GRAPHICS GEMS

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AGENDA

Anti-aliasing

- Practical Deferred MSAA
- Temporal Antialiasing: SMAA 1TX

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

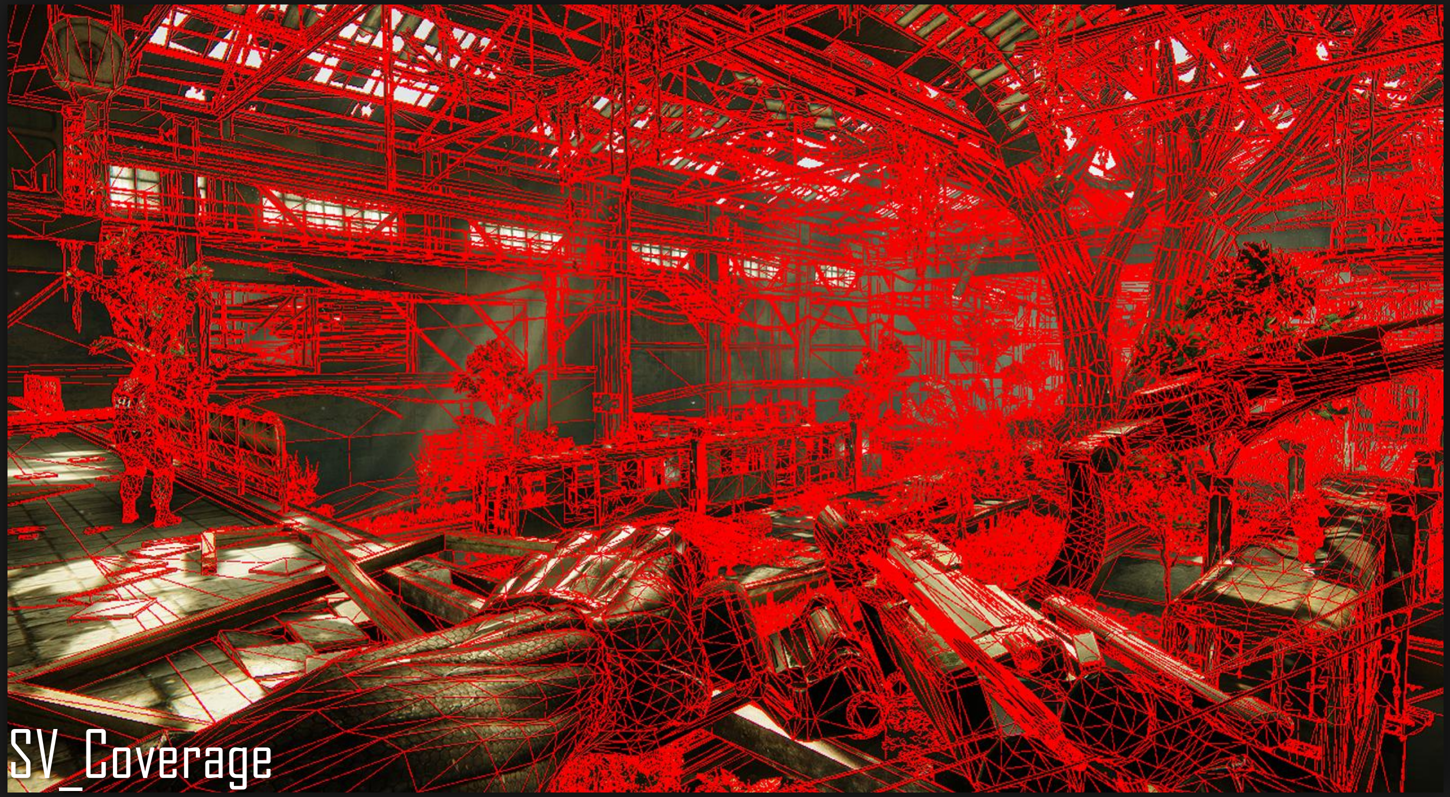
Do it upfront. Retrofitting a renderer to support Deferred MSAA is some work

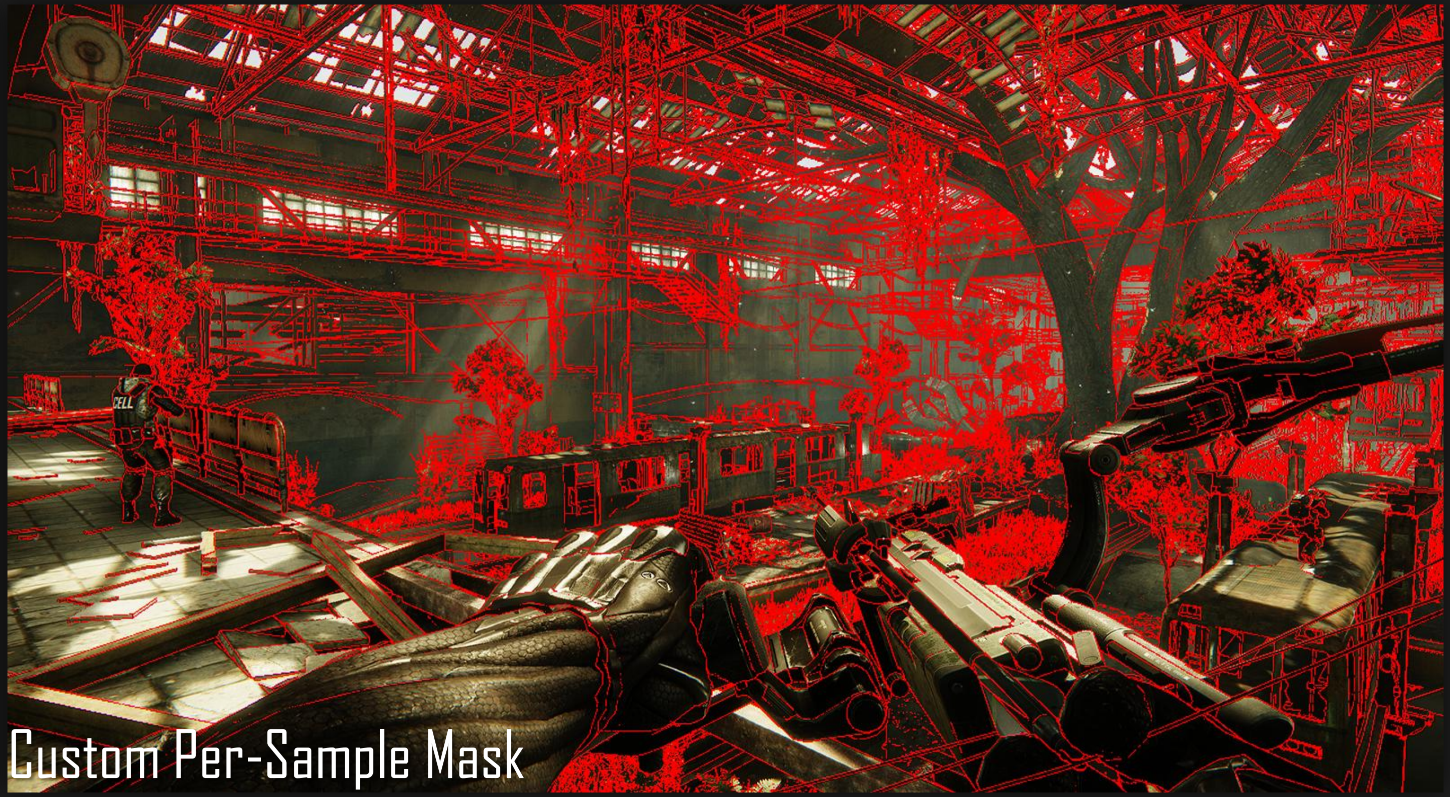
- And it is very finiky

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

```
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;
}
```


Alpha Test SSAA Disabled


Alpha Test SSAA Enabled

DEFERRED MSAA\PERFORMANCE SHORTCUTS

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

MSAA \ PERFORMANCE SHORTCUTS (3)

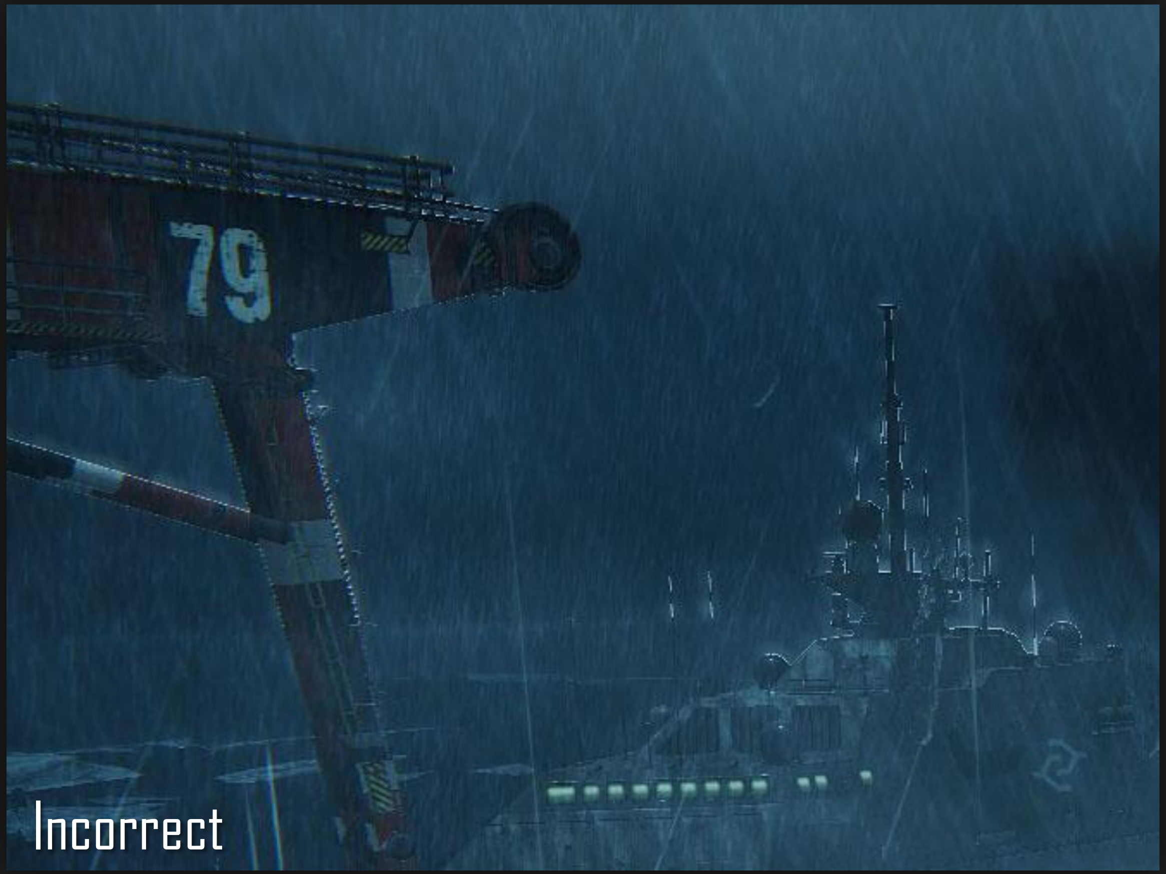
Many games, also doing:

