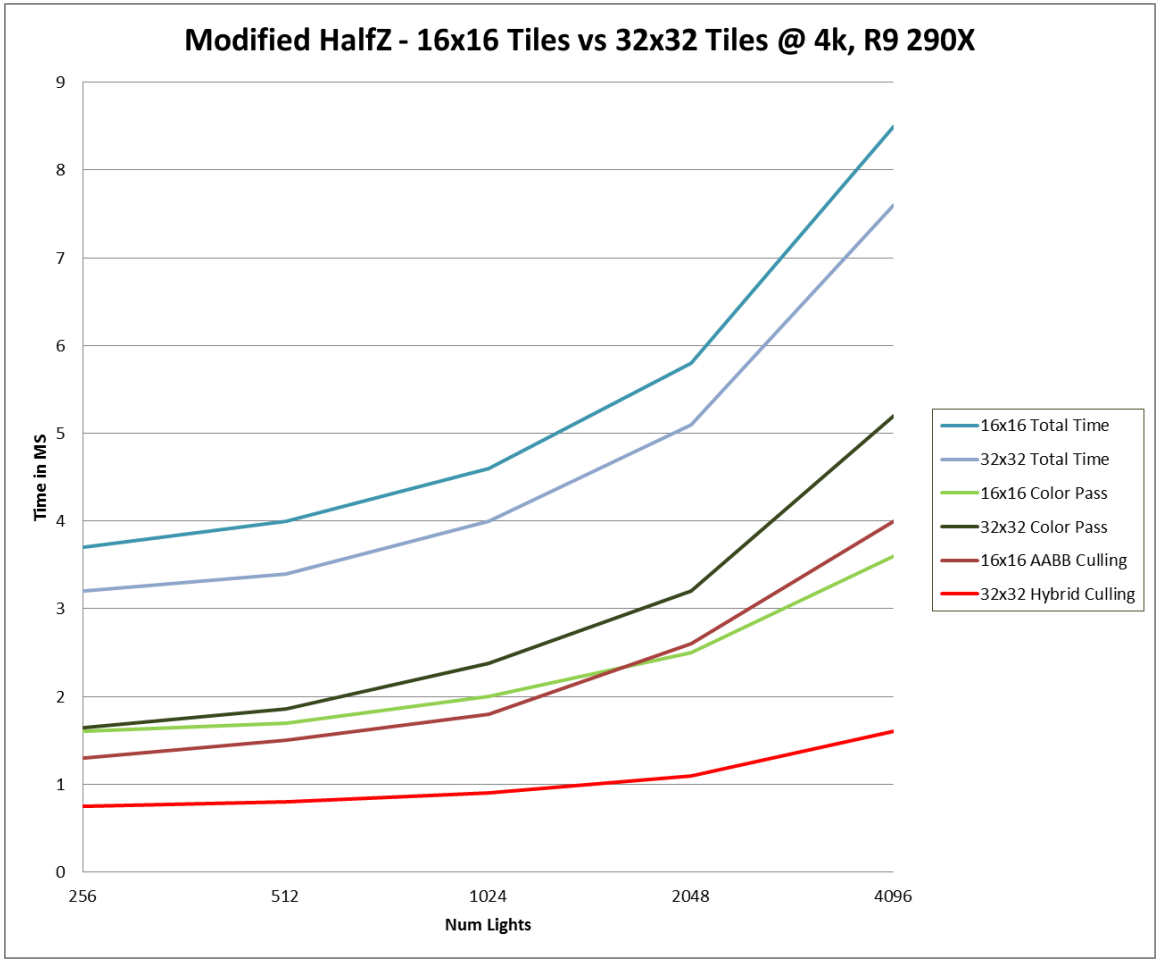

Color Pass Time - HalfZ vs 2.5D vs Modified HalfZ @ 4k, R9 290X
Time in MS
0
1
2
3
4
5
6
7
256
512
1024
2048
4096
Num Lights
MinMax, Frustum
HalfZ, AABB
2.5D, Hybrid
MHZ, AABB


Culling Time - MinMax vs 2.5D vs Modified HalfZ @ 4k, R9 290X
Time in MS
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
256
512
1024
2048
4096
Num Lights
MinMax, Frustum
MHZ, AABB
2.5D, Hybrid

What happens if we cull 32x32 tiles?

