AGENDA

Anti-aliasing
- Practical Deferred MSAA
- Temporal Antialiasing: SMAA ITX

Camera Post-Processing
- Depth of Field
- Motion Blur

Sharing results from ongoing research
- Results not used in a shipped game yet 😊
ANTIALIASING/DEFERRED MSAA REVIEW

The problem: Multiple passes + r/w from Multisampled RTs
- DX 10.1 introduced SV_SampleIndex / SV_Coverage system value semantics.
- Allows to solve via multipass for pixel/sample frequency passes [Thibieroz11]

SV_SampleIndex
- Forces pixel shader execution for each sub-sample and provides index of the sub-sample currently executed
- Index can be used to fetch sub-sample from a Multisampled RT. E.g. FooMS.Load(UnnormScreenCoord, nSampleIndex)

SV_Coverage
- Indicates to pixel shader which sub-samples covered during raster stage.
- Can modify also sub-sample coverage for custom coverage mask

DX 11.0 Compute Tiled based deferred shading/lighting MSAA is simpler
- Loop through MSAA tagged sub-samples
DEFERRED MSAA \ HEADS UP!

Simple theory, troublesome practice

- At least with complex deferred renderers

Non-MSAA friendly code accumulates fast.

- Breaks regularly, as new techniques added without MSAA consideration
- Even if still works.. Very often you’ll need to pinpoint and fix non-msaa friendly techniques, as these introduce visual artifacts.
- E.g. white/dark outlines, or no AA at all

Do it upfront. Retrofitting a renderer to support Deferred MSAA is some work

- And it is very finicky
**Deferred MSAA\CUSTOM RESOLVE & PER-SAMPLE MASK**

Post G-Buffer, perform a custom msaa resolve

- Pre-resolves sample 0, for pixel frequency passes such as lighting/other MSAA dependent passes
- In same pass create sub-sample mask (compare samples similarity, mark if mismatching)
- Avoid default SV_COVERAGE, since it results in redundant processing on regions not requiring MSAA
**DEFERRED MSAA\STENCIL BATCHING** [SOUSA13]

Batching per-sample stencil mask with regular stencil buffer usage

- Reserve 1 bit from stencil buffer
- Update with sub-sample mask
- Tag entire pixel-quad instead of just single pixel --> improves stencil culling efficiency
- Make usage of stencil read/write bitmask to avoid per-sample bit override
  - StencilWriteMask = 0x7F
- Restore whenever a stencil clear occurs

Not possible due to extreme stencil usage?

- Use clip/discard
- Extra overhead also from additional texture read for per-sample mask
DEFERRED MSAA\PIXEL AND SAMPLE FREQUENCY PASSES

Pixel Frequency Passes
- Set stencil read mask to reserved bits for *per-pixel* regions (~0x80)
- Bind pre-resolved (non-multisampled) targets SRVs
- Render pass as usual

Sample Frequency Passes
- Set stencil read mask to reserved bit for *per-sample* regions (0x80)
- Bind multisampled targets SRVs
- Index current sub-sample via SV_SAMPLEINDEX
- Render pass as usual
DEFERRED MSAA\ALPHA TEST SSAA

Alpha testing requires ad hoc solution
- Default SV_Coverage only applies to triangle edges

Create your own sub-sample coverage mask
- E.g. check if current sub-sample uses AT or not and set bit

```cpp
static const float2 vMSAAOffsets[2] = {float2(0.25, 0.25), float2(-0.25, -0.25)};
const float2 vDDX = ddx(vTexCoord.xy);
const float2 vDDY = ddy(vTexCoord.xy);
[unroll] for(int s = 0; s < nSampleCount; ++s)
{
    float2 vTexOffset = vMSAAOffsets[s].x * vDDX + (vMSAAOffsets[s].y * vDDY);
    float fAlpha = tex2D(DiffuseSmp, vTexCoord + vTexOffset).w;
    uCoverageMask |= ((fAlpha - fAlphaRef) >= 0)? (uint(0x1)<<i) : 0;
}
```
Deferred cascades sun shadow maps

