High Quality Temporal Supersampling

Brian Karis (@BrianKaris)

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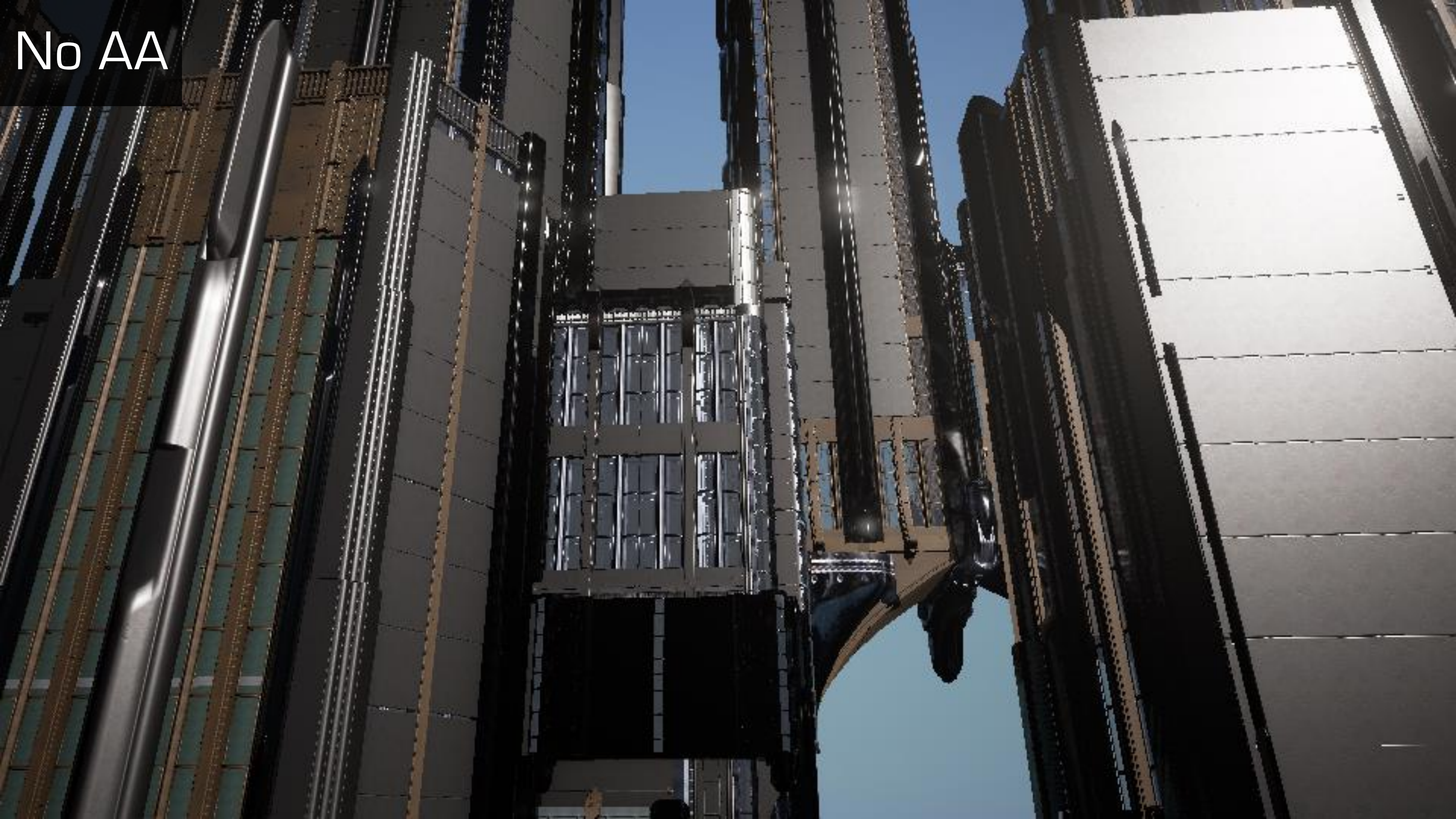
EPIC GAMES