- 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 transparents withouth 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:

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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(RT0)+Cost(RT1)..., 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

Highly Compressed 4k

Source 4k

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 all 11]

Shading Anti-aliasing

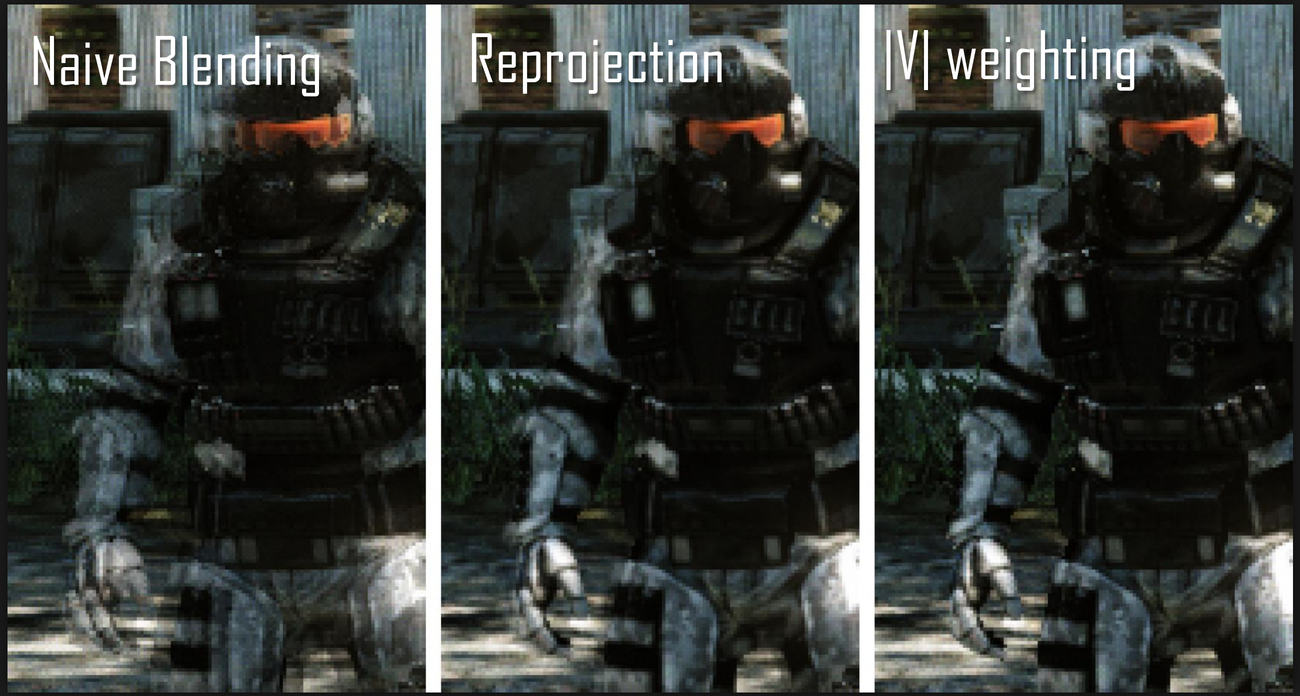
- "Mip mapping normal maps" [Toksvig04]
- "Spectacular Specular: LEAN and CLEAN Specular Highlights" [Baker11]
- "Rock-Solid Shading: Image Stability withouth Sacrificing Detail" [Hill12]

TEMPORAL SSAA \ SMAA 2TX/4X REVIEW [JIMENEZ11][SOUSA11]

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

$$w = 0.5 \cdot \max(0, 1 - K \cdot \sqrt{\left| \|v_c\| - \|v_p\| \right|})$$
$$c = (1 - w) \cdot c_c + w \cdot c_p$$



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

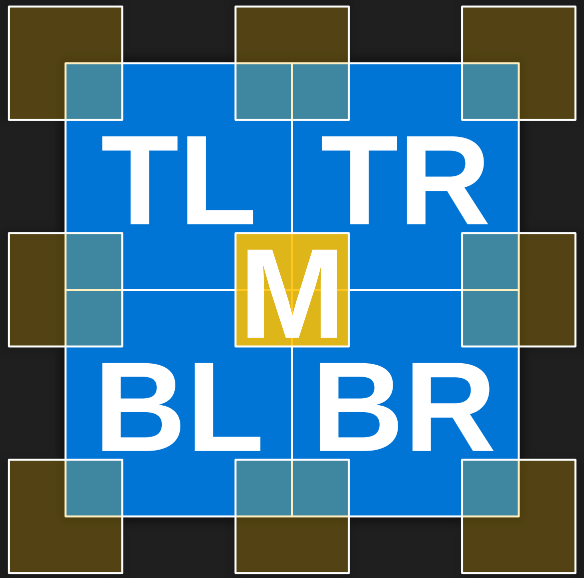
Can result in distracting errors
- E.g. "ghosting" on transparency, lighting, shadows and such
- Silhouettes might appear, from scatter and alike post processes (e.g. bloom)

Multi-GPU
- Simplest solution: force resource sync
- NVIDIA exposes driver hint to force sync resource , via NVAPI. This is solution used by NVIDIAs 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 [Lottes12]
- Re-project accumulation buffer
- 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).



Current Frame (t0)

Accumulation Buffer (tN)

SMAA 1TX\A MORE ROBUST TEMPORAL AA (2)

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

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- Re-project accumulation buffer
- 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).

$$c_{\max} = \max(c_{TL}, c_{TR}, c_{BL}, c_{BR})$$

$$c_{\min} = \min(c_{TL}, c_{TR}, c_{BL}, c_{BR})$$

$$c_{acc} = clamp(c_{acc}, c_{\min}, c_{\max})$$

$$w_k = \left|(c_{TL} + c_{TR} + c_{BL} + c_{BR}) * 0.25 - c_M\right|$$

$$w_{rgb} = clamp\left(\frac{1}{K_{lowfreq} * (1 - w_k) + K_{hifreq} * w_k}, 0, 1\right)$$

$$c = c_M * (1 - w_{rgb}) + c_{acc} * w_{rgb}$$

SMAA 1TX\A MORE ROBUST TEMPORAL AA (3)