- Render shadows as usual at pixel frequency
- Bilateral upscale during deferred shading composite pass
DEFERRED MSAA \ PERFORMANCE SHORTCUTS (2)

Non-opaque techniques accessing depth (e.g. Soft-Particles)

- Recommendation to tackle via per-sample frequency is fairly slow on real world scenarios
- Using Max Depth works ok for most cases and N-times faster
Many games, also doing:

- Skipping Alpha Test Super Sampling
  - Use alpha to coverage instead, or even no alpha test AA (let morphological AA tackle that)
- Render only opaque with MSAA
  - Then render transparencies without MSAA
- Assuming HDR rendering: note that tone mapping is implicitly done post-resolve resulting is loss of detail on high contrast regions
DEFERRED MSAA | MSAA FRIENDLINESS

Look out for these:

- No MSAA noticeably working, or noticeable bright/dark silhouettes.
DEFERRED MSAA\MSAA FRIENDLINESS

Look out for these:
- No MSAA noticeably working, or noticeable bright/dark silhouettes.
DEFERRED MSAA\RECAP

Accessing and/or rendering to Multisampled RTs?
- Then you need to care about accessing and outputting correct sub-sample

In general always strive to minimize BW
- Avoid vanilla deferred lighting
  - Prefer fully deferred, hybrids, or just skip deferred altogether.
- If deferred, prefer thin g-buffers
  - Each additional target on g-buffer incurs in export rate overhead [Thibieroz11]
  - NV/AMD (GCN): Export Cost = Cost(RTD)+Cost(RTI)…. AMD (older hw): Export Cost = (Num RTs) * (Slowest RT)
  - Fat formats are half rate sampling cost for bilinear filtering modes on GCN [Thibieroz13]
  - For lighting/some hdr post processes: 32 bit R11G11B10F fmt suffices for most cases
ANTIALIASING + 4K RESOLUTIONS \ WILL WE NEED MSAA AT ALL?

Likely can start getting creative here
ANTIALIASING \ THE QUEST FOR BETTER (AND FAST) AA

2011: the boom year of alternative AA modes (and naming combos)
- FXAA, MLAA, SMAA, SRAA, DEAA, GBAA, DLAA, ETC AA
- “Filtering Approaches for Real-Time Anti-Aliasing” [Jimenez et al. 11]

Shading Anti-aliasing
- “Mip mapping normal maps” [Toksvig04]
- “Spectacular Specular: LEAN and CLEAN Specular Highlights” [Baker11]
- “Rock-Solid Shading: Image Stability without Sacrificing Detail” [Hill12]
Morphological AA + MSAA + Temporal SSAA combo

- Balanced cost/quality tradeoff, techniques complement each other.
- Temporal component uses 2 sub-pixel buffers.
- Each frame adds a sub-pixel jitter for 2x SSAA.
- Reproject previous frame and blend between current and previous frames, via velocity length weighting.
- Preserves image sharpness + reasonable temporal stability

\[ w = 0.5 \cdot \max(0,1 - K \cdot \sqrt{\|v_c\| - \|v_p\|}) \]
\[ c = (1 - w) \cdot c_c + w \cdot c_p \]
TEMPORAL AA\COMMON ROBUSTNESS FLAWS

Relying on opaque geometry information
- Can’t handle signal (color) changes nor transparency.
- For correct result, all opaque geometry must output velocity

Pathological cases
- Alpha blended surfaces (e.g. particles), lighting/shadow/reflections/uv animation/etc
- Any scatter and alike post processes, before the AA resolve

Can result in distracting errors
- E.g. “ghosting” on transparency, lighting, shadows and such
- Silhouettes might appear, from scatter and alike post processes (e.g. bloom)

Multi-GPU
- Simplest solution: force resource sync
- NVIDIA exposes driver hint to force sync resource, via NVAPI. This is solution used by NVIDIA’s TXAA
  - Note to hw vendors: would be great if all vendors exposed such (even better if Multi-GPU API functionality generalized)
SMAA 1TX: A MORE ROBUST TEMPORAL AA

