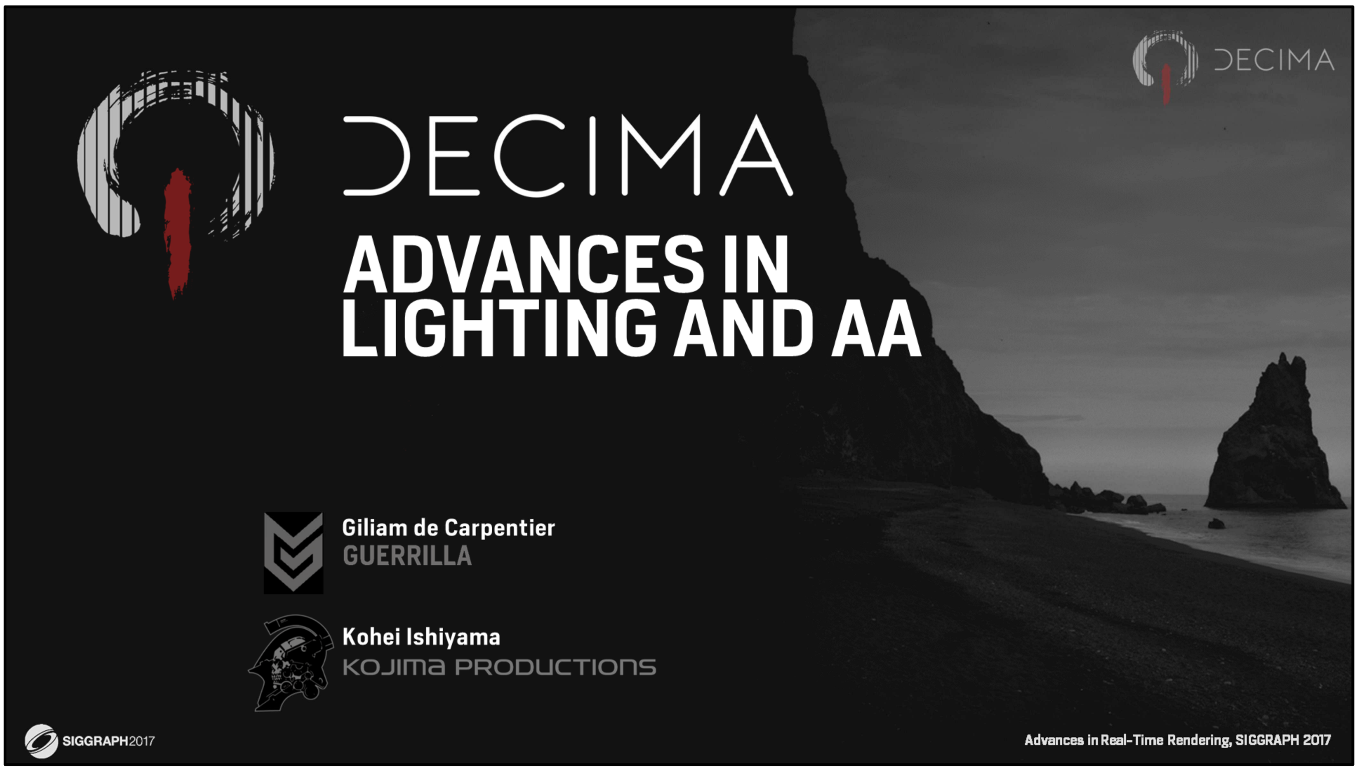


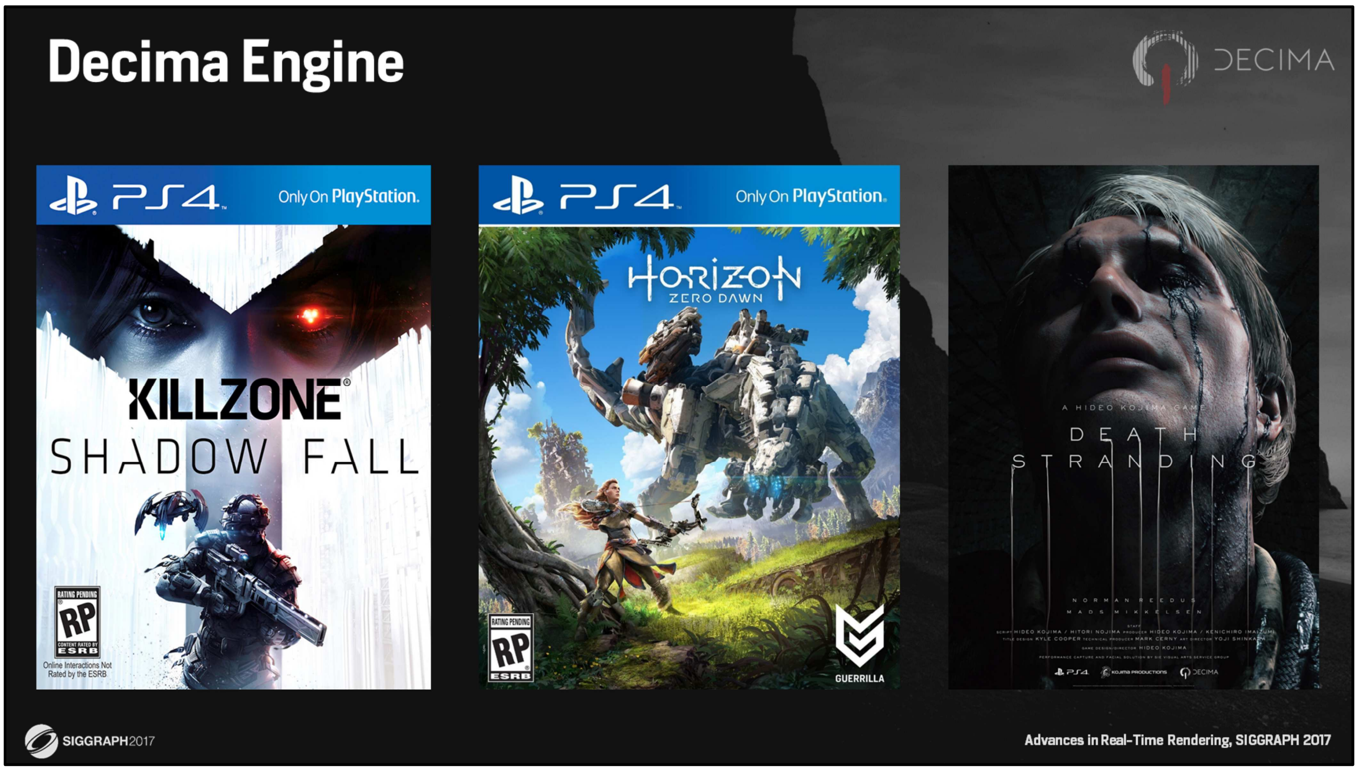
DECIMA
ADVANCES IN LIGHTING AND AA

Giliam de Carpentier
GUERRILLA

Kohei Ishiyama
KOJIMA PRODUCTIONS

Note: The PowerPoint PPT version of this presentation contains animations and movies.

In this talk we want share some of the tech behind the lighting and anti-aliasing used in the Decima engine.