Sample code

```
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.

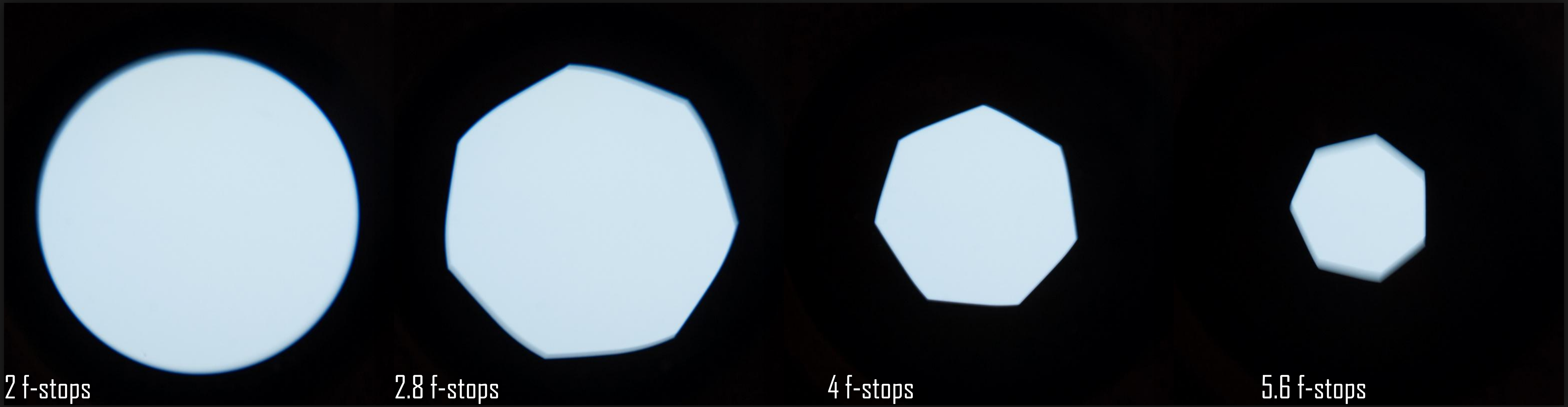
Wider fov, less bokeh

Shallow fov, more bokeh

DEPTH OF FIELD\FOCAL LENGTH

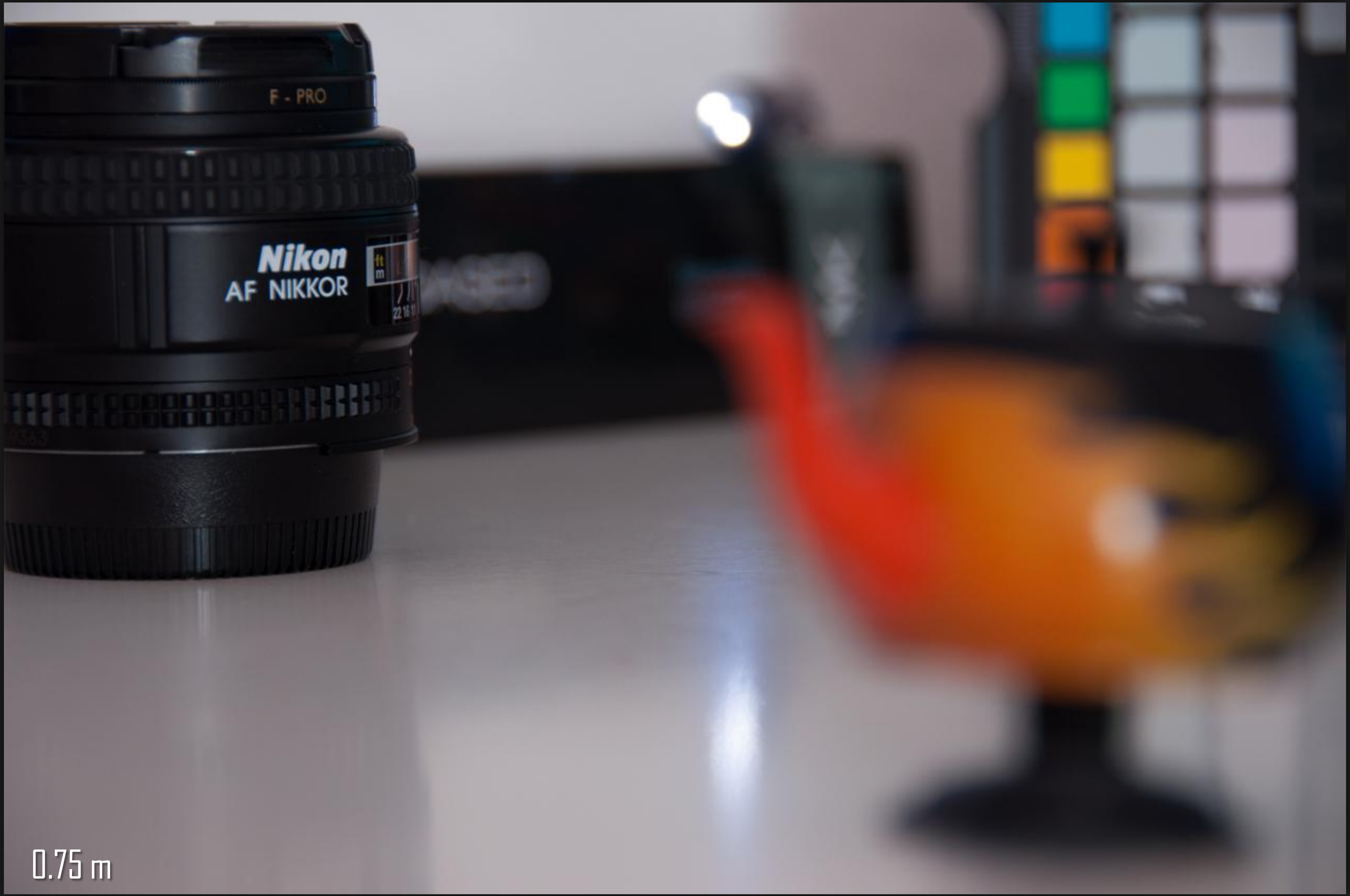
DEPTH OF FIELD\F-STOPS

DEPTH OF FIELD\F-STOPS (2)

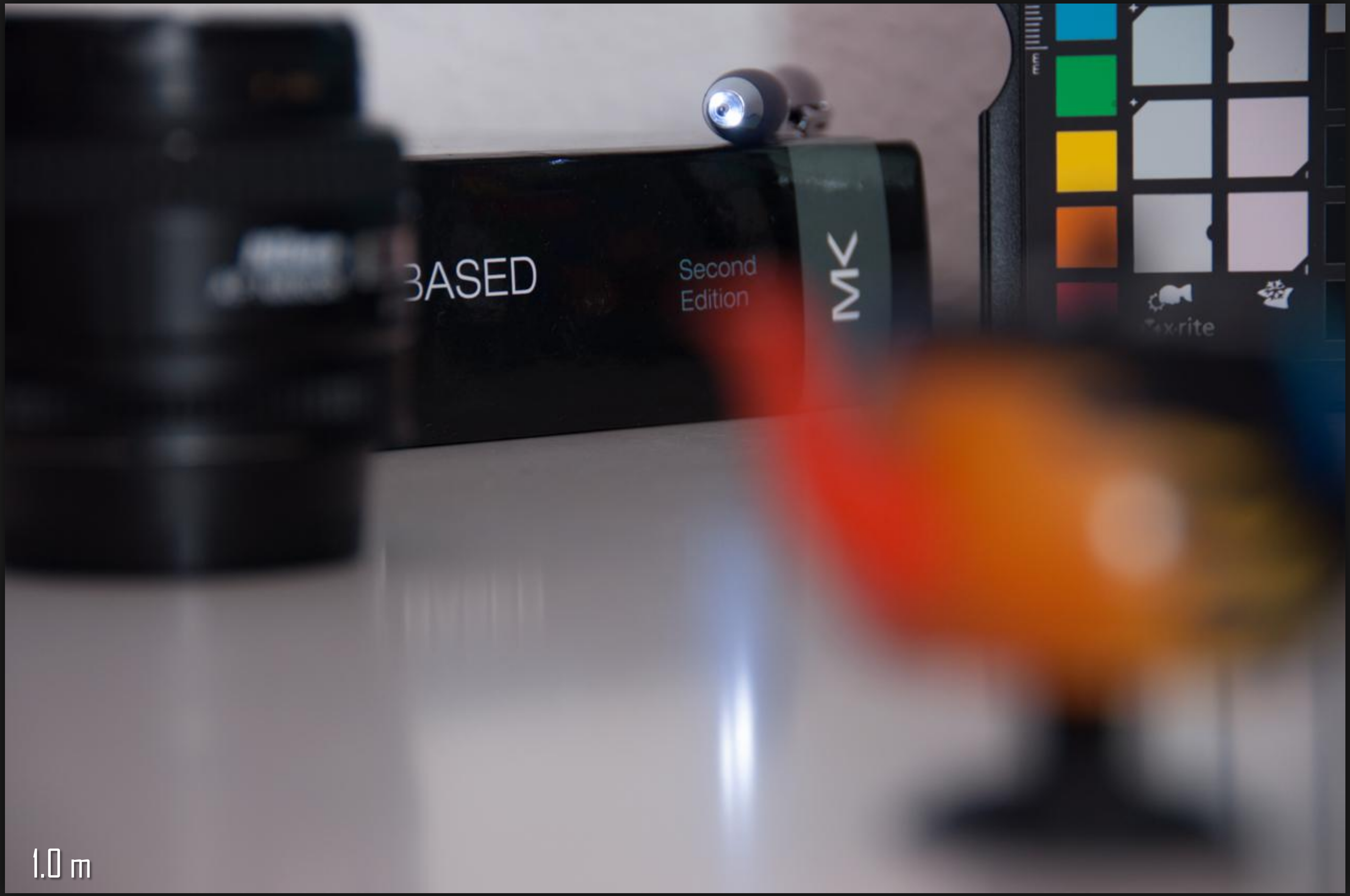


DEPTH OF FIELD \ FOCAL DISTANCE

DEPTH OF FIELD\FOCAL DISTANCE



DEPTH OF FIELD\FOCAL DISTANCE

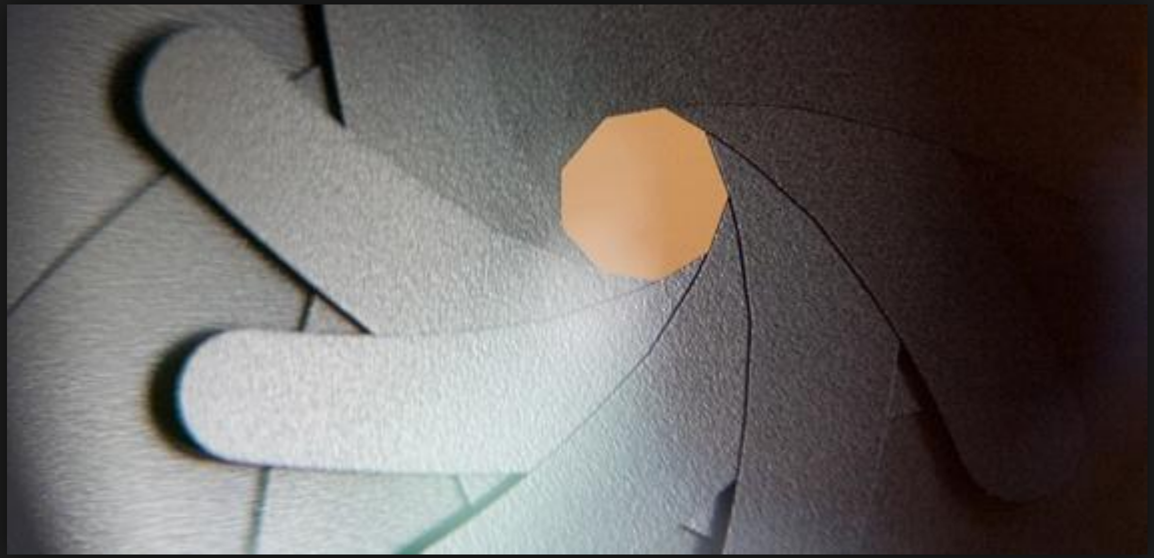


DEPTH OF FIELD\PLAUSIBLE DOF: BOKEH

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



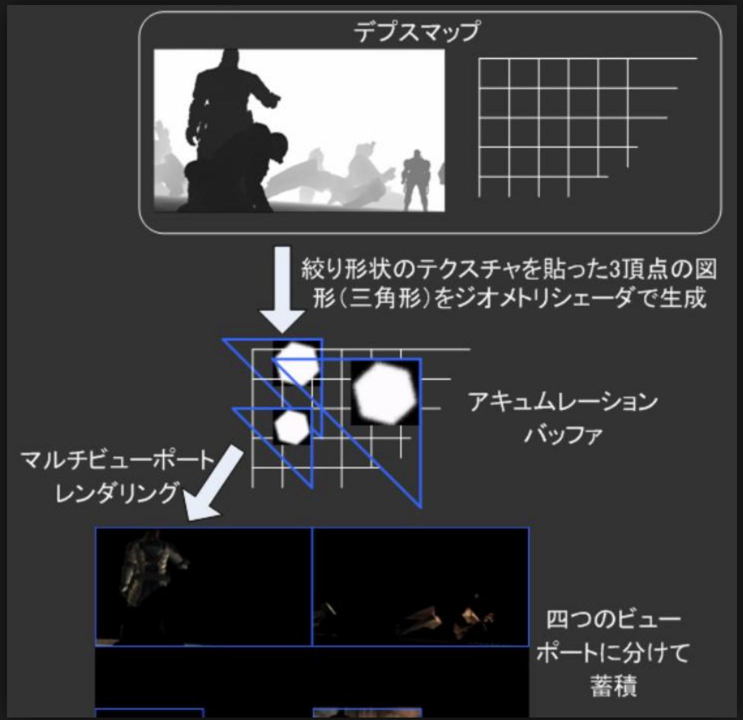
Bokeh kernel is flat

- 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



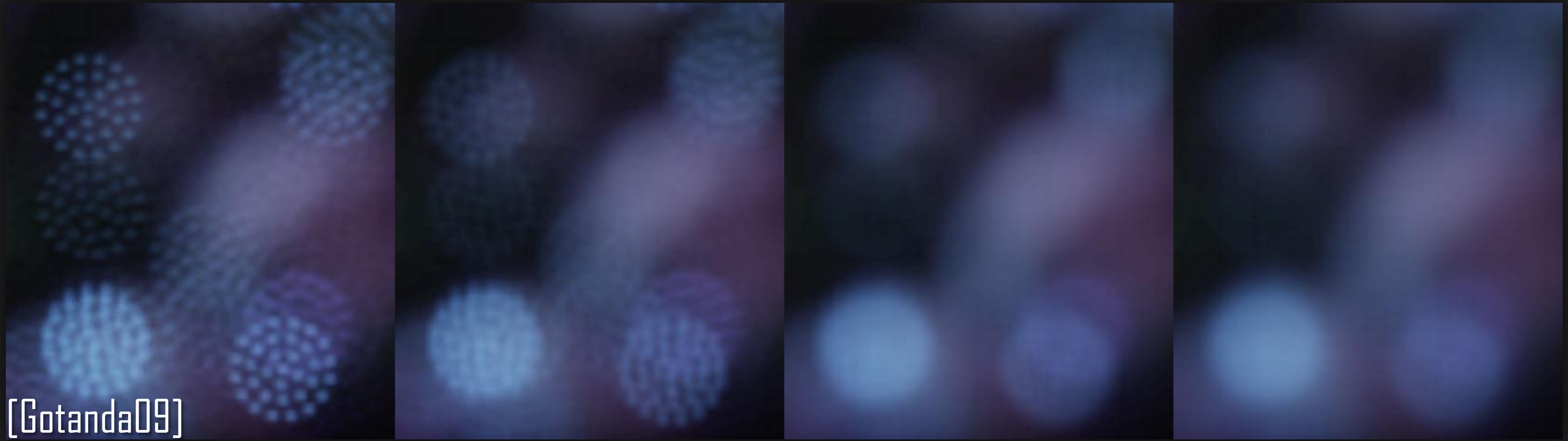
Simple implementation and nice results. Downside: performance, particularly on shallow DOF

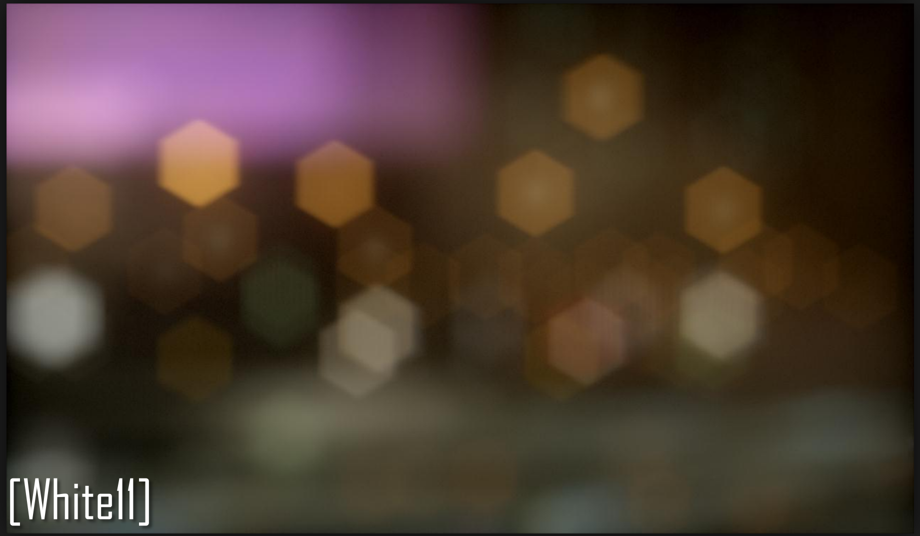
- Variable/inconsistent fillrate hit, depending on near/far layers resolution and aperture size might reach >5 ms
- Quad generation phase has fixed cost attached.