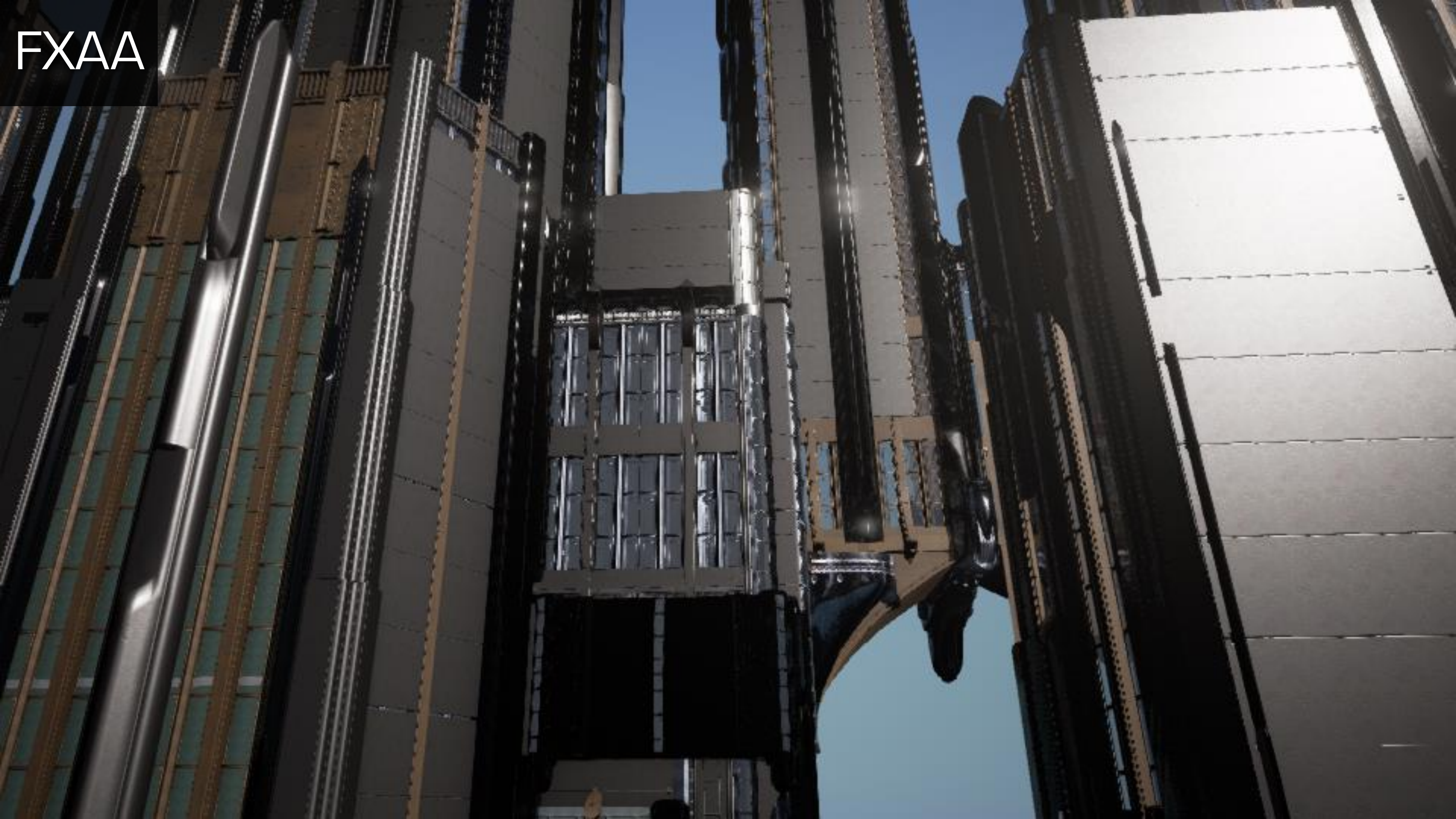
Context

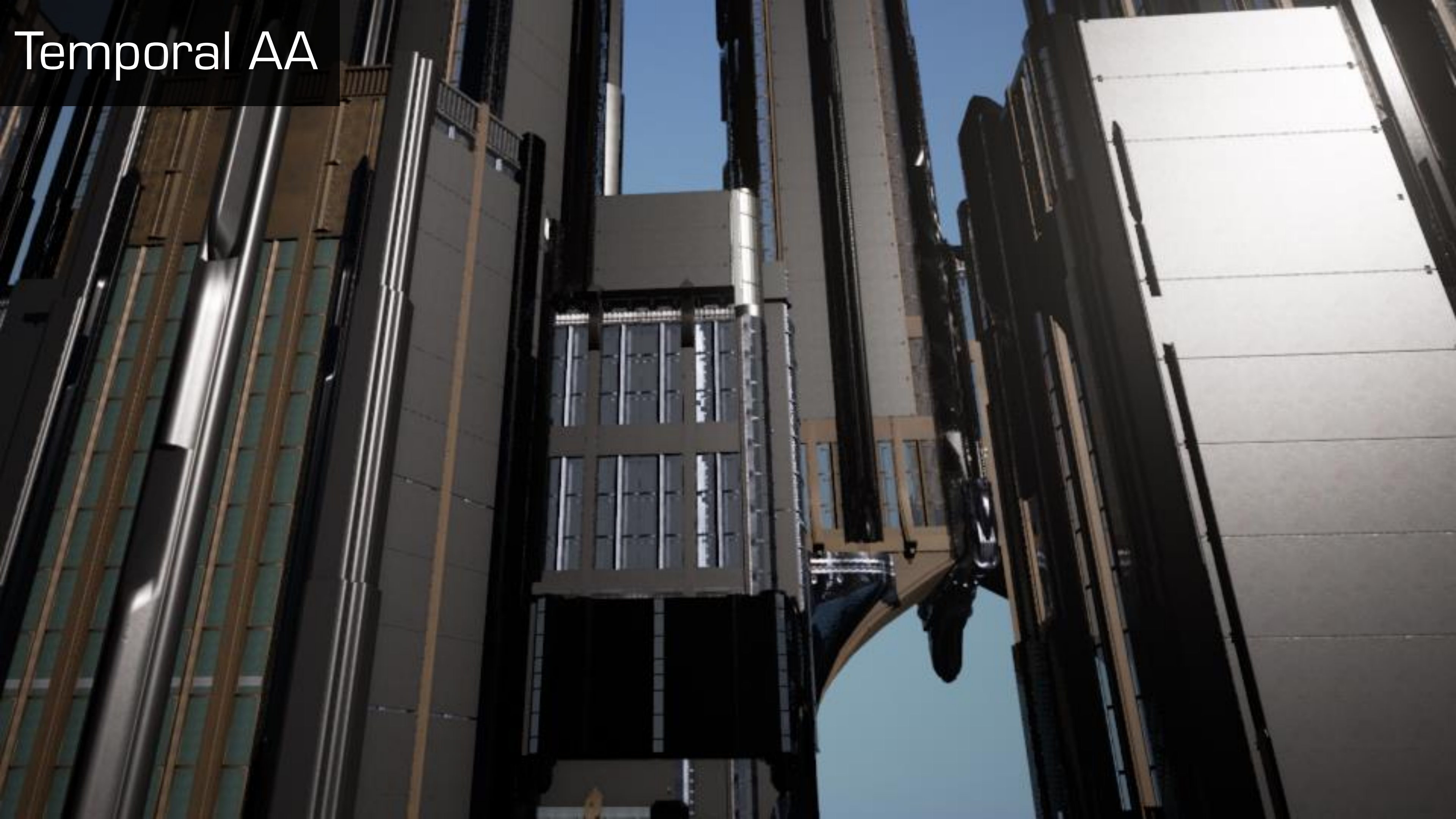
- Unreal Engine 4’s primary anti-aliasing solution
  - Referred to as Temporal AA in the engine
- First used in the UE4 Infiltrator tech demo
- Several major revisions since then
- Still ongoing work