Still using 16x16 thread groups




Modified HalfZ - 16x16 Tiles vs 32x32 Tiles @ 4k, R9 290X
Time in MS
0
1
2
3
4
5
6
7
8
9
256
512
1024
2048
4096
Num Lights
16x16 Total Time
32x32 Total Time
16x16 Color Pass
32x32 Color Pass
16x16 AABB Culling
32x32 Hybrid Culling

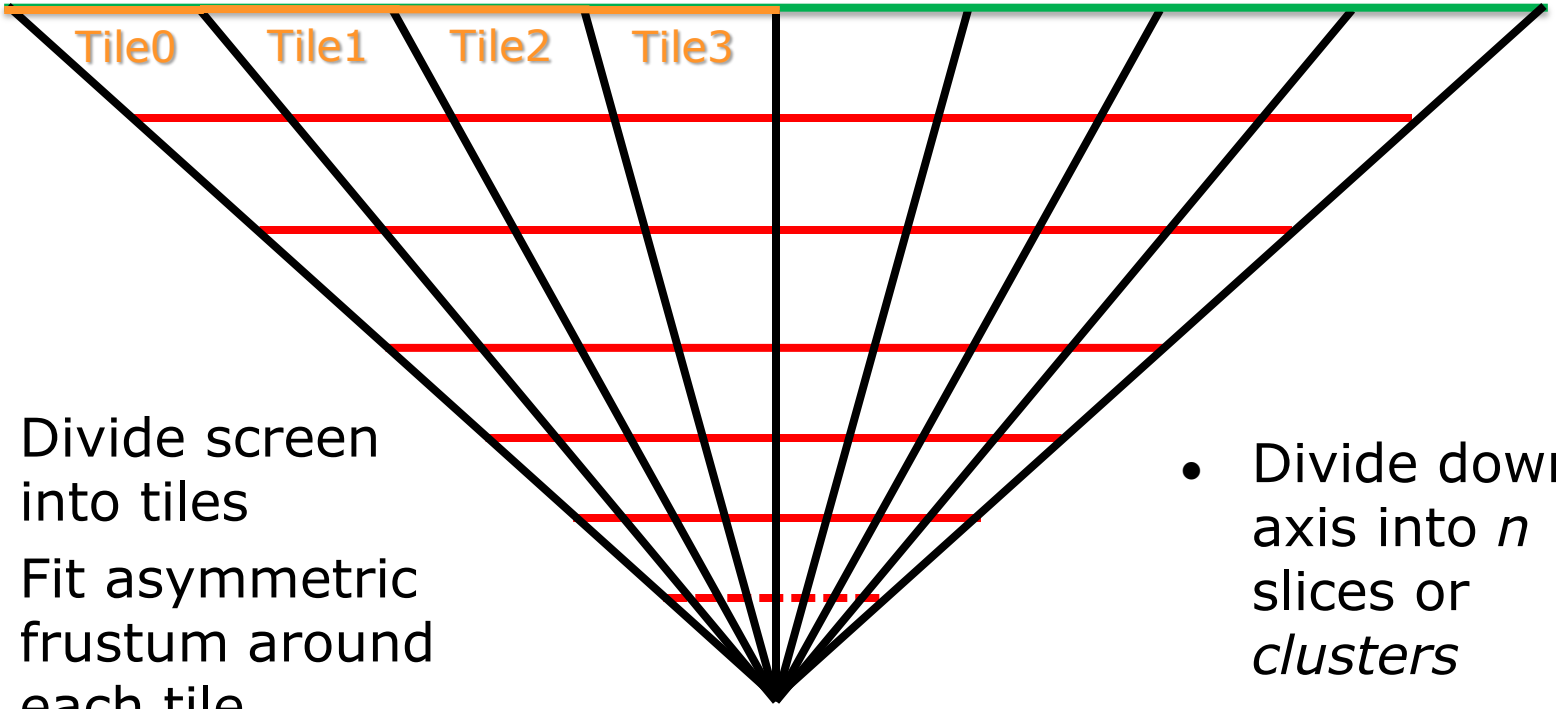
Culling Conclusion

- Modified HalfZ with AABBs generally works best
  - Even though generating MinZ2 and MaxZ2 adds a little cost
  - Even though culling each light against two AABBs instead of one
- 32x32 tiles saves a good chunk of time in the culling stage
  - …at the cost of color pass efficiency when pushing larger number of lights