DEPTH OF FIELD\STATE OF THE ART OVERVIEW (2)

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


[Kawase09]


[Gotanda09]


[White11]


[Andreev 12]


[Macintosh12]

CRYENGINE 3

CRYTEK

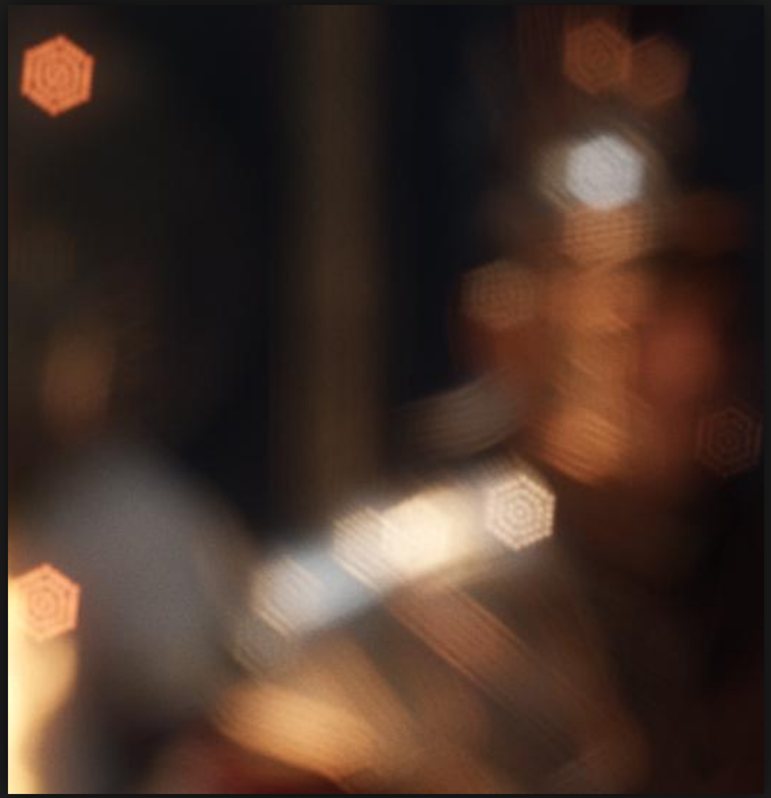
DEPTH OF FIELD\A PLAUSIBLE AND EFFICIENT DOF RECONSTRUCTION FILTER

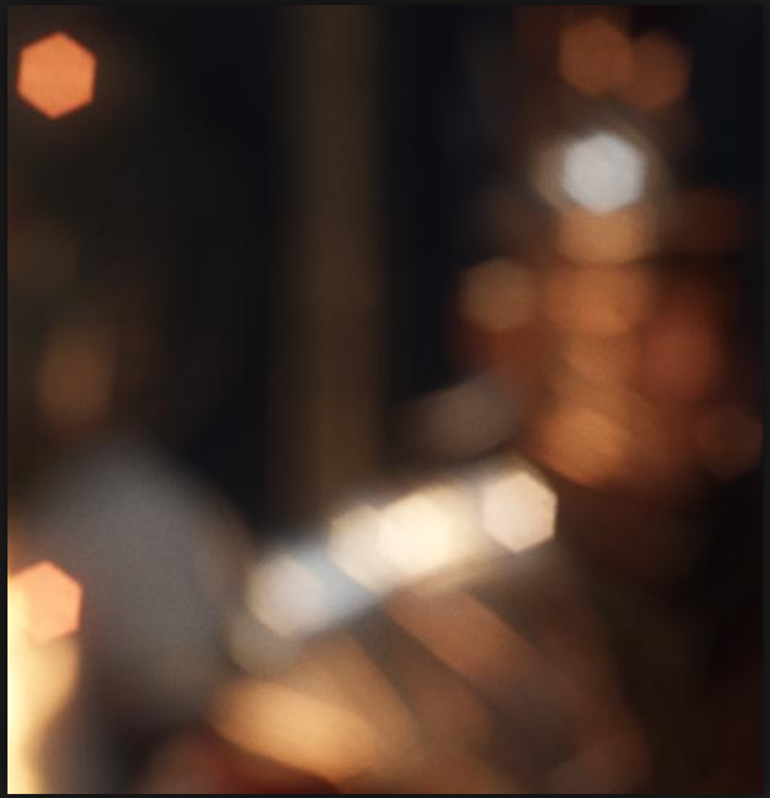
Separable flexible filter: low bandwidth requirement + different bokeh shape possible

- 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

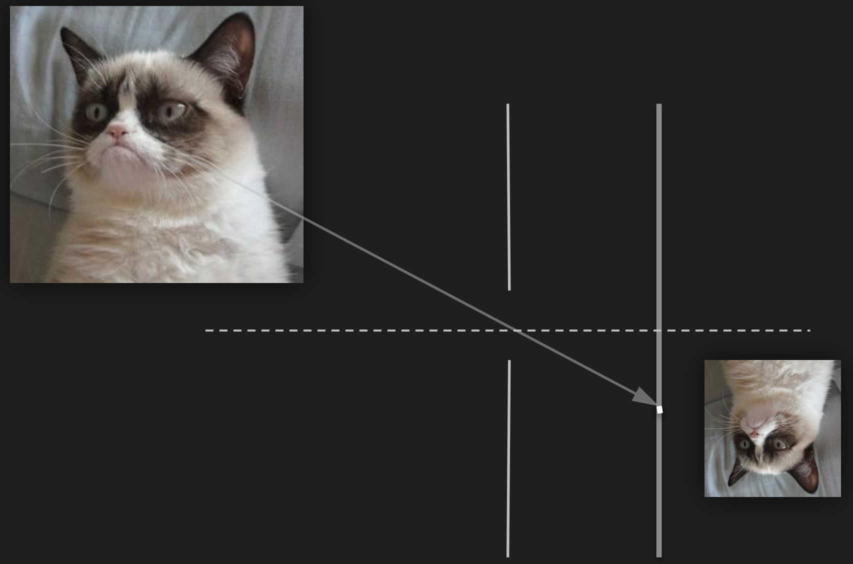




DEPTH OF FIELD\LENS REVIEW

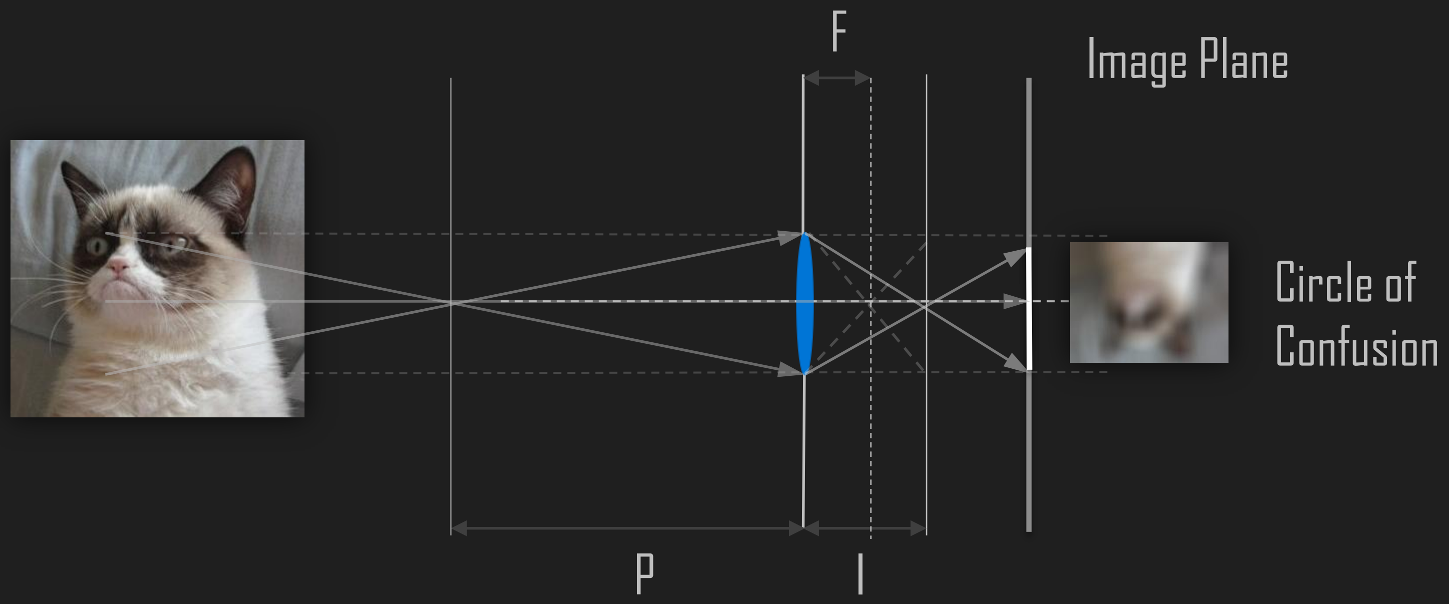
Pinhole "Lens"

- A camera withouth lens
- Light has to pass through single small aperture before hitting image plane
- Tipical realtime rendering



Thin lens

- Camera lenses have finite dimension
- Light refracts through lens until hitting image plane.
- F = Focal lenght
- 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