UE4 renderer

- Deferred shading
- Physically based
- HDR


No AA


FXAA


Temporal AA

Problem

- Horrifically aliased input
- Both geometric and shading aliasing
- Mostly from subpixel features
- Want temporal stability

MSAA?

- Too expensive with deferred
  - Don’t want to shade more than once per pixel
- Doesn’t affect shading aliasing
  - More significant aliasing inside triangles than at their edges

Spatial filter?

- MLAA, FXAA, SMAA, etc.
- Essentially edge finding, reduces stair stepping
  - Primarily not a stair stepping problem
- No knowledge of subpixel features
- Not temporally stable
  - Even on simple stair stepping

[Reshetov09], [Lottes11], [Jimenez12]

Specular Lobe filtering?

- Toksvig, LEAN, vMF, etc.
- Filters shading input to prevent subpixel shading output
- Difficult to pre-filter everything
  - Geometric features are major contributor
  - Often no existing unique roughness map
  - Procedural texturing
  - Still aliases
- Screen space filter aliases
  - Misses subpixel features

[Hill12], [Neubelt13], [Mittring12]

Temporal filtering

- Distribute samples over multiple frames
- I've had great success with this in the past
  - SSAO
  - SSR
- Replaced spatial filter
  - Higher quality
  - Cheaper
- Do the same with supersampling?

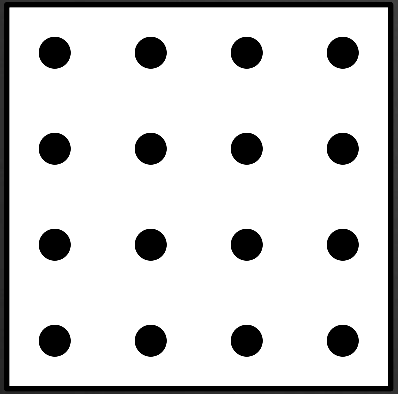
Step 1: Static scene

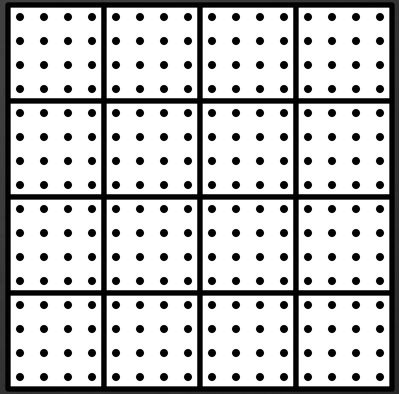
Jittering

- Adjust projection matrix

```
ProjMatrix[2][0] += ( SampleX * 2.0f – 1.0f ) / ViewRect.Width();
ProjMatrix[2][1] += ( SampleY * 2.0f – 1.0f ) / ViewRect.Height();
```