Concept: Only track signal changes, don’t rely on geometry information

- For higher temporal stability: accumulate multiple frames in an accumulation buffer, alike TXAA \cite{Lottes12}
- Re-project accumulation buffer
- Weighting: Map acc. buffer colors into the range of curr. frame neighborhood color extents \cite{Malan2012}; different weight for hi/low frequency regions (for sharpness preservation).
SMAA 1TX \ a more robust temporal AA (2)

Concept: Only track signal changes, don’t rely on geometry information
- For higher temporal stability: accumulate multiple frames in an accumulation buffer, alike TXAA [Lottes12]
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- Weighting: Map acc. buffer colors into the range of curr. frame neighborhood color extents [Malan2012]; different weight for hi/low frequency regions (for sharpness preservation).

\[
c_{\text{max}} = \max(c_{TL}, c_{TR}, c_{BL}, c_{BR})
\]
\[
c_{\text{min}} = \min(c_{TL}, c_{TR}, c_{BL}, c_{BR})
\]
\[
c_{\text{acc}} = \text{clamp}(c_{\text{acc}}, c_{\text{min}}, c_{\text{max}})
\]
\[
w_k = \left| (c_{TL} + c_{TR} + c_{BL} + c_{BR}) \ast 0.25 - c_M \right|
\]
\[
w_{\text{rgb}} = \text{clamp}\left(\frac{1}{K_{\text{lowfreq}} \ast (1 - w_k) + K_{\text{highfreq}} \ast w_k}, 0, 1\right)
\]
\[
c = c_M \ast (1 - w_{\text{rgb}}) + c_{\text{acc}} \ast w_{\text{rgb}}
\]
SMAA ITX \ A MORE ROBUST TEMPORAL AA (3)

Sample code

```c
float3 cM = tex2D(tex0, tc.xy);
float3 cAcc = tex2D(tex0, reproj_tc.xy);

float3 cTL = tex2D(tex0, tc0.xy);
float3 cTR = tex2D(tex0, tc0.zw);
float3 cBL = tex2D(tex0, tc1.xy);
float3 cBR = tex2D(tex0, tc1.zw);

float3 cMax = max(cTL, max(cTR, max(cBL, cBR)));
float3 cMin = min(cTL, min(cTR, min(cBL, cBR)));

float3 wk = abs((cTL+cTR+cBL+cBR)*0.25-cM);

return lerp(cM, clamp(cAcc, cMin, cMax), saturate(rcp(lerp(kl, kh, wk))));
```
DEPTH OF FIELD
DEPTH OF FIELD\PLAUSIBLE DOF: PARAMETERIZATION

Artist friendly parameters is one reason why games DOF tends to look wrong

- Typical controls such as “focus range” + “blur amount” and others have not much physical meaning
- CoC depends mainly on f-stops, focal length and focal distance. These last 2 directly affect FOV.
- If you want more Bokeh, you need to max your focal length + widen aperture. This means also getting closer or further from subject for proper framing.
  - Not the typical way a game artist/programmer thinks about DOF.

Wider fov, less bokeh

Shallow fov, more bokeh
DEPTH OF FIELD \ F-STOPS

2 f-stops

8 f-stops

22 f-stops
DEPTH OF FIELD \ F-STOP S (2)

2 f-stops  
2.8 f-stops  
4 f-stops  
5.6 f-stops
DEPTH OF FIELD / FOCAL DISTANCE

0.5 m
DEPTH OF FIELD / FOCAL DISTANCE

0.75 m
DEPTH OF FIELD\FOCAL DISTANCE

1.0 m
DEPTH OF FIELD\PLAUSIBLE DOF: BOKEH

Out of focus region is commonly referred in photography as “Bokeh” (Japanese word for blur)
Bokeh shape has direct relation to camera aperture size (aka f-stops) and diaphragm blades count

- Bigger aperture = more “circular” bokeh, smaller aperture = more polygonal bokeh
  - Polygonal bokeh look depends on diaphragm blades count
  - Blades count varies on lens characteristics
- Bigger aperture = more light enters, smaller aperture = less light
  - On night shots, you might notice often more circular bokeh and more motion blur

Bokeh kernel is flat

- Almost same amount of light enters camera iris from all directions
  - Edges might be in shadow, this is commonly known as Vignetting
  - Poor lenses manufacturing may introduce a vast array of optical aberrations [Wiki01]