Decima Engine

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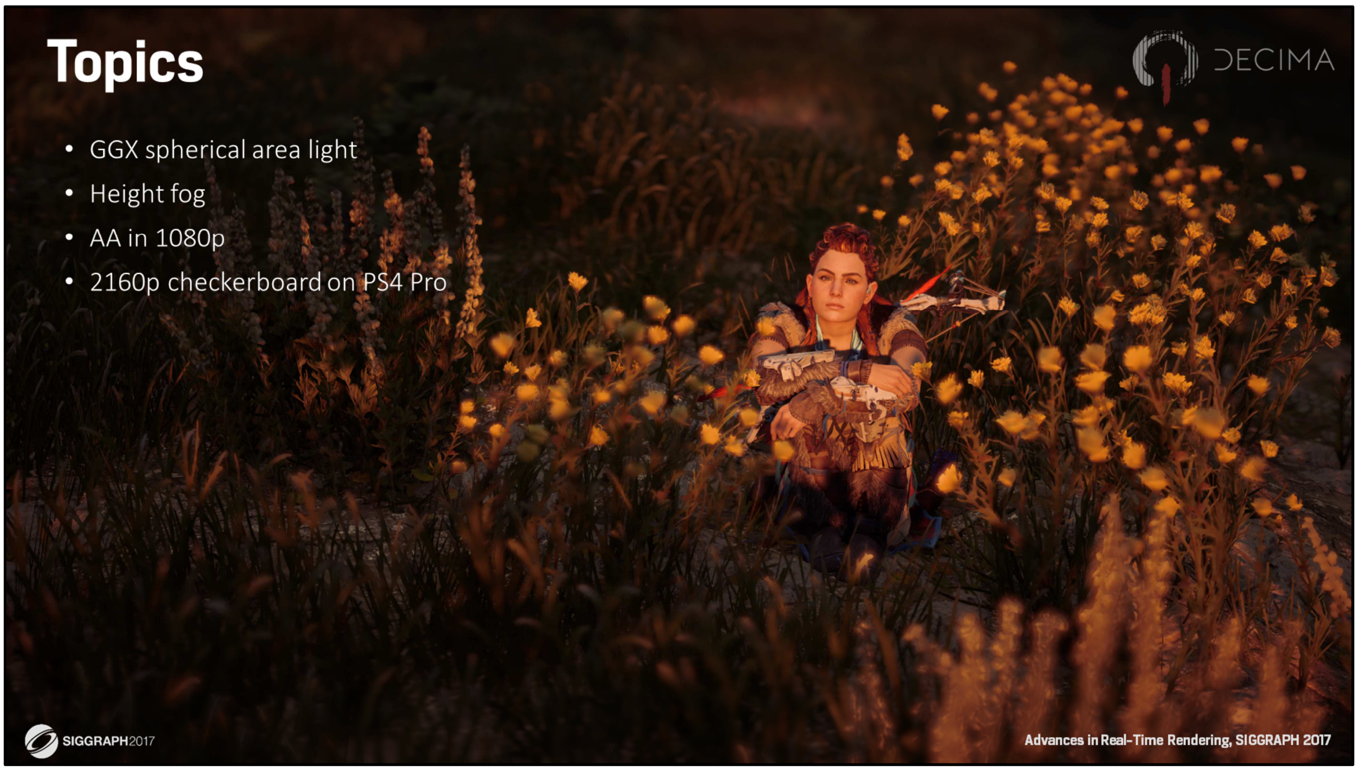
And for those who don't know what that is:
The Decima Engine is the game engine created by Guerrilla Games for the Killzone series.
But it has been extended and optimized since, to support bigger and more beautiful worlds, including that of Horizon Zero Dawn.
And recently, we also started sharing the Decima engine with Kojima Productions, and they're now using it develop Death Stranding.



Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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Today, Kohei and myself will talk about a few different and separate ways in which we recently extended the engine.
I'll start with our spherical area light implementation.
Kohei will then talk about height fog system that's being developed for Death Stranding.
And then I'll talk about the anti-aliasing and checkerboard rendering in Horizon.

Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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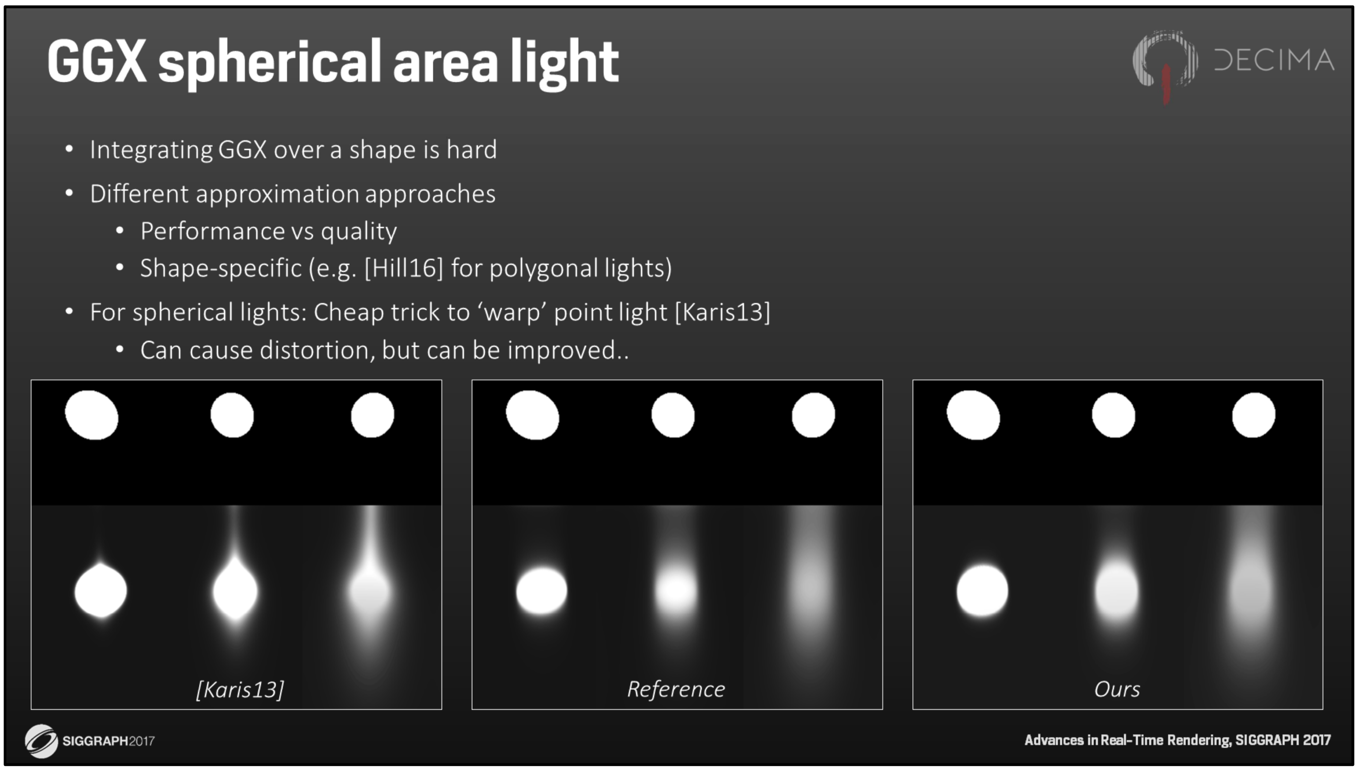
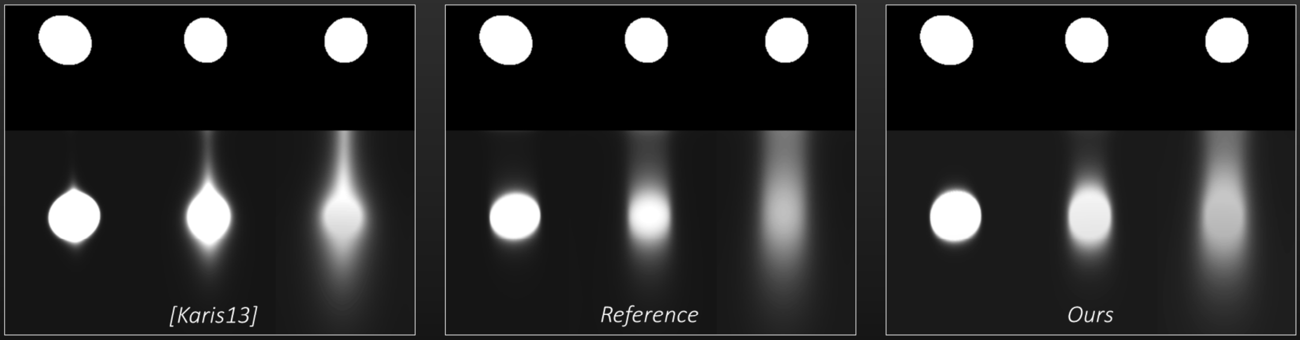
So, first up is spherical area lighting.