Regular grid

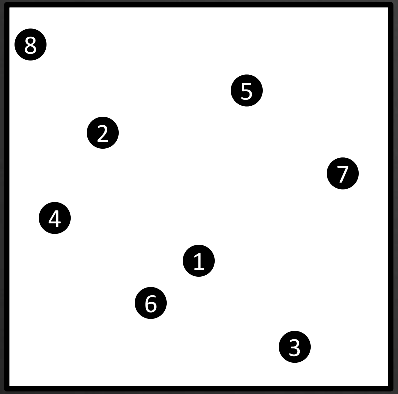


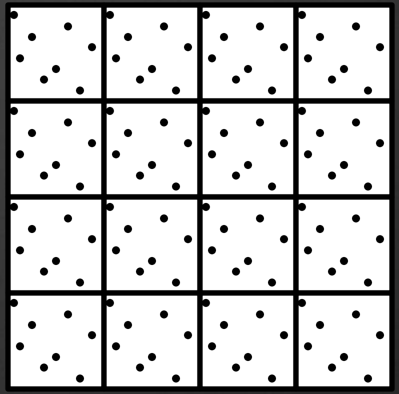


Sample pattern

- Want a low discrepancy progressive sequence
  - No clustering in either space or time
- Halton (2,3) worked well enough
  - Better than any HW MSAA sample ordering

Halton





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Moving average

- Simple moving average
  - Not enough samples
  - $n = 2$ practical for color
  - $n = 5$ if luma only
- Exponential moving average
  - Nearly infinite number of samples with fixed storage

$$s_t = \frac{1}{n}\sum_{k=0}^{n-1} x_{t-k}$$

$$s_t = \alpha x_t + (1 - \alpha)s_{t-1}$$

Exponential smoothing

- When α is small exponential $\approx$ simple

$$s_t = \alpha x_t + (1-\alpha)s_{t-1} = \alpha \sum_{k=0}^{\infty} (1-\alpha)^k x_{t-k}$$

$$x_t = x_{t-n} \Rightarrow s_t = \frac{\alpha}{1-(1-\alpha)^n} \sum_{k=0}^{n-1} (1-\alpha)^k x_{t-k}$$

$$\lim_{\alpha \to 0} \frac{\alpha}{1-(1-\alpha)^n} \sum_{k=0}^{n-1} (1-\alpha)^k x_{t-k} = \frac{1}{n} \sum_{k=0}^{n-1} x_{t-k}$$

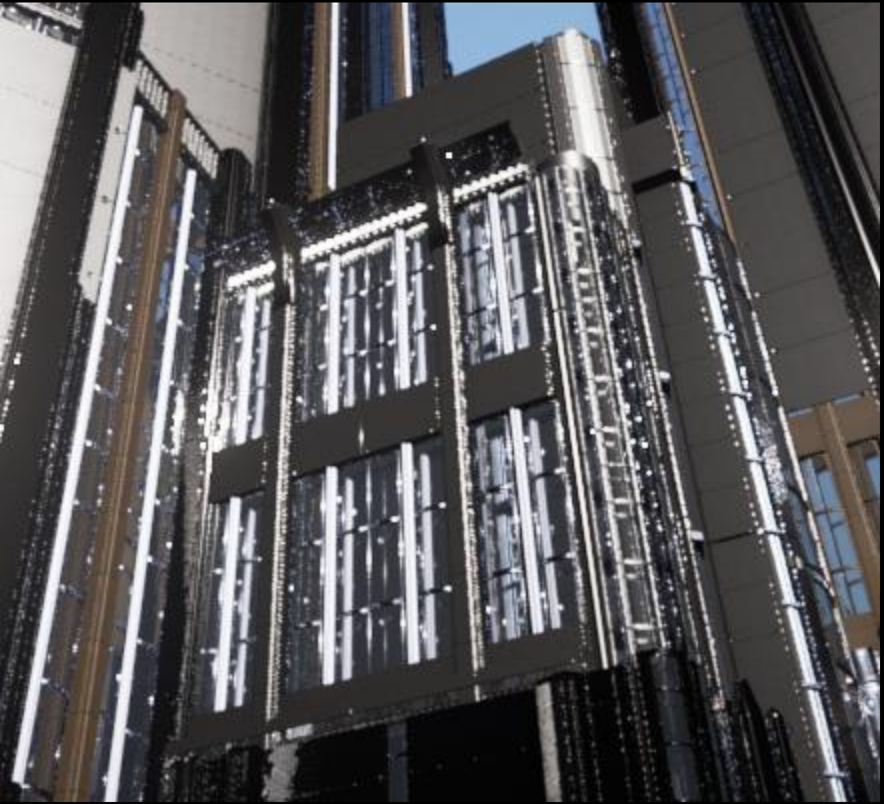
When to average?