Clustered Rendering [Olsson et al12]

- Production proven in Forza Horizon 2
- Additional benefits on top of 2D culling:
  - No mandatory Z prepass
  - Just works™ for transparencies and volumetric effects
- Can a further reduction in lights per pixel improve performance?

Clustered Rendering 101

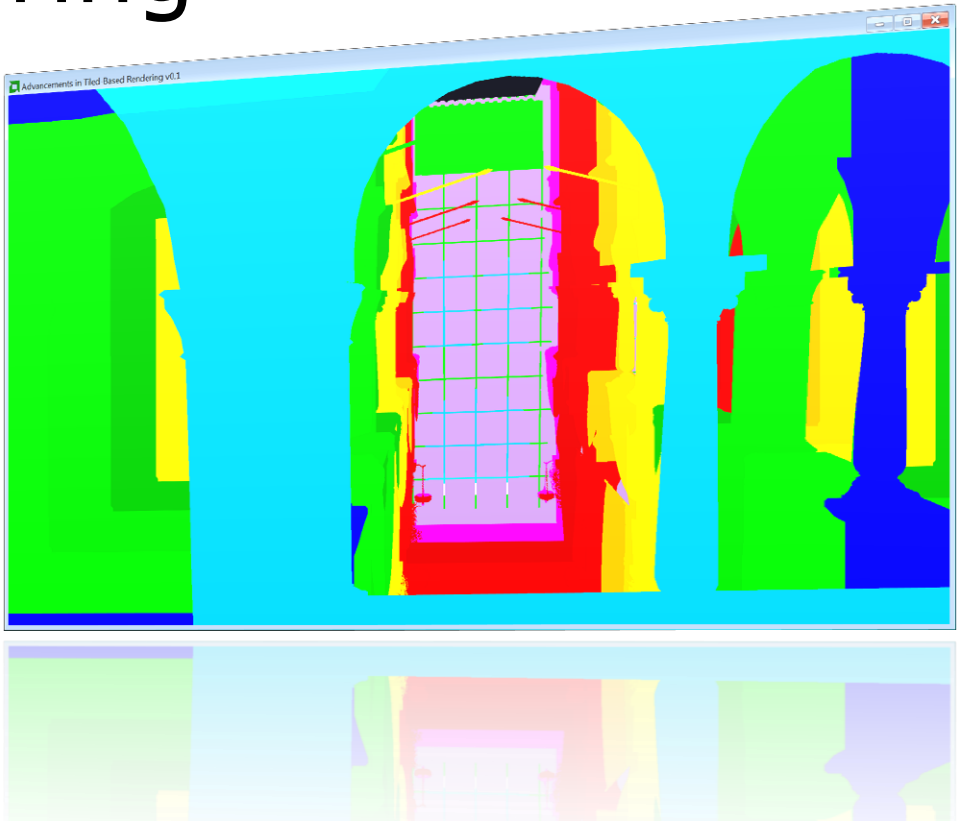


- Divide screen into tiles
- Fit asymmetric frustum around each tile

- Divide down Z axis into *n* slices or *clusters*

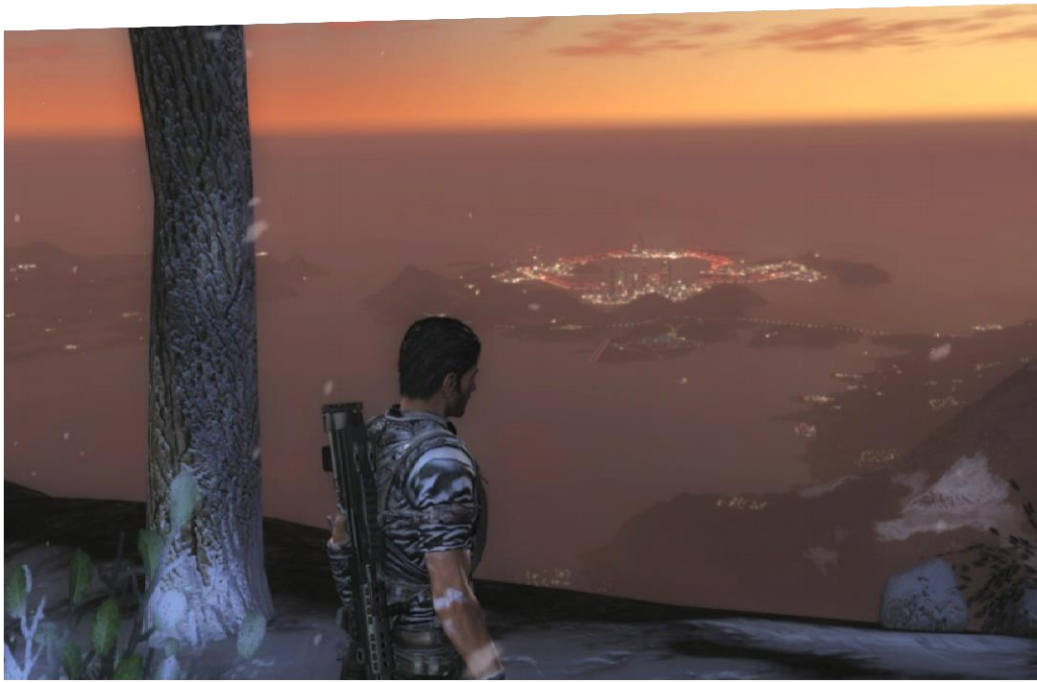