$$CoC=\left|\left(\frac{F\cdot D}{D-F}\right)-\left(\frac{F\cdot P}{P-F}\right)\right|\cdot\left(\frac{D-F}{f\cdot D}\right) \qquad f=\frac{F}{A}$$

Simplifies to:

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

$$CoC=\left|A\cdot\left(\frac{F\cdot(P-D)}{D\cdot(P-F)}\right)\right|$$

Camera FOV:

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

$$\theta=2\cdot\arctan\left(\frac{width_{film}}{2\cdot F}\right) \qquad F=\frac{0.5\cdot width_{film}}{\tan(\theta/2)}$$

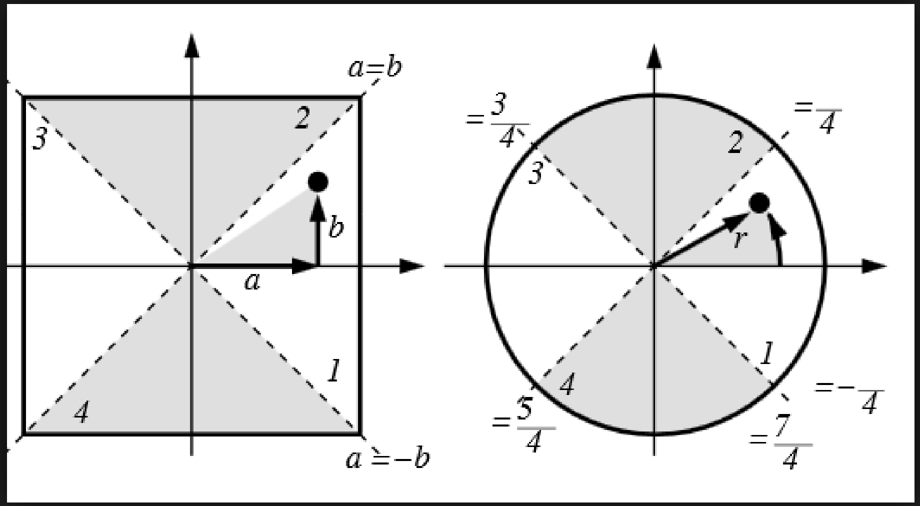
DEPTH OF FIELD\SAMPLING

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:

$$r = a$$

$$\theta = \frac{PI \cdot b}{4 \cdot a}$$

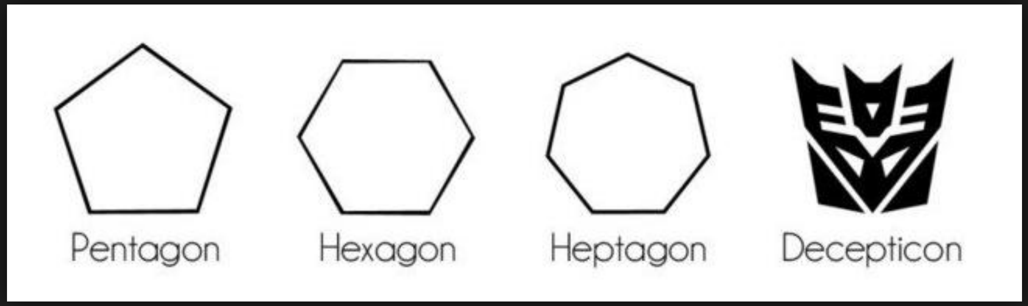


Diaphragm simulation by morphing samples to n-gons

- Via a modified equation for the regular polygon.

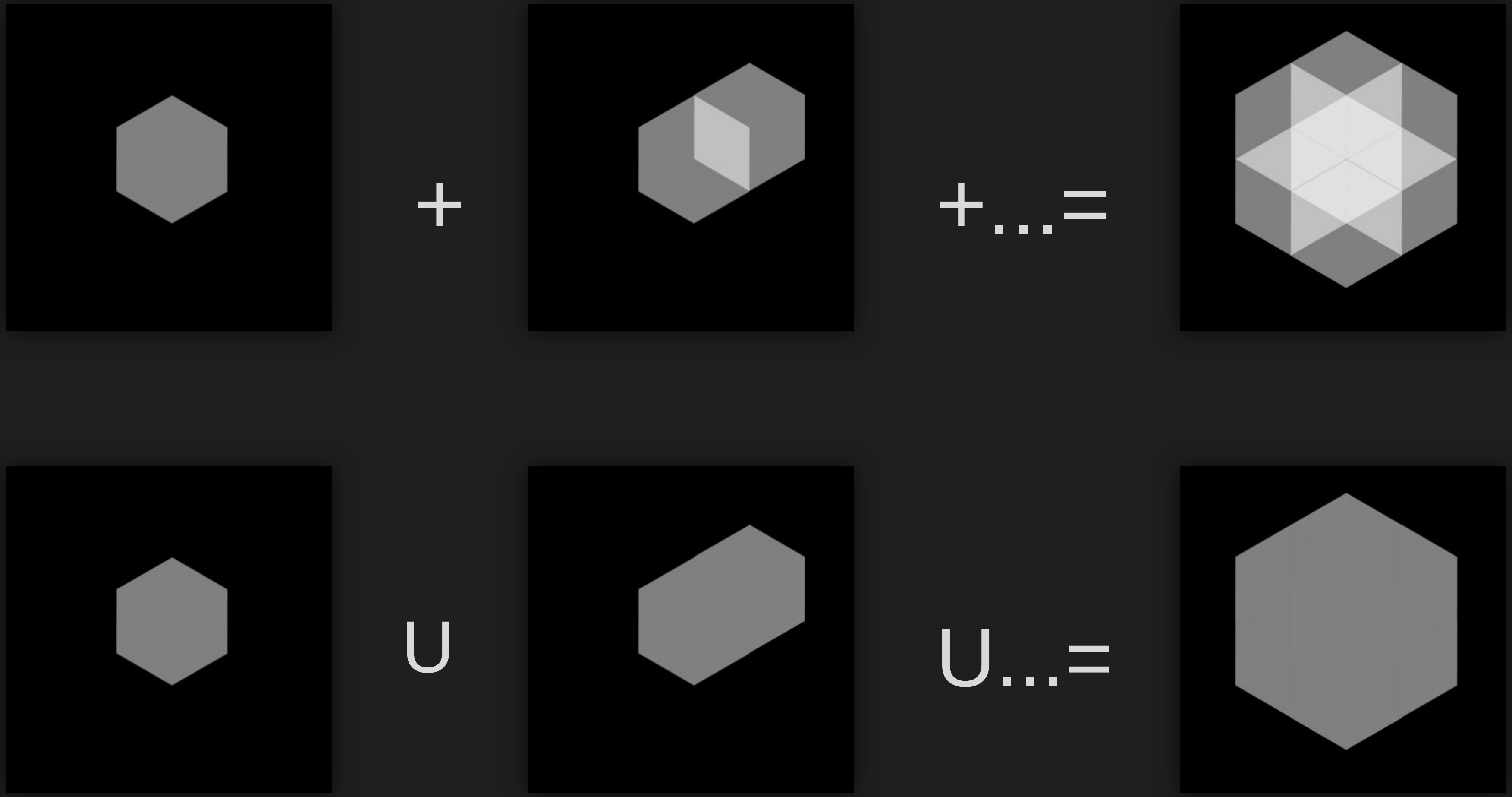
$$f = \frac{(f_{stops} - f_{stops\_min})}{(f_{stops\_max} - f_{stops\_min})} \qquad \theta = \theta + f \cdot \theta_{shutter\_max}$$

$$r_{ngon} = r \cdot \left(\frac{\cos(PI/n)}{\cos(\theta - (2 \cdot PI/n) \cdot floor((n \cdot \theta + PI)/(2 \cdot PI)))} \right)^{f}$$