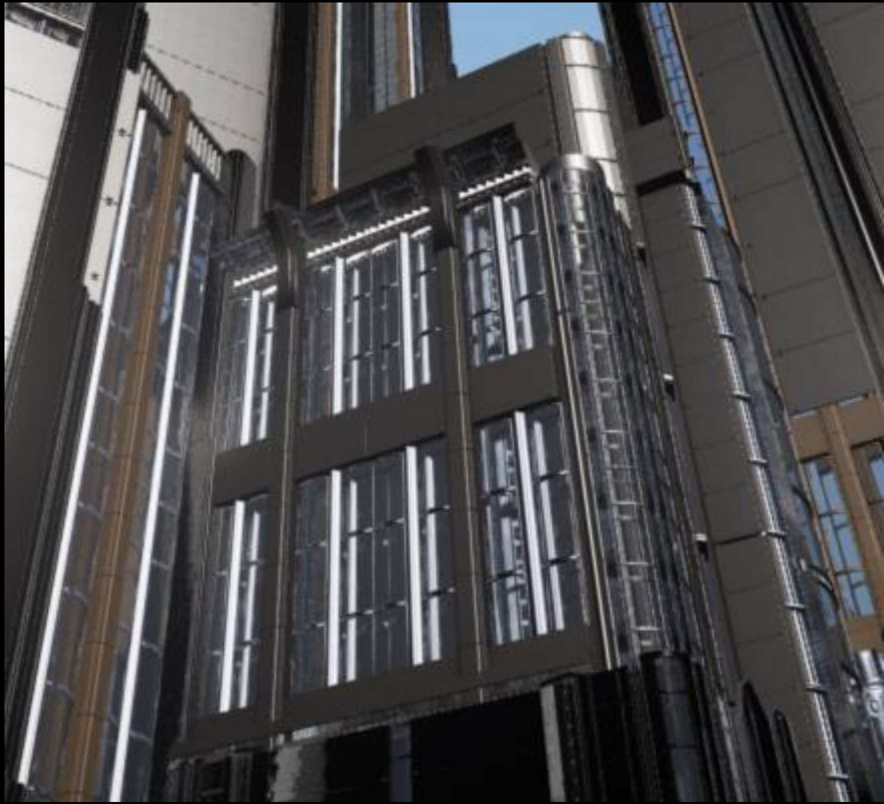
- Before tone mapping
  - The physically correct location
  - Bright values dominate
  - Aliases badly with limited # of samples
- After tone mapping
  - All post filters flicker
  - Aliased input → aliased output

Before

Tone map

After





Straightforward tone map solution

- Hybrid of before and after
  - Apply before all post
  - Tone map input
  - Accumulate samples
  - Reverse tone map output
- Same AA quality as after tone mapping
- Provides AAed input to post processing chain
  - No more flickering bloom

Better tone map solution

- Tone mapping desaturates bright pixels
- Weight samples instead based on luminance
  - Maintains chroma
  - Perceptually closer to ground truth
- No need to store the weight
  - Rederive weight
  - Saves GPRs
- See my blog post: [Karis13]

$$weight = \frac{1}{1 + luma}$$

$$T(color) = \frac{color}{1 + luma}$$

$$T^{-1}(color) = \frac{color}{1 - luma}$$

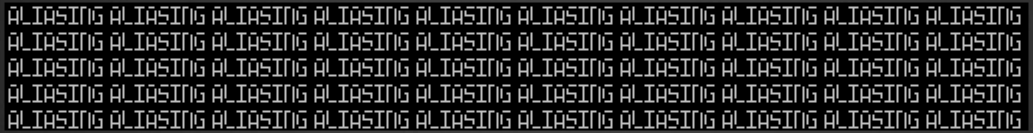
Tone map

Luma weight

Reconstruction filter

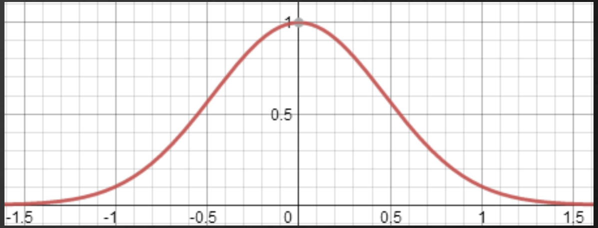
- Box filter is not stable under motion

Box



Gaussian

- PRMan anti-aliasing guide
- Gaussian fit to Blackman-Harris 3.3
  - Support is ~2 pixels wide



$$W(x) = e^{-2.29x^2}$$

[Burley07]

Step 2: Dynamic scene

Reprojection

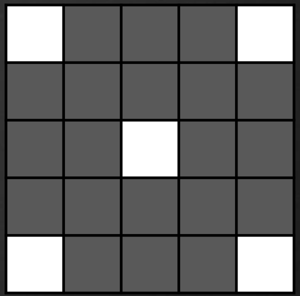
- History for current pixel may be elsewhere on screen
  - May not exist at all
- Use same velocity buffer calculation as motion blur
- Remember to remove jitter

Velocity accuracy

- Need velocity (motion vectors) for everything
  - Motion without correct velocity will smear
- Accuracy is super important
  - Minor imprecision will streak a static image
  - 16:16 RG velocity buffer
- Can be tricky
  - Procedural animation
  - Scrolling textures
  - Almost opaque translucent objects

Motion on edges

- Moving silhouette edges lose AA
  - Smooth AAed edge doesn't move with object
  - Effectively an aliased mask in the velocity buffer
- Dilate velocity
  - Take front most velocity



Ghosting

Ghosting

- Depth compare?
  - All samples don't share same depth
- Velocity weighting?
  - Shading changes
  - Translucency