Clustered Rendering

- Divide up Z axis exponentially
- Start at some sensible near slice
- Cap at some sensible value



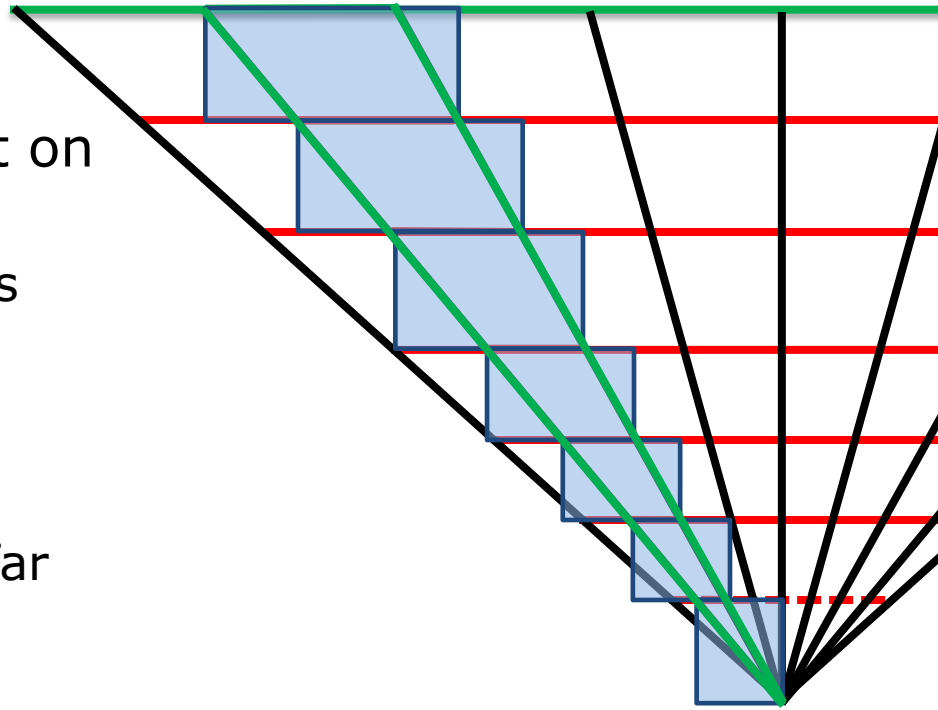
Provision for far lights

- Fade them out
- Drop back to glares
- Prebake



Light Culling

- View space AABBs worked best on 2D grid
  - Bad when running say 16 slices
- View space frustum planes are better
  - Calculate per tile planes
  - Then test each slice near and far
  - Optionally, *then* test AABBs