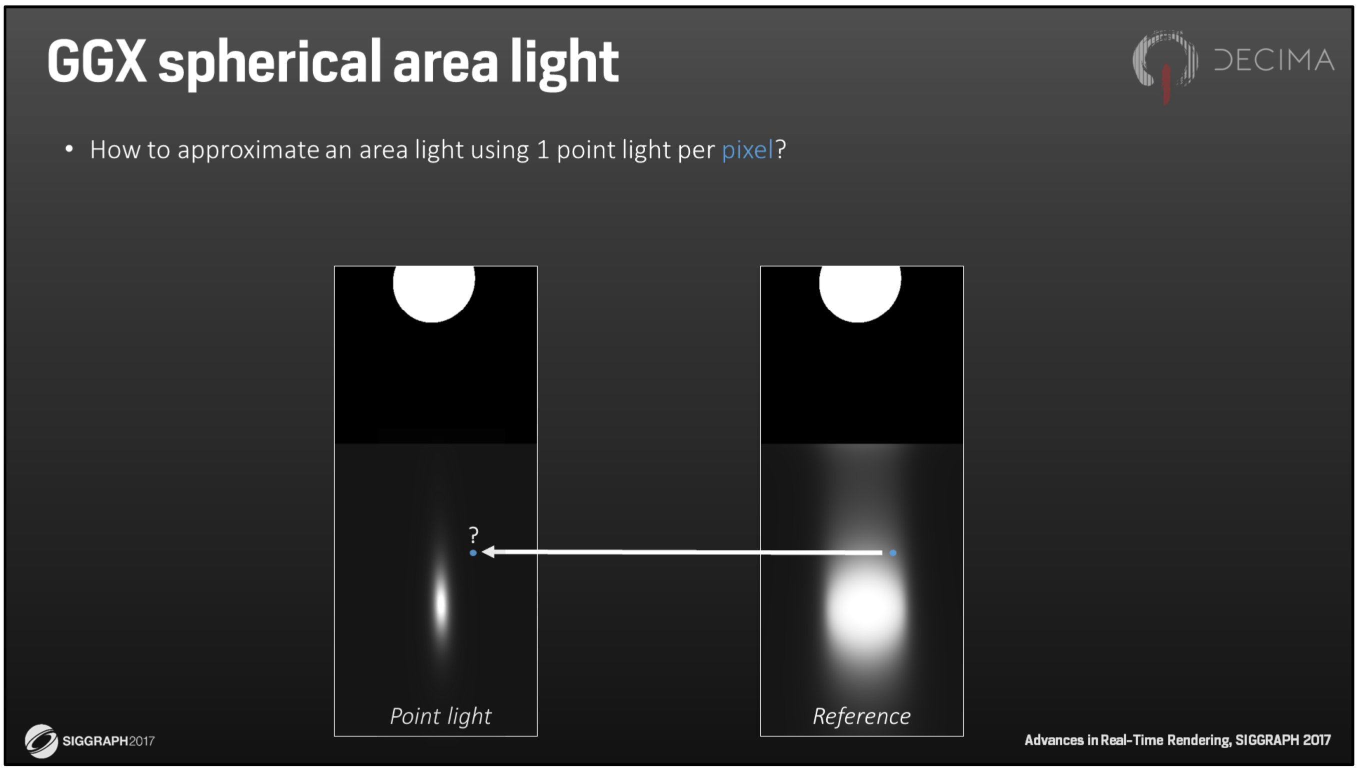


GGX spherical area light

- Integrating GGX over a shape is hard
- Different approximation approaches
  - Performance vs quality
  - Shape-specific (e.g. [Hill16] for polygonal lights)
- For spherical lights: Cheap trick to 'warp' point light [Karis13]
  - Can cause distortion, but can be improved..



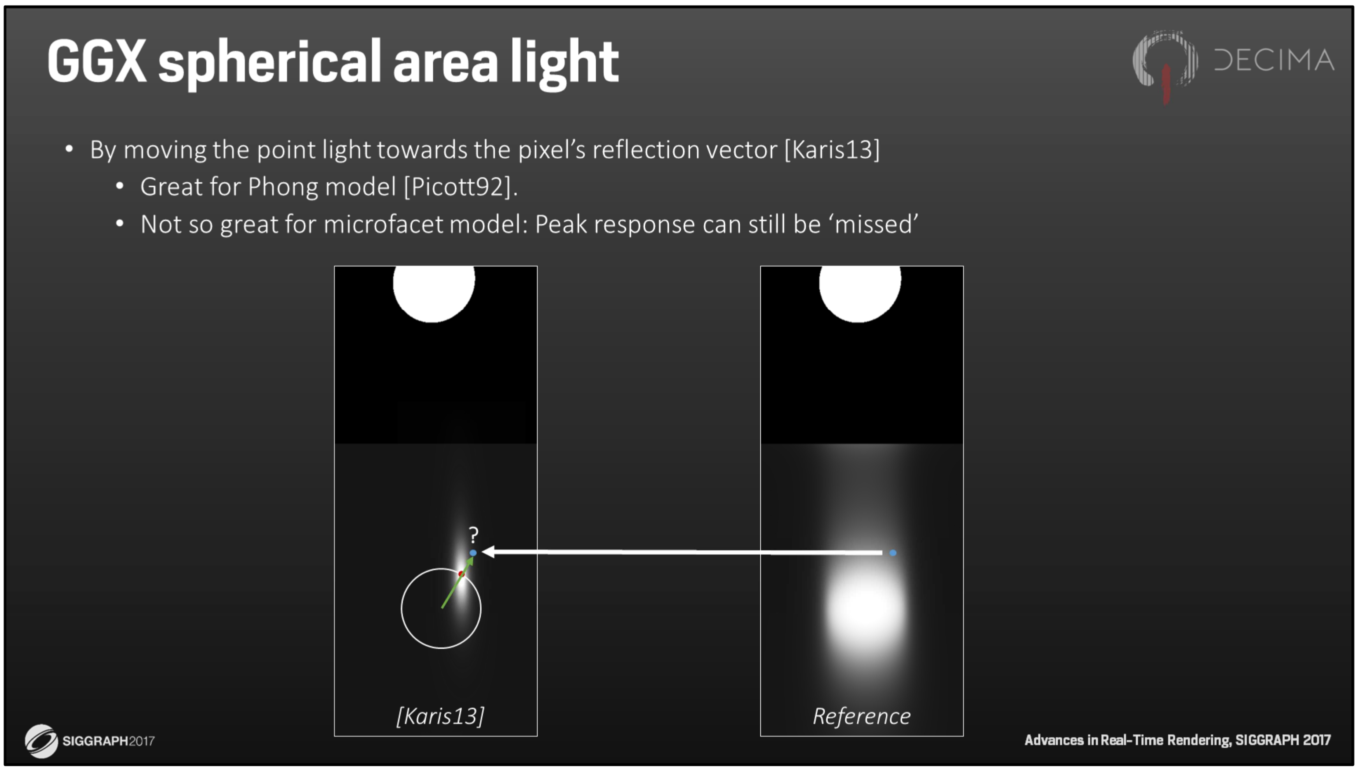
The Decima engine was probably one of the first game engines to support lighting using AREA lights.
But that initial implementation didn't support GGX, and that was becoming a limiting factor for us.
So we recently started upgrading our area light system, and we wanted to add GGX to our SPHERICAL area lights first.
However, integrating a micro-facet BRDF like GGX into an area light is difficult and requires some sort of approximation technique.
In fact, a few different techniques have emerged over the years to do just that. Some of these techniques prefer quality over performance and some prefer the opposite. And many of these technique are particularly suited for just one type of shape. For our new SPHERICAL area lights, we looked around, and ended up picking the light bending trick described by Brian Karis.
It's cheap, and it's successfully being used by many different game engines.
And the results are often pretty decent.
But it can cause some unexpected shapes to emerge, especially at grazing angles.
You can clearly see that in the image on the left. But we found one way to improve that technique, and get what you see in the image on the right. So, how does this work?