[Nehab07], [Sousa11]

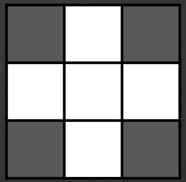
Neighborhood clamping

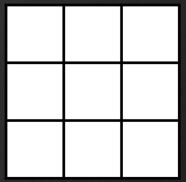
- New kid in town!
  - [Lottes11] , [Malan12]
- Restrict history to the range of current frame's local neighborhood
  - Assumes AA result is blend of neighbors
  - Clamp with min/max of 3x3 neighborhood

Neighborhood clamping artifacts

Shaped neighborhood clamp

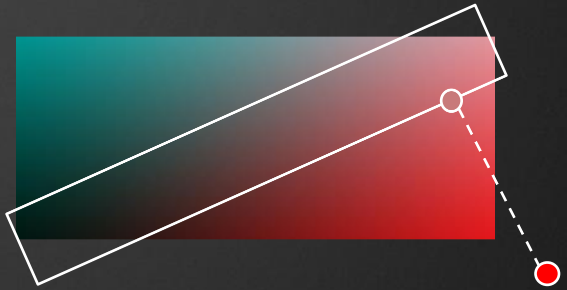
- Simple clamp to min/max of 8 neighbors results in 3x3 box artifacts
- Want min/max to appear filtered
  - Round out the shape
- Solution: average 2 neighborhood's min/max





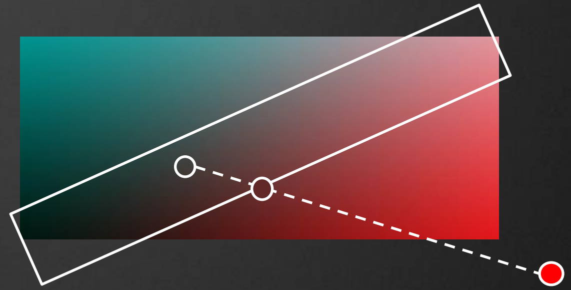
YCoCg box

- Basic min/max is an AABB in RGB space
- Ideally use convex hull of neighborhood colors
  - Too expensive
- Orient box in luma direction
  - Luma has high local contrast
  - Chroma typically doesn't



Clip instead of clamp

- Constrain to a blend of history and neighborhood average
- Clip line segment to box
- Colors don't collect in box corners like clamping does



Basic min/max RGB clamp

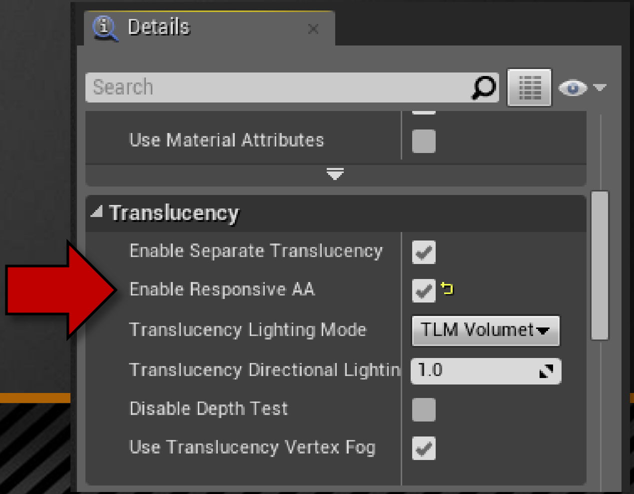
Clipped to shaped YCoCg box

Translucency

- Translucency is a poor fit for temporal
  - Single history
  - Single velocity
- Ideally render translucency separate and composite
  - Can't unjitter depth buffer to compare against
- Possible solution: 4xMSAA depth prepass
  - Alternate which sample to shade