- This is main reason why gaussian blur, diffusion dof, and derivative techniques look wrong/visually unpleasant
DEPTH OF FIELD STATE OF THE ART OVERVIEW

Scatter based techniques [Cyril05][Sawada07][3DMark11][Mittring11][Sousa11]

- Render 1 quad or tri per-pixel, scale based on CoC

Simple implementation and nice results. Downside: performance, particularly on shallow DOF

- Variable/inconsistent fillrate hit, depending on near/far layers resolution and aperture size might reach >5 ms
- Quad generation phase has fixed cost attached.
DEPTH OF FIELD\STATE OF THE ART OVERVIEW (2)

Gather based: separable (inflexible kernel) vs. kernel flexibility

[Kawase09]  [Gotanda09]  [Macintosh12]

[White11]  [Andreev12]
DEPTH OF FIELD \ A PLAUDBLE AND EFFICIENT DOF RECONSTRUCTION FILTER

Separable flexible filter: low bandwidth requirement + different bokeh shape possible

- 1st pass $N^2$ taps (e.g: 7x7).
- 2nd pass $N^2$ taps (e.g: 3x3) for flood filling shape
- R11G11B10F: downscaled HDR scene; R8G8: CoC
- Done at half resolution
- Far/Near fields processed in same pass
- Limit offset range to minimize undersampling
- Higher specs hw can have higher tap count

Diaphragm and optical aberrations sim
Physically based CoC
DEPTH OF FIELD \ LEN S REVIEW

Pinhole “Lens”
- A camera without a lens
- Light has to pass through a single small aperture before hitting the image plane
- Typical real-time rendering

Thin lens
- Camera lenses have finite dimensions
- Light refracts through the lens until hitting the image plane.
- F = Focal length
- P = Plane in focus
- I = Image distance
DEPTH OF FIELD\LENS REVIEW (2)

The thin lens equation gives relation between:

- F = Focal length (where light starts getting in focus)
- P = Plane in focus (camera focal distance)
- I = Image distance (where image is projected in focus)

\[
\frac{1}{P} + \frac{1}{I} = \frac{1}{F}
\]

**Circle of Confusion** (Potmesil81)

- f = f-stops (aka as the f-number or focal ratio)
- D = Object distance
- A = Aperture diameter

Simplifies to:

- Note: f and F are known variables from camera setup
- Folds down into a single mad in shader

**Camera FOV:**

- Typical film formats (or sensor), 35mm/70mm
- Can alternatively derive focal length from FOV

\[\theta = 2 \cdot \arctan \left( \frac{width_{film}}{2 \cdot F} \right)\]

\[F' = \frac{0.5 \cdot width_{film}}{\tan(\theta / 2)}\]
DEPTH OF FIELD\SAMPLING

Concentric Mapping ([Shirley97]) used for uniform sample distribution

- Maps unit square to unit circle
- Square mapped to \((a,b) [-1,1]^2\) and divided into 4 regions by lines \(a=b, a=-b\)
- First region given by:

\[
\begin{align*}
  r &= a \\
  \theta &= \frac{\pi \cdot b}{4 \cdot a}
\end{align*}
\]

Diaphragm simulation by morphing samples to n-gons

- Via a modified equation for the regular polygon.

\[
f = \frac{f_{\text{stops}} - f_{\text{stops min}}}{f_{\text{stops max}} - f_{\text{stops min}}} \quad \theta = \theta + f \cdot \theta_{\text{shutter max}}
\]

\[
r_{\text{gon}} = r \left( \frac{\cos(\pi / n) \cos(\theta - (2 \cdot \pi / n) \cdot \text{floor((n \cdot \theta + \pi) / (2 \cdot \pi))})}{\cos(\theta - (2 \cdot \pi / n) \cdot \text{floor((n \cdot \theta + \pi) / (2 \cdot \pi)))}} \right)^f
\]
DEPTH OF FIELD\SAMPLING: 2\textsuperscript{ND} ITERATION

To floodfill final shape, composite via boolean union, similarly to [McIntosh12]
DEPTH OF FIELD\Separable Filter Passes