VRAM Usage

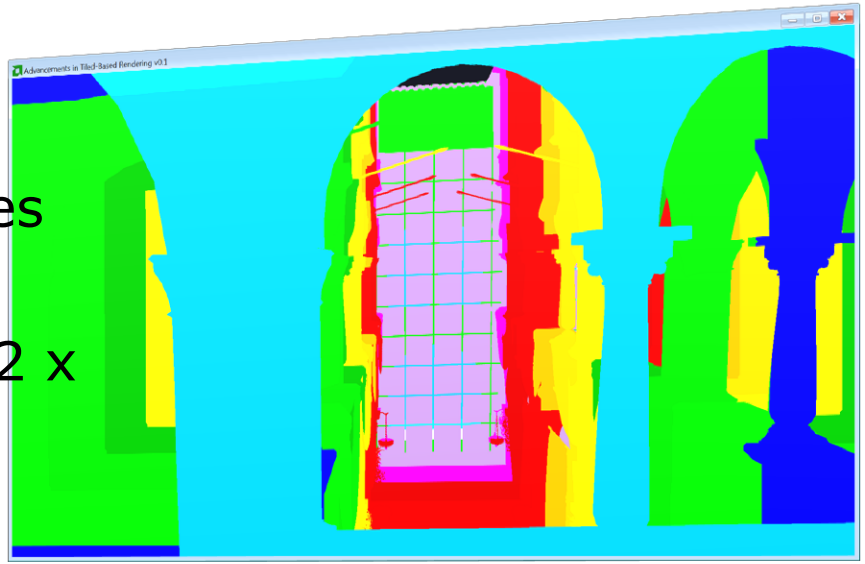
- 16x16 pixel 2D grid requires numTilesX x numTilesY x maxLights
  - 1080p: 120x68x512xuint16 = 8MB
  - 4k: 240x135x512xuint16 = 32MB
- List for each light type (points & spots): 64MB
- So 32 slices: 1GB for point lights only ☹
- Either use coarser grid
- Or use a compacted list