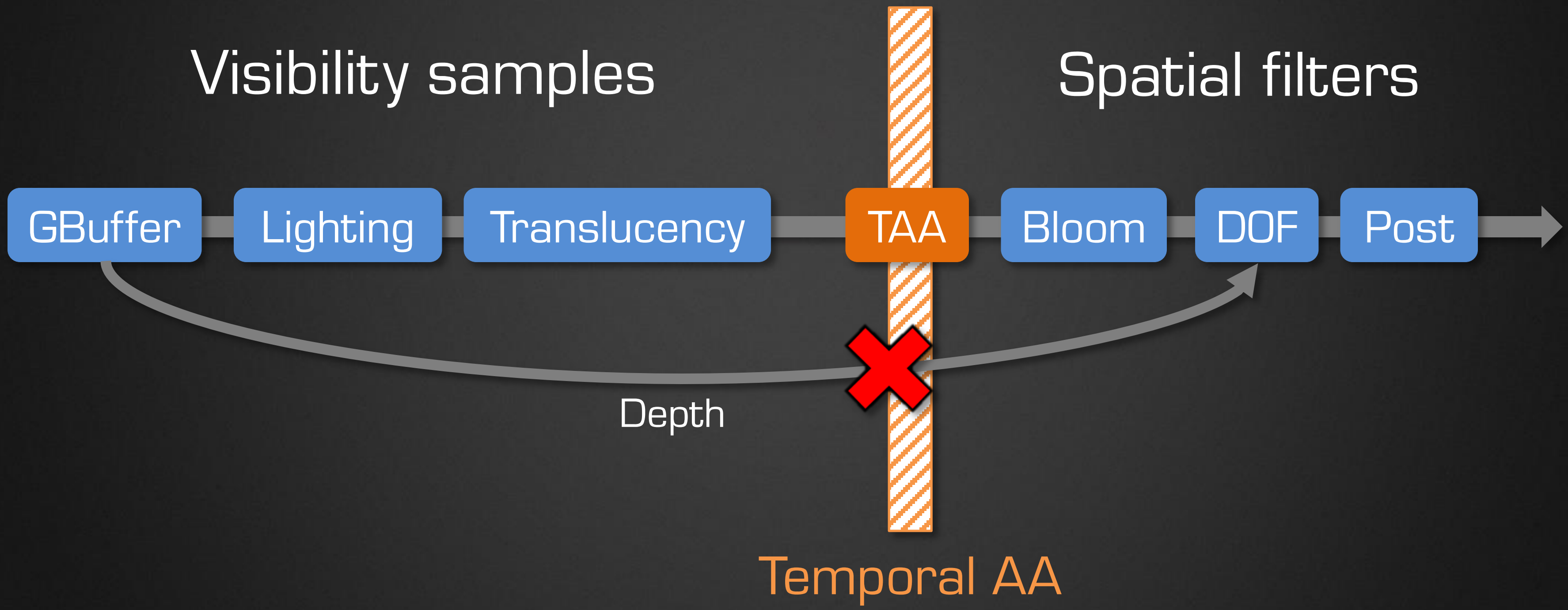
Our translucency solution

- “Responsive AA” material flag
- Sets stencil when rendering translucency
- Temporal AA pass tests stencil and uses minimal feedback
  - Unfortunately need >0 feedback to prevent visible jittering
- Only useful for small particles like sparks
  - Neighborhood clamping handles the rest

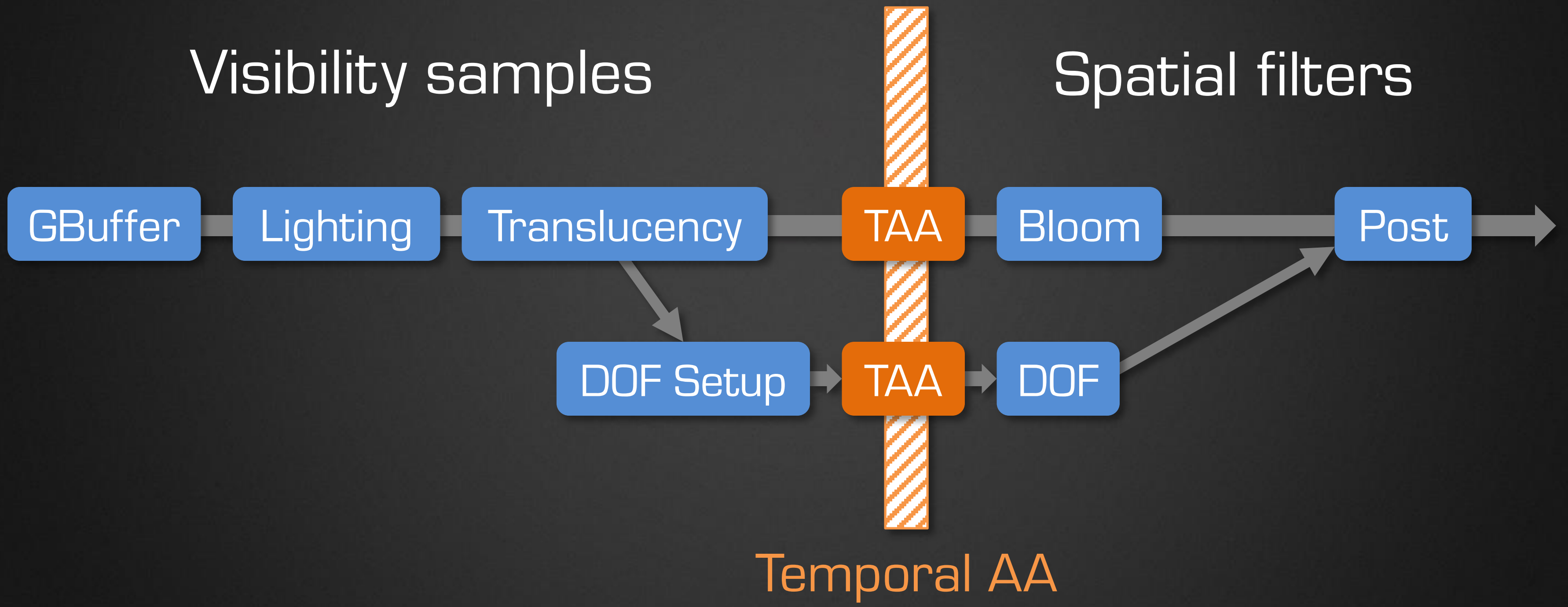



Without
Responsive AA

Temporal AA is a firewall



Temporal AA is a firewall



Flickering

- Camera is static but some pixels flicker
- Missing subpixel feature's history gets clamped
  - Often vertical or horizontal lines due to coherent jitter
- Clamping is an instantaneous impulse
- This leads to saw tooth waves which appear as flickering