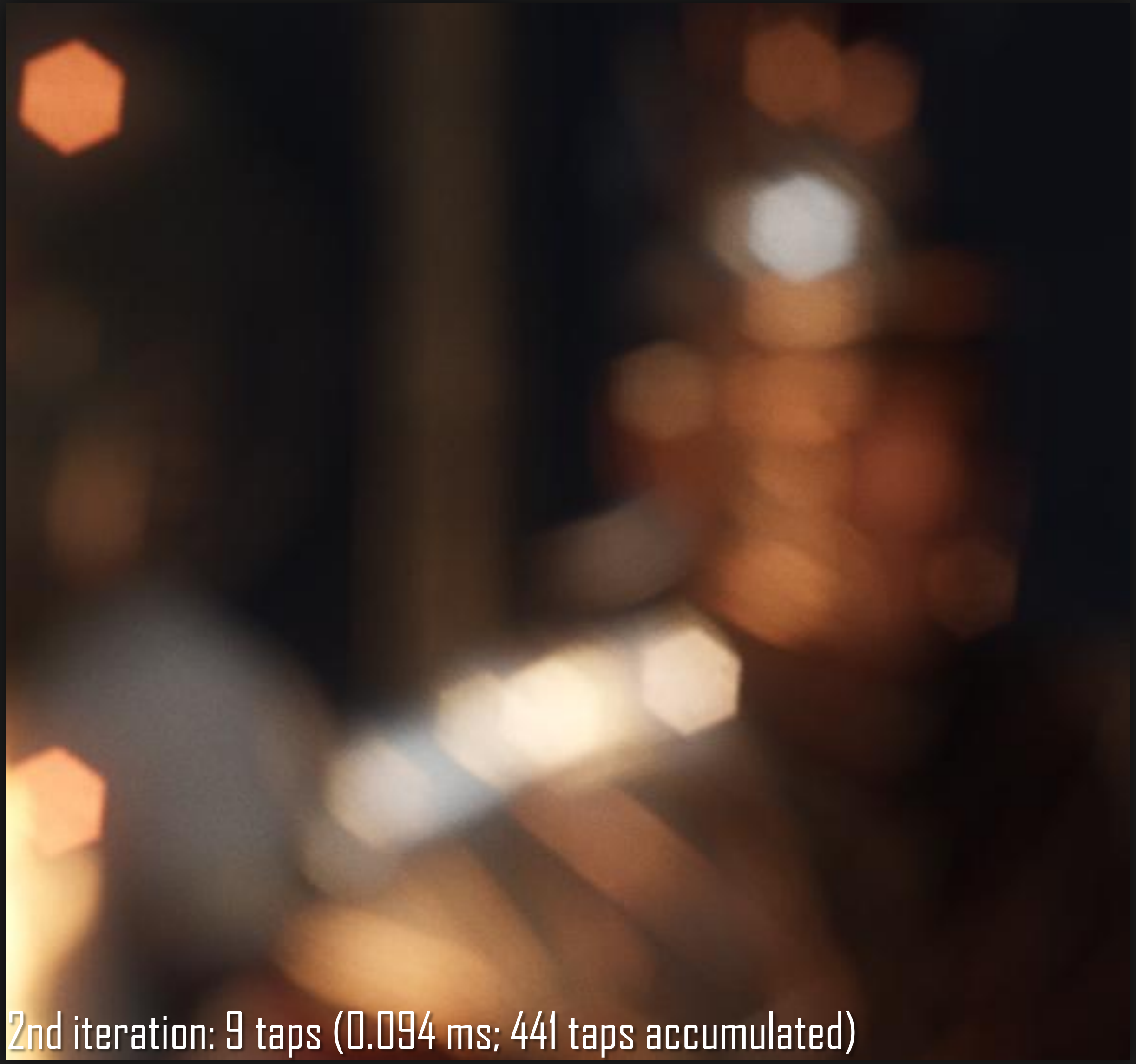


DEPTH OF FIELD\SAMPLING: 2ND ITERATION

To floodfill final shape, composite via boolean union, similarly to [McIntosh12]



DEPTH OF FIELD\SEPARABLE FILTER PASSES



DEPTH OF FIELD\REFERENCE VS SEPARABLE FILTER

DEPTH OF FIELD\DIAPHRAGM SIMULATION IN ACTION

2f-stops

4f-stops

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

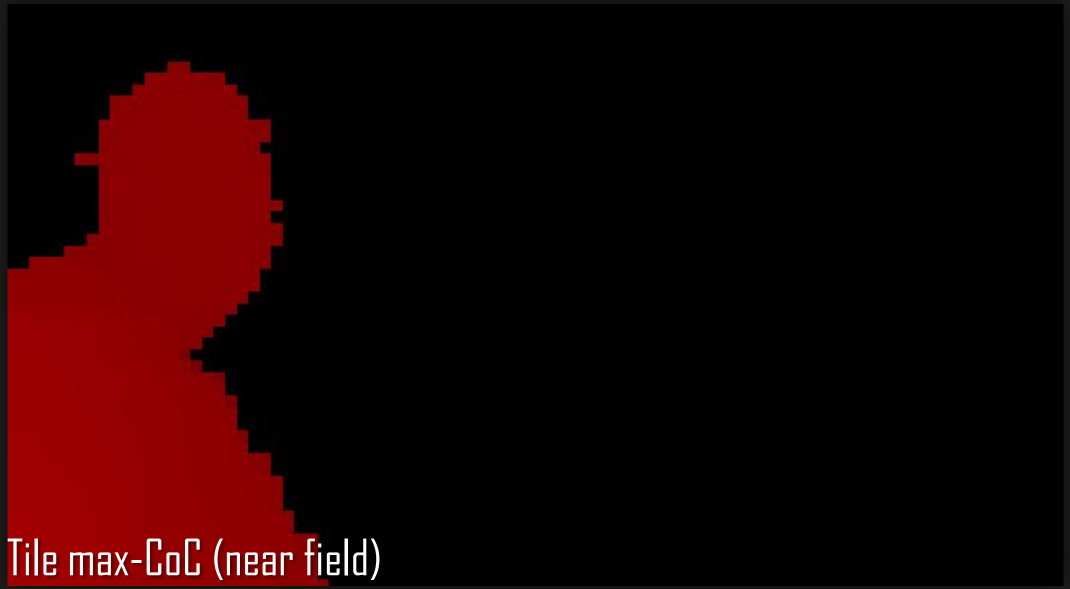
Used to process near/far fields in same pass

- 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

Tile min-CoC (far field)



Tile max-CoC (near field)

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

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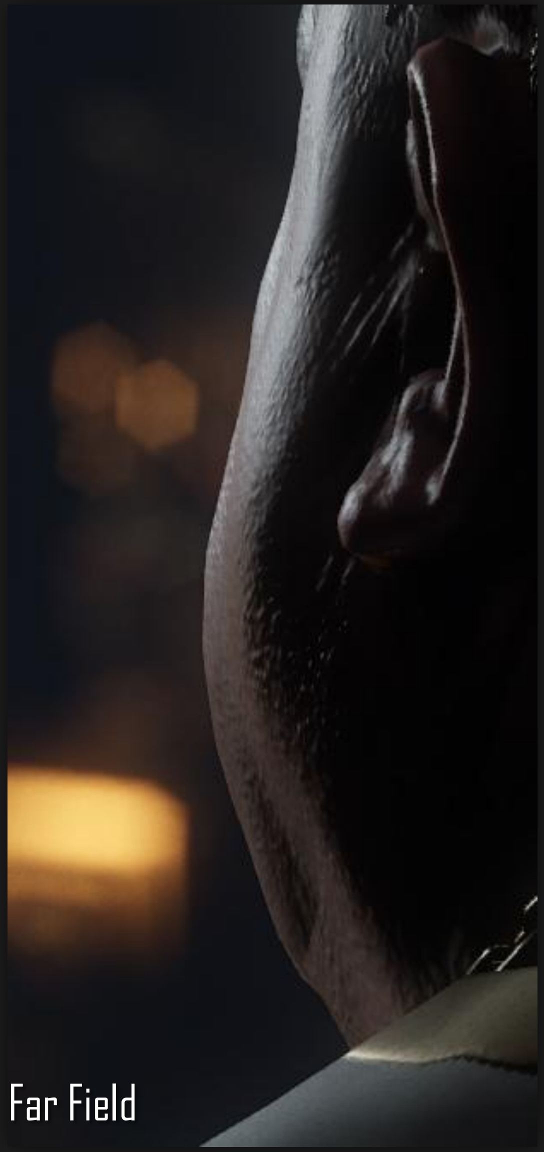
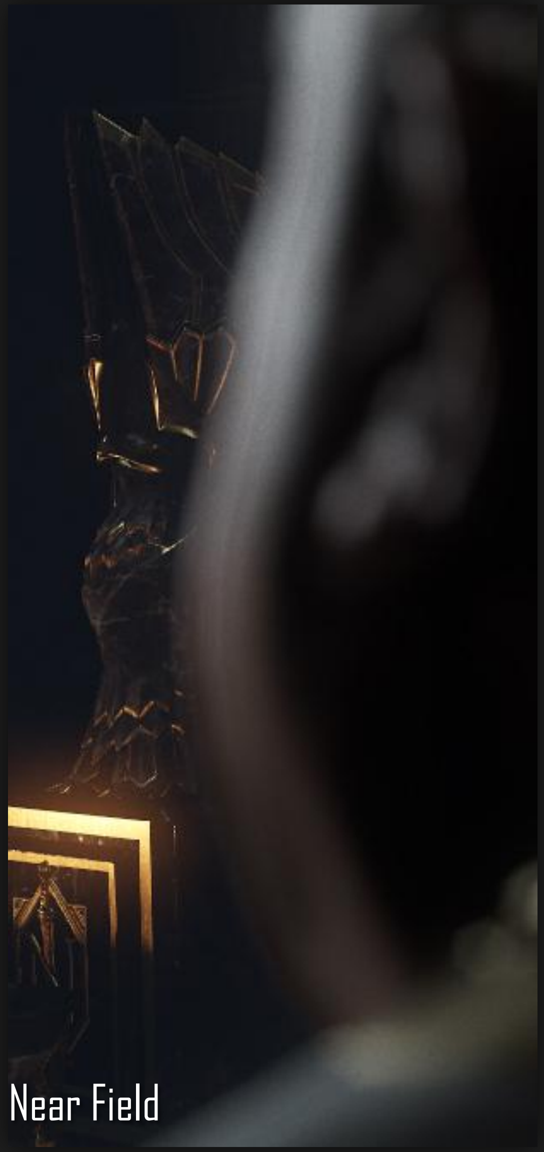
Near Field

- Scatter as gather aproximation
- 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 [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