GGX spherical area light

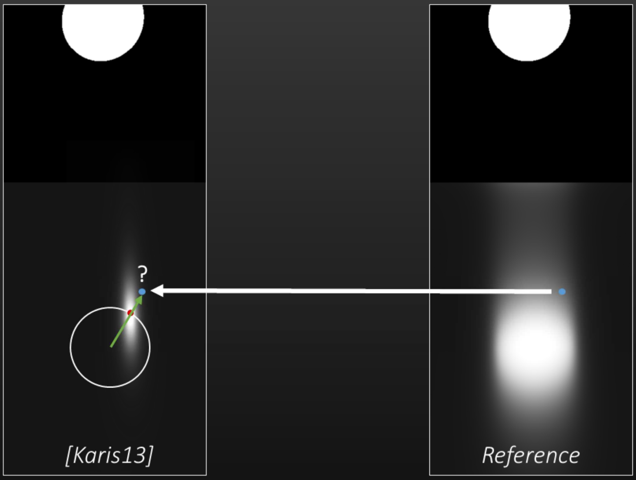
- How to approximate an area light using 1 point light per pixel?

Well, let's start by going over Brian Karis' technique first. The idea is that we want to approximate the result on the right with a single point light.
And we can do that by moving the point light towards the perimeter of the area light in the direction of the reflection vector, like so…



GGX spherical area light

- By moving the point light towards the pixel's reflection vector [Karis13]
  - Great for Phong model [Picott92].
  - Not so great for microfacet model: Peak response can still be 'missed'