Bright edge missing in one frame

Basic anti-flickering idea

- Bias towards impulse frame
  - Shrinks amplitude of wave
- Reduce exponential smoothing blend factor
  - Reduces recovery from impulses
- Only where needed
  - Overly blurry results if done everywhere

Bright edge missing in one frame

First anti-flickering attempt

- Store historical variance data in alpha channel
  - Remember clamping events
  - Reduce blend factor and recover over time
- Responsiveness issues
  - Can result in ghosting or blurring
  - Can bias towards aliased result

Our current anti-flickering solution

- Reduce blend factor when history is near clamping
  - Will happen after clamp events
  - Memory specific to event
  - Doesn't require additional storage
- Not completely solved
  - <u>Extremely difficult!</u>
  - Impossible to solve multiple opposing clamps

Blurring: filter kernel

- Mipmap bias all textures
  - Incorrect derivatives for supersampling
- If low contrast then reduce filter kernel size
  - Technically aliases but looks fine
- Can add additional post sharpen filter
  - Mitchell 4.0 filter's negative lobes are >1 pixel away

Blurring: reprojection diffusion

- Could use back and forth error compensation
  - Haven't had good results
- Could store history at higher resolution
  - Really expensive
- When reprojecting outside pixel reduce filter size and feedback

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[Valient14], [Yang09]

Noise filter

- Not its original purpose
  - Really nice side effect
- Used for SSR and SSAO
  - Stochastic sampling works pretty well
  - Doesn’t cost anything extra
  - Almost perfect mirror reflections with only 16 ray march steps

Many more potential applications

- Stochastic transparency
- Single sample anisotropic specular IBL
- Soft shadows
- Reduced steps for ray casting
  - Parallax occlusion mapping
  - Volumetric lighting
- Path tracing?
- VR?

Video

Future directions

- Combine spatial and temporal
- Separate translucency
  - Visibility and shading sample disconnect
- Different jitter per pixel
  - Custom MSAA sample placement
- More complete motion vectors
  - Translucency
  - Motion estimation

Conclusion

- Temporal supersampling is production ready
  - High quality
  - High performance
- Needs a lot of perceptual tuning

Thanks

- Timothy Lottes, co-inventor
- Epic
  - Rendering team

Full source code available!

unrealengine.com

$19/mo + 5%

Epic is hiring!

References

- [Burley07] "Filtering in PRMan" http://www.renderman.org/RMR/st/PRMan_Filtering/Filtering_In_PRMan.html
- [Hill12] "Rock-Solid Shading: Image Stability Without Sacrificing Detail"
- http://advances.realtimerendering.com/s2012/Ubisoft/Rock-Solid%20Shading.pdf
- [Jimenez12] "SMAA: Enhanced Subpixel Morphological Antialiasing" http://www.iryoku.com/smaa/
- [Karis13] "Tone mapping" http://graphicrants.blogspot.com/2013/12/tone-mapping.html
- [Lottes11] "FXAA" http://developer.download.nvidia.com/assets/gamedev/files/sdk/11/FXAA_WhitePaper.pdf
- [Lottes11] http://timothylottes.blogspot.com/2011/04/tssaa-temporal-super-sampling-aa.html
- [Malan12] "Real-Time Global Illumination and Reflections in Dust 514" http://advances.realtimerendering.com/s2012/CCP/Malan-Dust_514_GI_reflections(Siggraph2012).pptx
- [Mittring12] "The Technology Behind the Unreal Engine 4 Elemental demo" http://advances.realtimerendering.com/s2012/Epic/The%20Technology%20Behind%20the%20Elemental%20Demo%2016x9.pptx
- [Nehab07] "Accelerating Real-Time Shading with Reverse Reprojection Caching" http://gfx.cs.princeton.edu/pubs/Nehab_2007_ARS/NehEtAl07.pdf
- [Neubelt13] "Crafting a Next-Gen Material Pipeline for The Order: 1886" http://blog.selfshadow.com/publications/s2013-shading-course/
- [Reshetov09] "Morphological antialiasing" http://visual-computing.intel-research.net/publications/papers/2009/mlaa/mlaa.pdf
- [Sousa11] "Anti-Aliasing Methods in CryENGINE 3" http://www.crytek.com/cryengine/presentations/anti-aliasing-methods-in-cryengine-3
- [Valient14] "Taking Killzone Shadow Fall Image Quality into the Next Generation" http://www.guerrilla-games.com/presentations/GDC2014_Valient_Killzone_Graphics.pdf
- [Yang09] "Amortized Supersampling" http://www.cs.virginia.edu/~gfx/pubs/Yang_2009_AMS/yang2009.pdf