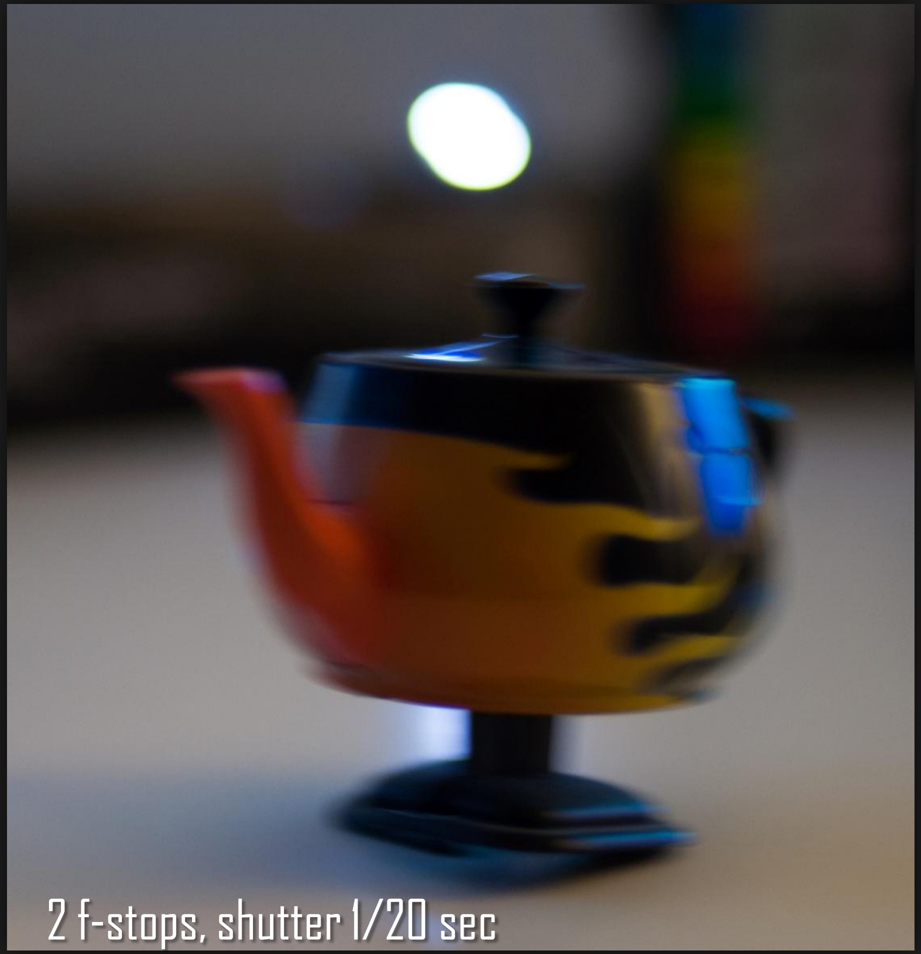
- Linear blending doesn't look good (signal frequency soup)
  - Can be seen in many games, including all Crysis series (puts hat of shame)
- Simple to address: use non-linear blend factor instead.

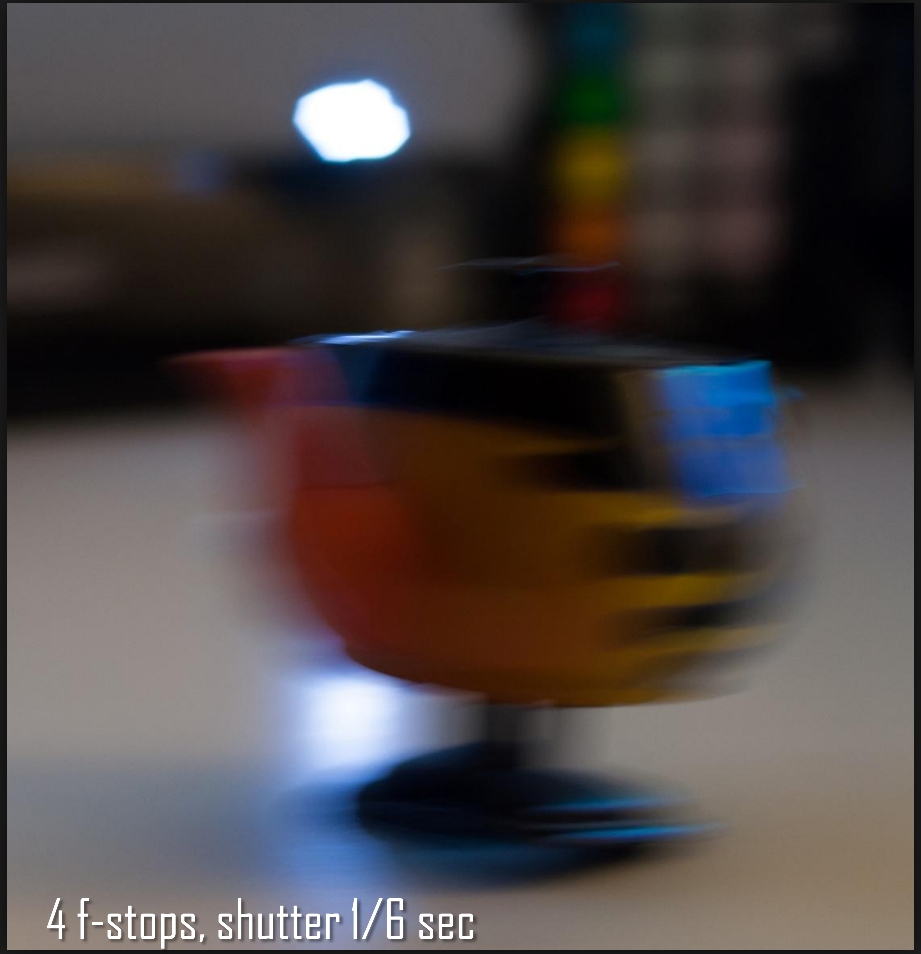
MOTION BLUR

MOTION BLUR\SHUTTER SPEED AND F-STOPS 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

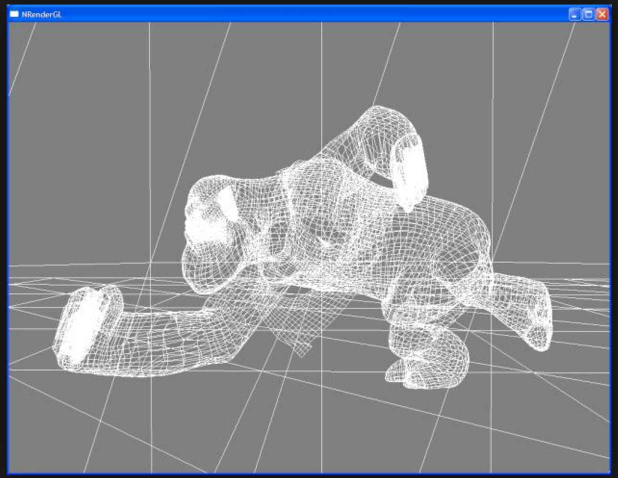

2 f-stops, shutter 1/20 sec

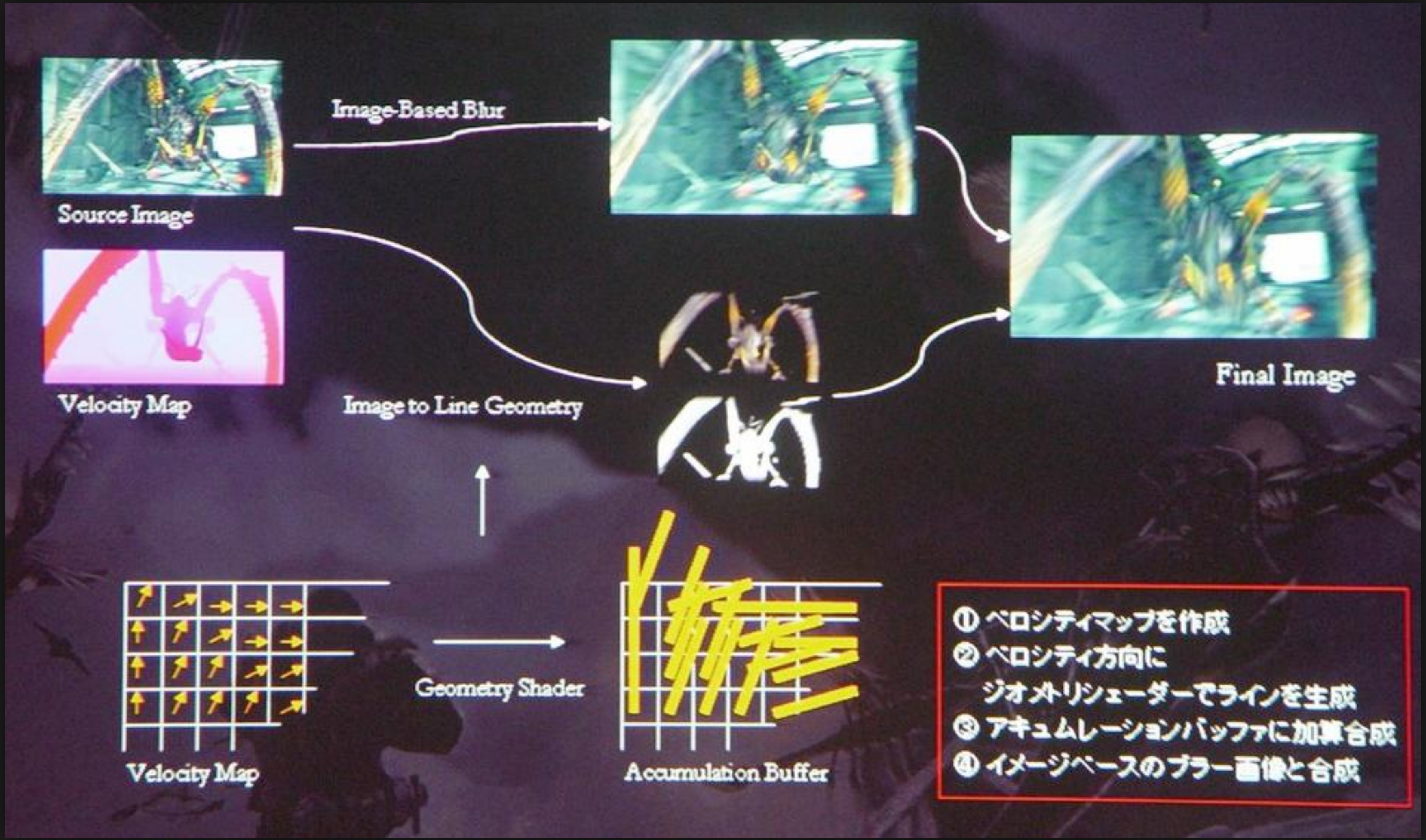

4 f-stops, shutter 1/6 sec

MOTION BLUR\STATE OF THE ART OVERVIEW

Scatter via geometry expansion [Green03][Sawada07]

- Require additional geometry pass + gs shader usage *

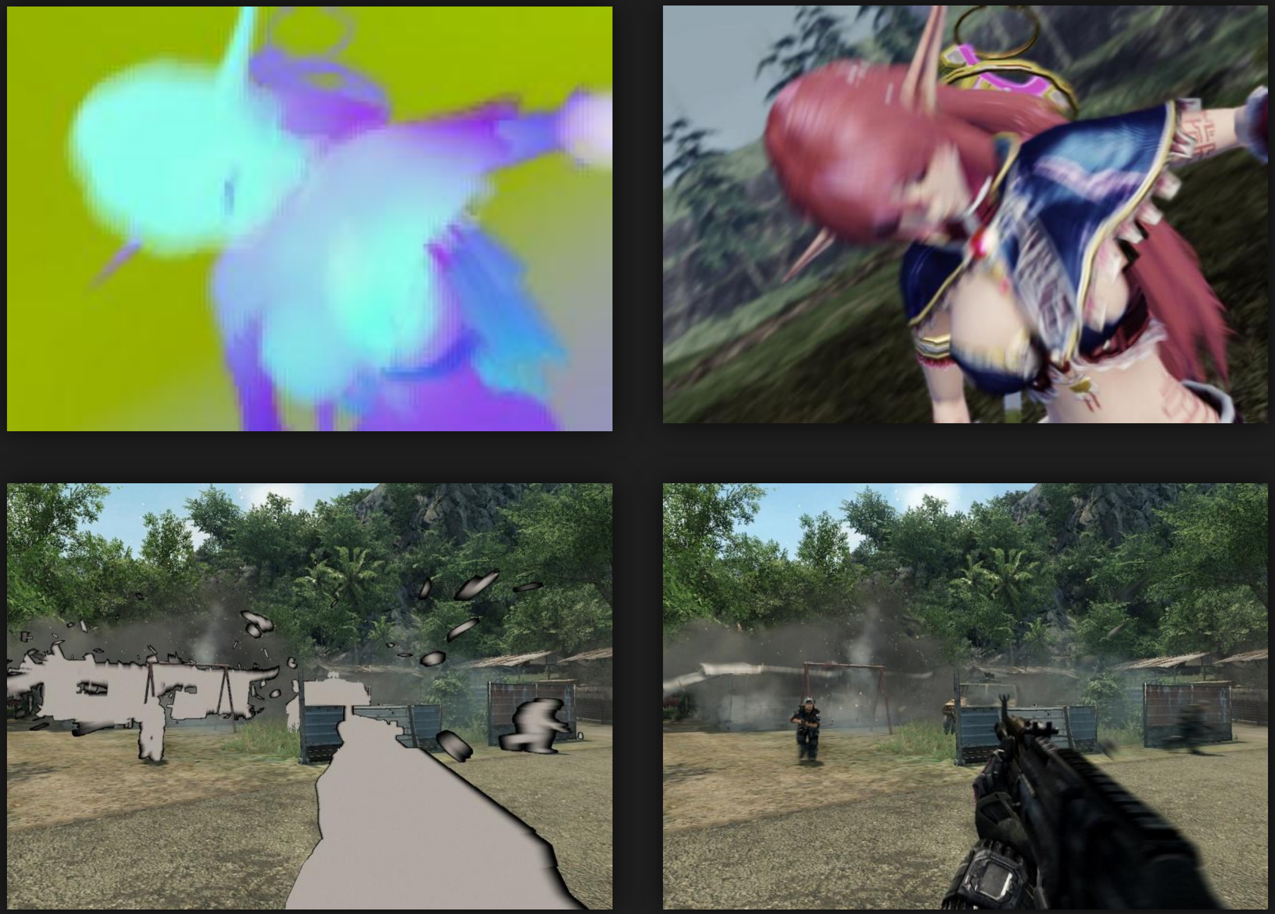


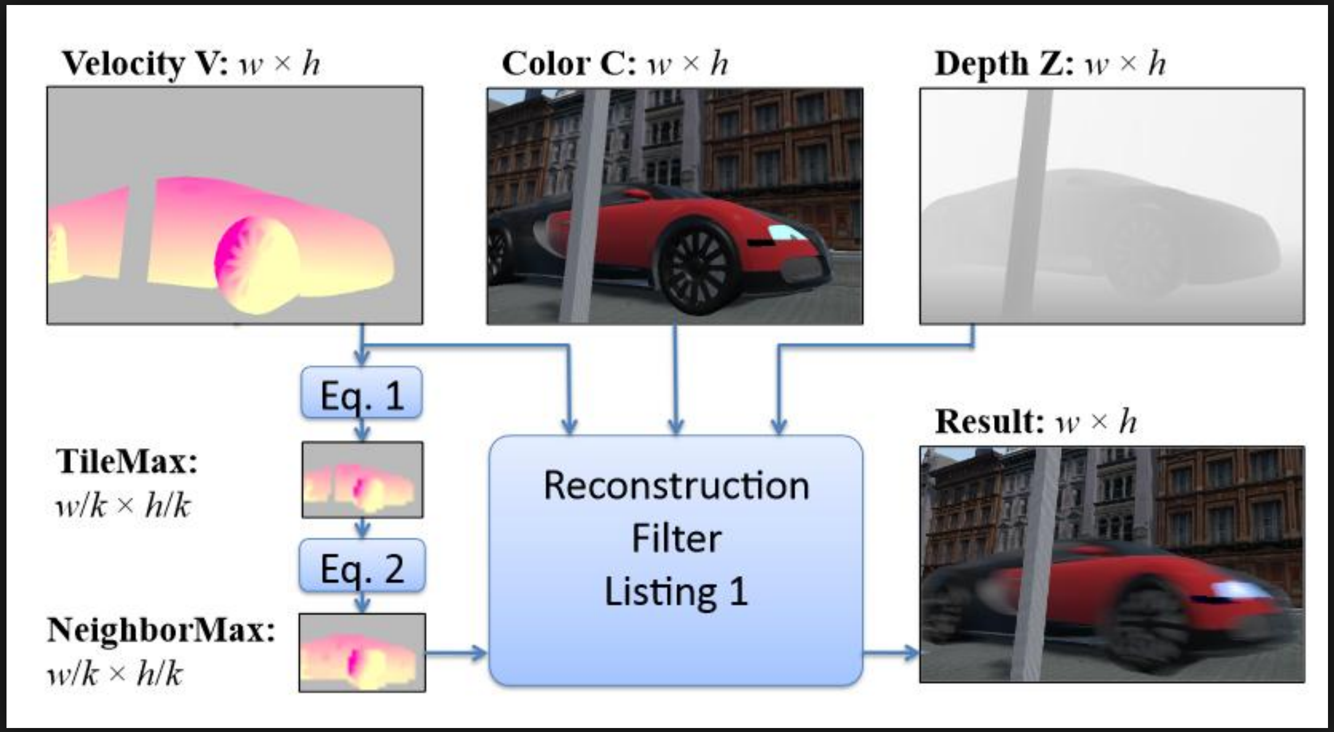


MOTION BLUR\STATE OF THE ART OVERVIEW (2)

Scatter as gather [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





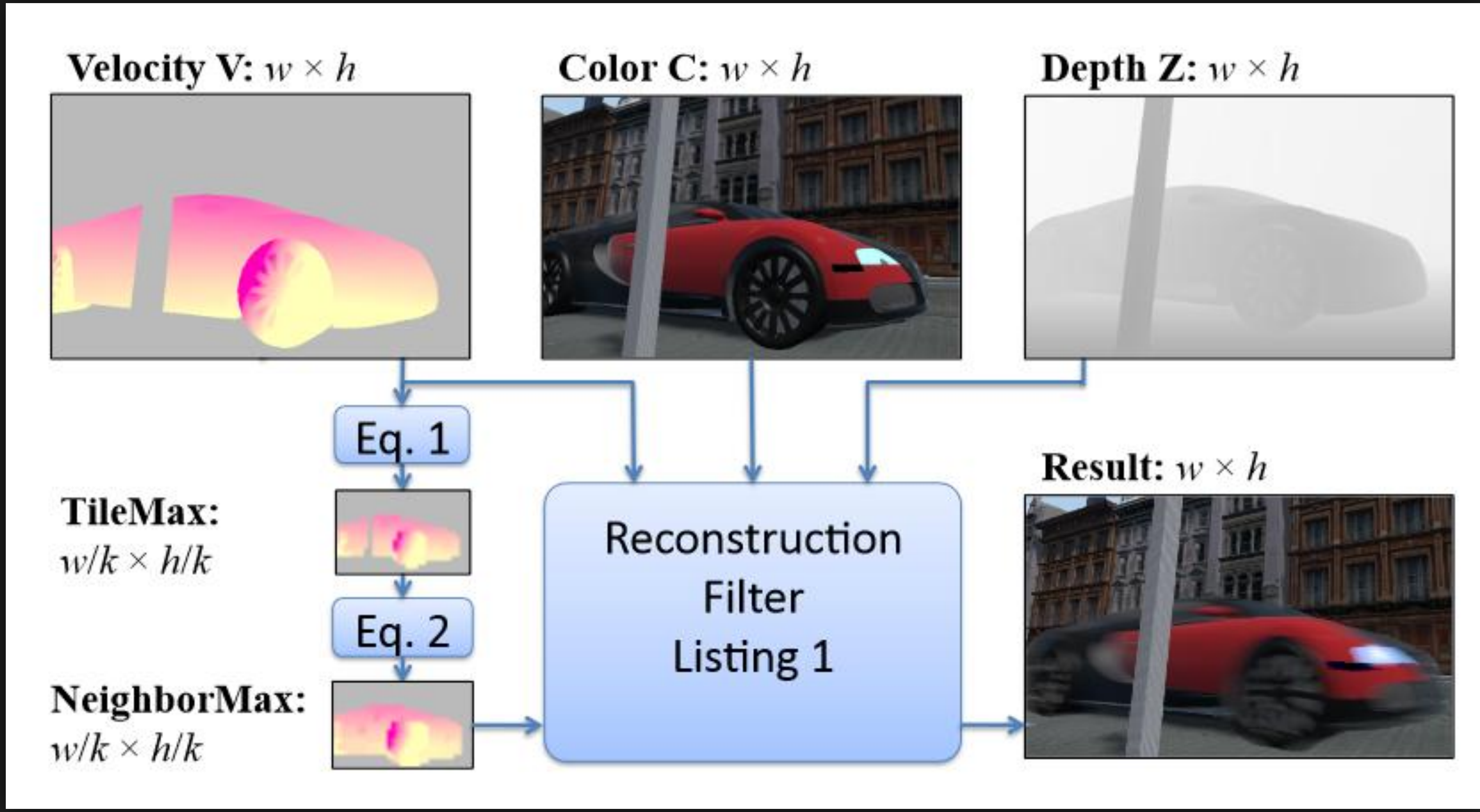
MOTION BLUR\RECONSTRUCTION FILTER FOR PLAUSIBLE MB [MCGUIRE12]

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: R11G11B10F for scene , bake ||V|| and 8 bit depth into a R8G8 target
- Make it separable, 2 passes [Sousa08]

MOTION BLUR\AN IMPROVED RECONSTRUCTION FILTER (2)

Inner loop sample

```
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.xyxy)) + 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

$$v_{enc} = \sqrt{|v_{xy}|} * \mathrm{sgn}(v_{xy}) * (127.0/255.0) + 0.5$$

Decode

$$v_{enc} = (v_{enc} - 127.0/255.0)/255.0$$

$$v = (v_{enc} * v_{enc}) * \mathrm{sgn}(v_{enc})$$

Object velocity

Composite with camera velocity

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


MB before DOF


MB after DOF

FINAL REMARKS

Practical MSAA details

- Do's and Dont'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: 0.236 ms, 2nd pass: 0.236ms. Sum: 0.472ms for reconstruction filter *

* 1080p + AMD 7970

SPECIAL THANKS

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WE ARE HIRING !

QUESTIONS ?

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