Advancements in Tiled-Based Compute Rendering

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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
Tiled Rendering 101

Index0 • Lights=2
Index1 • 1
Index2 • 4
Index3 • Empty
Index4 • Empty
...

Light0 • Position • Radius
Light1 • Position • Radius
Light2 • Position • Radius
Light3 • Position • Radius
Light4 • Position • Radius
...
Light10 • Position • Radius
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]
```c
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 lds2Min[64];
groupshared float lds2Max[64];

[numthreads(8,8,1)]
void CalculateDepthBoundsCS( uint3 globalIdx : SV_DispatchThreadID, uint3 localIdx : SV_GroupThreadID, uint3 groupIdx : SV_GroupID )
{
    uint2 sampleIdx = globalIdx.xy;  // Assuming globalIdx.xy is used for simplicity
    float depth00 = g_SceneDepthBuffer.Load<uint3>(sampleIdx.x, sampleIdx.y, 0).x;
    float viewPos00 = ConvertProjDepthToView(depth00);
    float depth01 = g_SceneDepthBuffer.Load<uint3>(sampleIdx.x, sampleIdx.y+1, 0).x;
    float viewPos01 = ConvertProjDepthToView(depth01);
    float depth02 = g_SceneDepthBuffer.Load<uint3>(sampleIdx.x+1,sampleIdx.y, 0).x;
    float viewPos02 = ConvertProjDepthToView(depth02);
    float depth03 = g_SceneDepthBuffer.Load<uint3>(sampleIdx.x+1,sampleIdx.y+1, 0).x;
    float viewPos03 = ConvertProjDepthToView(depth03);
    float viewPos20 = ConvertProjDepthToView(depth10);
    float viewPos21 = ConvertProjDepthToView(depth11);
    float minZ00 = (depth00 <= 0.f) ? viewPos00 : FLT_MAX;
    float maxZ00 = (depth00 <= 0.f) ? viewPos00 : 0.0f;
    float minZ01 = (depth01 <= 0.f) ? viewPos01 : FLT_MAX;
    float maxZ01 = (depth01 <= 0.f) ? viewPos01 : 0.0f;
    float minZ02 = (depth02 <= 0.f) ? viewPos02 : FLT_MAX;
    float maxZ02 = (depth02 <= 0.f) ? viewPos02 : 0.0f;
    float minZ03 = (depth03 <= 0.f) ? viewPos03 : FLT_MAX;
    float maxZ03 = (depth03 <= 0.f) ? viewPos03 : 0.0f;

    uint threadNum = localIdx.x + localIdx.y*8;
    ldsZMin[threadNum] = min(minZ00,min(minZ01,min(minZ02,minZ03)));
    ldsZMax[threadNum] = max(maxZ00,max(maxZ01,max(maxZ02,maxZ03)));
    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[globalIdx.xy] = float2(ldsZMin[0],ldsZMax[0]);
    }
}
Parallel Reduction - Performance

<table>
<thead>
<tr>
<th></th>
<th>Atomic Min/Max</th>
<th>Parallel Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMD R9 290X</td>
<td>1.8ms</td>
<td>1.60ms</td>
</tr>
<tr>
<td>NVIDIA GTX 980</td>
<td>1.8ms</td>
<td>1.54ms</td>
</tr>
</tbody>
</table>

- 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

Max Z

Min Z
Sphere-Frustum Test
AABB around Frustum

Frustum planes

Max Z

Min Z
AABB around long frustum

AABB around short frustum

Max Z

Min Z
Arvo Intersection Test [Arvo90]

```cpp
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

Scene Geometry

False Positives
2.5D Culling [Harada et al 12]
HalfZ

MinZ

MaxZ

Scene Geometry

HalfZ

HalfZ low bits

HalfZ high bits

numLights near side

numLights far side

light indices...

3

4

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
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
Modified HalfZ in one light list

MinMax Depth Bounds
What happens if we cull 32x32 tiles?

Still using 16x16 thread groups
Modified HalfZ - 16x16 Tiles vs 32x32 Tiles @ 4k, R9 290X
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 \( \text{numTilesX} \times \text{numTilesY} \times \text{maxLights} \)
  - 1080p: \( 120 \times 68 \times 512 \times \text{uint16} = 8\text{MB} \)
  - 4k: \( 240 \times 135 \times 512 \times \text{uint16} = 32\text{MB} \)
- 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`
Color Pass Time - Modified HalfZ vs Clustered @ 4k, R9 290X

- Modified HalfZ
- Clustered 64x64x32
- Clustered 32x32x32
- Clustered 64x64x128

Time in MS vs Num Lights
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

Thanks

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