1st iteration: 49 taps (0.426ms)

2nd iteration: 9 taps (0.094 ms; 441 taps accumulated)
DEPTH OF FIELD\REFERENCE VS SEPARABLE FILTER

44 taps (1.31ms)  vs  58 taps (0.52ms)
DEPTH OF FIELD DIAPHRAGM SIMULATION IN ACTION

2f-stops

4f-stops

Advances in Real-Time Rendering course, Siggraph 2013
DEPTH OF FIELD\TILE MIN/MAX COC

Tile Min/Max CoC
- Downscale CoC target k times (k = tile count)
- Take min fragment for far field, max fragment for near field
- R8G8 storage

Used to process near/far fields in same pass
- Dynamic branching using Tile Min/Max CoC for both fields
- Balances cost between far/near
- Also used for scatter as gather approximation for near field

Can fold cost with other post-processes
- Initial downscale cost folded with HDR scene downscale for bloom, also pack near/far fields HDR input into R11G11B10F - all in 1 pass
DEPTH OF FIELD\FAR + NEAR FIELD PROCESSING

Both fields use half resolution input
- Careful: downscale is source of error due to bilinear filtering
- Use custom bilinear (bilateral) filter for downscaling

Far Field
- Scale kernel size and weight samples with far CoC [Scheumerman05]
- Pre-multiply layer with far CoC [Gotanda09]
  - Prevents bleeding artifacts from bilinear/separable filter

![No weighting](image1)
![CoC weighting](image2)
![CoC weighting + CoC pre-multiply](image3)
DEPTH OF FIELD\FAR + NEAR FIELD PROCESSING

Both fields use half resolution input

- Careful: downscale is source of error due to bilinear filtering
- Use custom bilinear (bilateral) filter for downscaling

Far Field

- Scale kernel size and weight samples with far CoC [Scheumerman05]
- Pre-multiply layer with far CoC [Gotanda09]
  - Prevents bleeding artifacts from bilinear/separable filter

Near Field

- Scatter as gather approximation
- Scale kernel size + weight fragments with Tile Max CoC against near CoC
- Pre-multiply with near CoC
  - Only want to blur near field fragments (cheap partial occlusion approximation)
DEPTH OF FIELD\FINAL COMPOSITE

Far field: upscale via bilateral filter
- Take 4 taps from half res CoC, compare against full res CoC
- Weighted using bicubic filtering for quality \( \text{[Sigg05]} \)
- Far field CoC used for blending

Near field: upscale carelessly
- Half resolution near field CoC used for blending
- Can bleed as much as possible
- Also using bicubic filtering

Carefull with blending
- Linear blending doesn’t look good (signal frequency soup)
  - Can be seen in many games, including all Crysis series (puts hat of shame)
- Simple to address: use non-linear blend factor instead.
MOTION BLUR
MOTION BLUR \ SHUTTER SPEED AND F-STOP REVIEW

Amount of motion blur is relative to camera shutter speed and f-stops usage

- The longer the exposure (slower shutter), the more light received (and the bigger amount of motion blur), and vice-versa
- The lower f-stops the faster the exposure can be (and have less motion blur), and vice versa

![2 f-stops, shutter 1/20 sec](image1)

![4 f-stops, shutter 1/6 sec](image2)
MOTION BLUR\STATE OF THE ART OVERVIEW

Scatter via geometry expansion (Green03)(Sawada07)

- Require additional geometry pass + gs shader usage *
MOTION BLUR \ STATE OF THE ART OVERVIEW (2)

Scatter as gather \cite{Sousa08,Gotanda09,Sousa11,Maguire12}:
- E.g. velocity dilation, velocity blur, tile max velocity; single vs. multiple pass composite; depth/v/obj ID masking; single pass DOF+MB
MOTION BLUR\RECONSTRUCTION FILTER FOR PLAUSIBLE MB [MCGUIRE12]

Tile Max Velocity and Tile Neighbor Max Velocity
- Downscale Velocity buffer by k times (k is tile count)
- Take max length velocity at each step