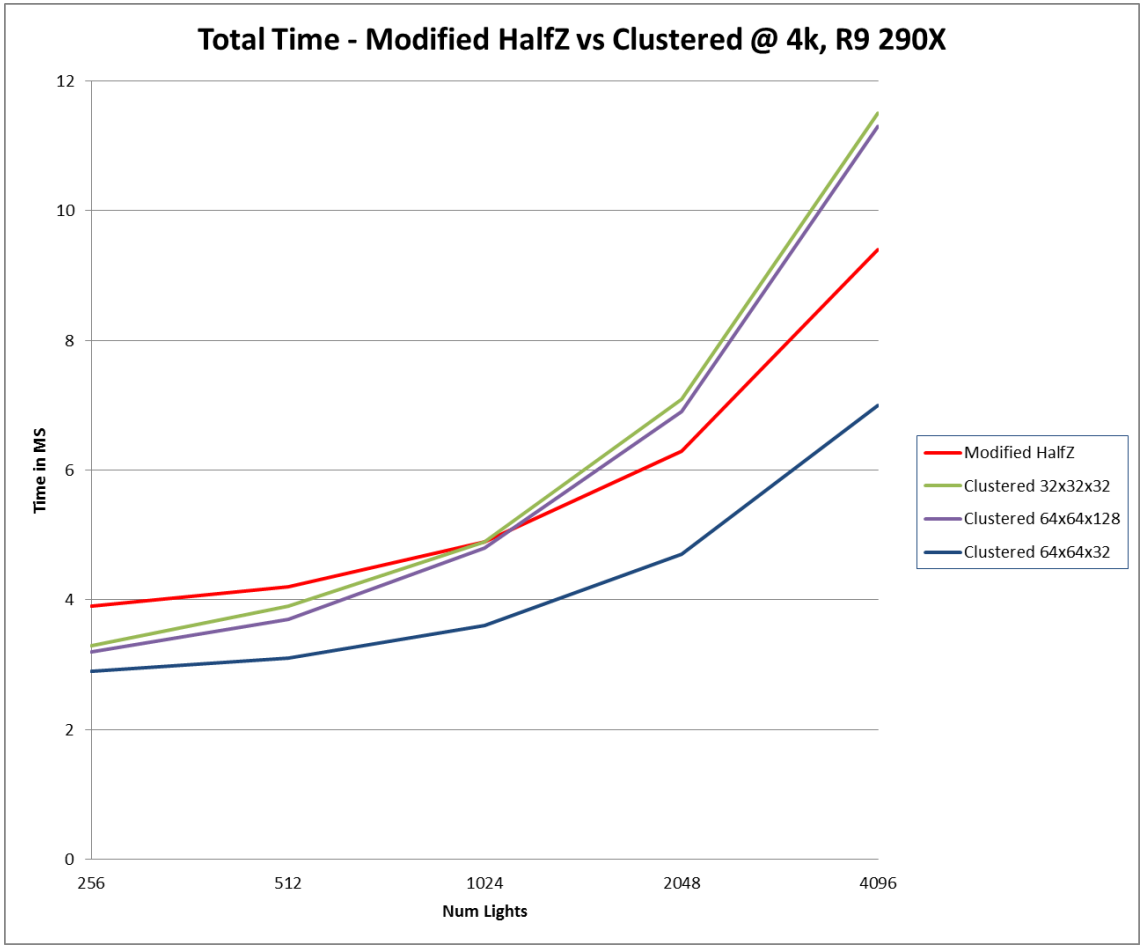
Compacted List

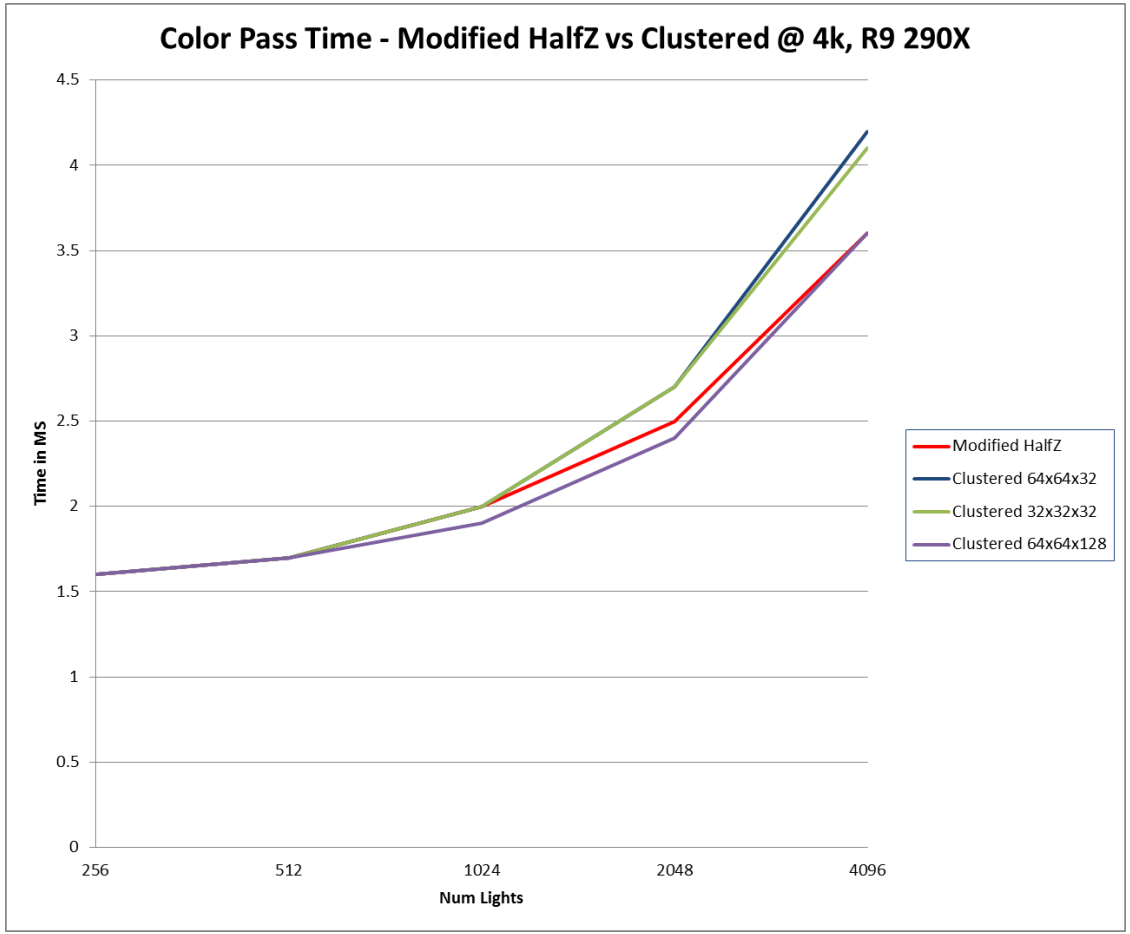
- Option 1:
  - Do all culling on CPU [Olsson et al12] [Persson13][Dufresne14]
    - But some of the lights may be spawned by the GPU
    - My CPU is a precious resource!
- Option 2:
  - Cull on GPU
  - Keep track of how many lights per slice in TGSM
  - Write table of offsets in light list header
  - Only need maxLights x “safety factor” per tile

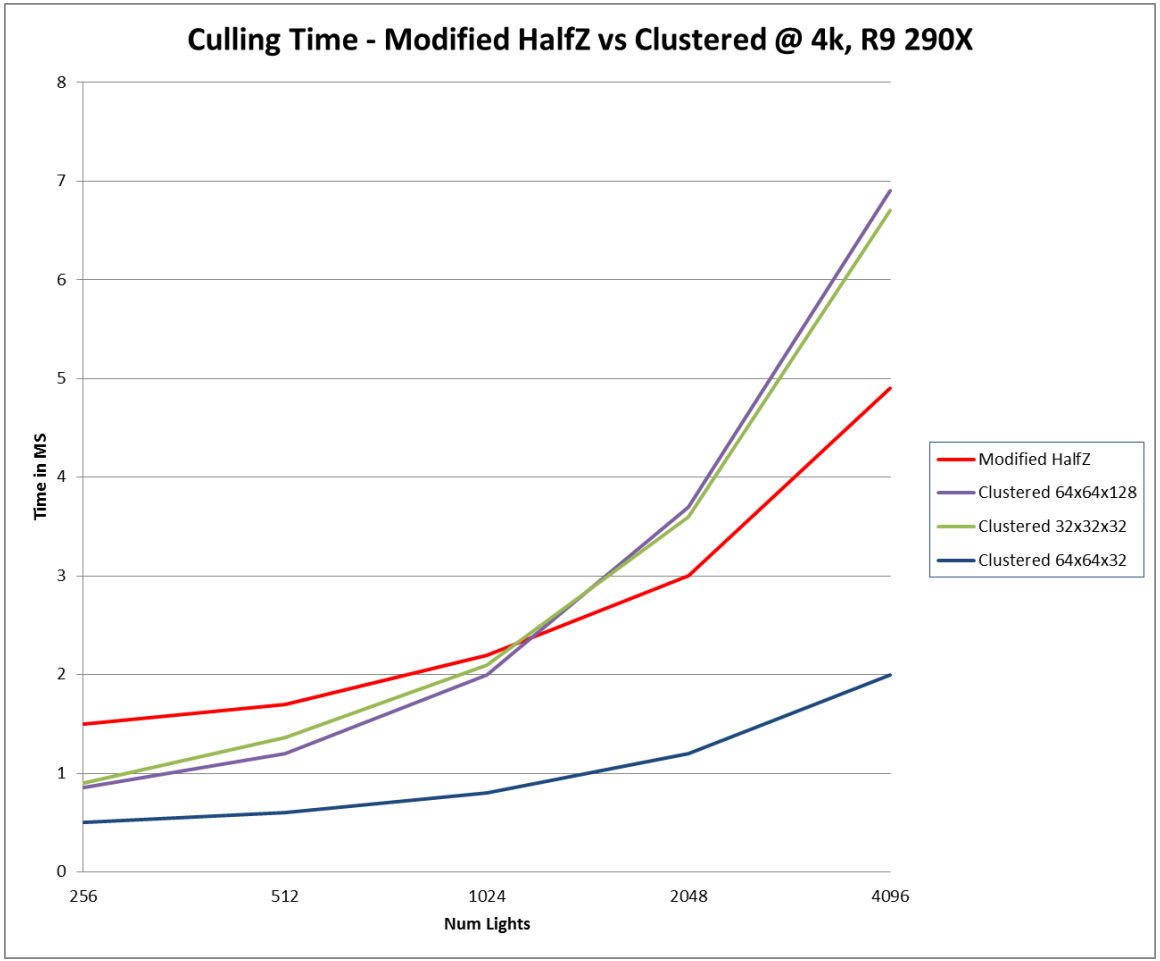
Coarse Grid

- Example:
  - 4k resolution
  - 64x64 pixel tiles with 64 slices
  - maxLights = 512
  - 60 x 34 tiles x 64 slices x 512 x uint16 = 128MB




Total Time - Modified HalfZ vs Clustered @ 4k, R9 290X
Time in MS
0
2
4
6
8
10
12
256
512
1024
2048
4096
Num Lights
Modified HalfZ
Clustered 32x32x32
Clustered 64x64x128
Clustered 64x64x32


Color Pass Time - Modified HalfZ vs Clustered @ 4k, R9 290X
Time in MS
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
256
512
1024
2048
4096
Num Lights
Modified HalfZ
Clustered 64x64x32
Clustered 32x32x32
Clustered 64x64x128


Culling Time - Modified HalfZ vs Clustered @ 4k, R9 290X
Time in MS
0
1
2
3
4
5
6
7
8
256
512
1024
2048
4096
Num Lights
Modified HalfZ
Clustered 64x64x128
Clustered 32x32x32
Clustered 64x64x32

Z Prepass

- Very scene dependant
- Often considered too expensive
- DirectX12 can help draw submission cost
- *Should* already have a super optimized depth only path for shadows!
  - Position only streams
  - Index buffer to batch materials together
- A partial prepass can really help lighten the geometry load

Conclusions

- Parallel Reduction - faster than atomic min/max
- AABB-Sphere test in conjunction with Modified HalfZ is a good choice
- Clustered shading
  - Potentially a big saving on the tile culling
  - Less overhead for low light numbers
  - Offers other benefits over 2D tiling
- Aggressive culling is very worthwhile
  - The best optimisation for your expensive color scene

References

- [Andersson09] Johan Andersson, “Parallel Graphics in Frostbite – Current & Future”, Beyond Programmable Shading, SIGGRAPH 2009
- [Harada et al12] Takahiro Harada, Jay McKee, Jason C Yang, “Forward+: Bringing Deferred Lighting to the Next Level”, Eurographics 2012
- [Harris07] Mark Harris, “Optimizing Parallel Reduction in CUDA”, NVIDIA 2007
- [Engel14] Wolfgang Engel, “Compute Shader Optimizations for AMD GPUs: Parallel Reduction”, Confetti 2014
- [Harada12] Takahiro Harada, “A 2.5D Culling for Forward+”, Technical Briefs, SIGGRAPH Asia 2012
- [Arvo90] Jim Arvo, “A simple method for box-sphere intersection testing”, Graphics Gems 1990
- [Dufresne14] Marc Fauconneau Dufresne, “Forward Clustered Shading”, Intel 2014
- [Persson13] Emil Persson, “Practical Clustered Shading”, Avalanche 2013
- [Olsson et al12] Ola Olsson, Markus Billeter, Ulf Assarsson, “Clustered Deferred and Forward Shading”, HPG 2012
- [Schulz14] Nicolas Schulz, “Moving to the Next Generation – The Rendering Technology of Ryse”, GDC 2014

Thanks

- Jason Stewart, AMD
- Epic Rendering Team
- Emil Persson, Avalanche Studios


Questions?
gareth.thomas@amd.com