Motion Blur Pass
- Tile Neighbor Max for early out
- Tile Max Velocity as center velocity tap
- At each iteration step weight against full resolution ||V|| and Depth
MOTION BLUR\ AN IMPROVED RECONSTRUCTION FILTER

Performant Quality

- Simplify and vectorize inner loop weight computation (ends up in couple mads)
- Fat buffers sampling are half rate on GCN hw with bilinear (point filtering is fullrate, but doesn’t look good due to aliasing)
- Inputs: R1G1B1I0F for scene, bake $||V||$ and 8 bit depth into a R8G8 target
- Make it separable, 2 passes [Sousa08]

1 iteration: 6 taps (0.236 ms)

2nd iter: 6 taps (+0.236 ms; 36 taps acc.)
MOTION BLUR\AN IMPROVED RECONSTRUCTION FILTER (2)

Inner loop sample

```cpp
const float2 tc = min_tc + blur_step * s;
const float lensq_xy = abs(min_len_xy + len_xy_step * s);
const float2 vy = tex2Dlod(tex1, float4(tc.xy, 0, 0)); // x=||v||, y=depth
const float2 cmp_z = DepthCmp(float2(vx.y, vy.y), float2(vy.y, vx.y), 1);
const float4 cmp_v = VelCmp(lensq_xy, float2(vy.x, lensq_vx));
const float w = (dot(cmp_z.xy, cmp_v.xy) + (cmp_v.z * cmp_v.w) * 2);
acc.rgb += tex2Dlod(tex0, float4(tc.xy, 0, 0)) * w;
wacc += w;

float2 DepthCmp(float2 z0, float2 z1, float2 fSoftZ) {
    return saturate( (1.0f + z0* fSoftZ) - z1* fSoftZ );
}
float4 VelCmp(float lensq_xy, float2 vxy) {
    return saturate((1.0f - lensq_xy.xxxx *rcp(vxy.xyy)) + float4(0.0f, 0.0f, 0.95f, 0.95f));
}
```
**MOTION BLUR\ AN IMPROVED RECONSTRUCTION FILTER (3)**

**Output object velocity in G-Buffer (only when required)**
- Avoids separate geometry passes.
- Rigid geometry: object distance < distance threshold
- Deformable geometry: if amount of movement > movement threshold
- Moving geometry rendered last
- R8G8 fmt

**Composite with camera velocity**
- Velocity encoded in gamma 2.0 space
- Precision still insufficient, but not much noticeable in practice

Encode: \[ v_{\text{enc}} = \sqrt{v_{xy}} \cdot \text{sgn}(v_{xy}) \cdot (127.0 / 255.0) + 0.5 \]

Decode: \[ v_{\text{enc}} = (v_{\text{enc}} - 127.0 / 255.0) / 255.0 \]
\[ v = (v_{\text{enc}} \cdot v_{\text{enc}}) \cdot \text{sgn}(v_{\text{enc}}) \]
MOTION BLUR\MB OR DOF FIRST?

In real world MB/DOF occur simultaneously
- A dream implementation: big $N^2$ kernel + batched DOF/MB
- Or sprite based with MB quad stretching
- Full resolution! 1 Billion taps! FP16! Multiple layers!

But... performance still matters (consoles):
- DOF before MB introduces less error when MB happening on focus
  - This is due MB is a scatter as gather op relying on geometry data.
  - Any other similar op after will introduce error. And vice-versa.
  - Error from MB after DOF is less noticeable.
- Order swap makes DOF harder to fold with other posts
  - Additional overhead
FINAL REMARKS

Practical MSAA details
- Do’s and Don’t’s

SMAA 1TX: A More Robust Temporal AA
- For just 4 extra texture ops and couple alu

A Plausible and Performant DOF Reconstruction Filter
- Separable flexible filter, any bokeh kernel shape doable
- 1st pass: 0.426ms, 2nd pass: 0.094ms. Sum: 0.52ms for reconstruction filter *

An Improved Reconstruction Filter for Plausible Motion Blur
- Separable, 1st pass: 0.236ms, 2nd pass: 0.236ms. Sum: 0.472ms for reconstruction filter *

* 1080p + AMD 7970
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