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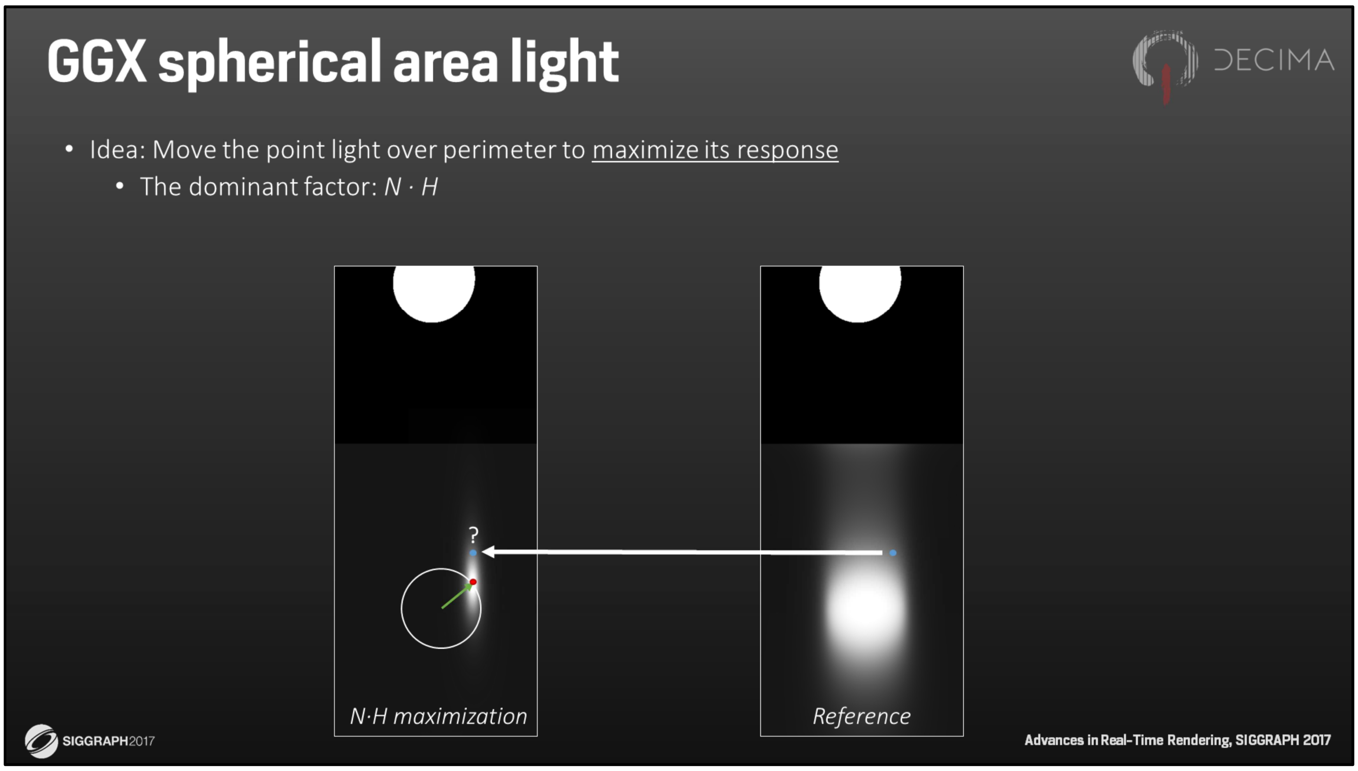
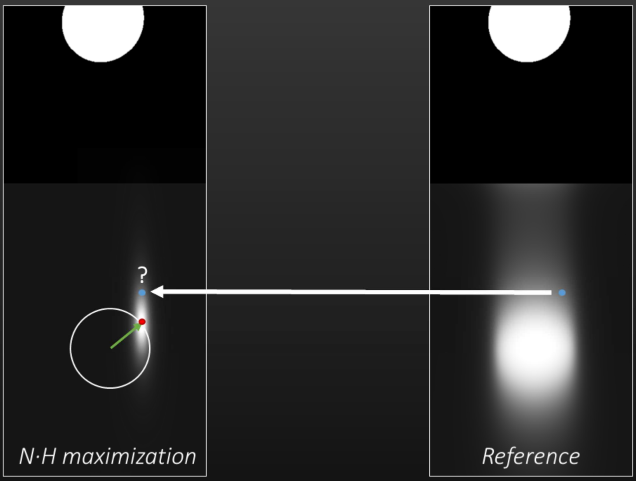
This works quite well for Phong-based lighting, and was already described in '92.
But it doesn't always work that well for microfacet-based models like GGX.
That's because the selected position for the point light isn't always a good representation of the most dominant influence.

In other words, the general idea here is to bring the peak towards the pixel, but the pixel can still miss the peak this way.



GGX spherical area light

- Idea: Move the point light over perimeter to maximize its response
  - The dominant factor: $N \cdot H$



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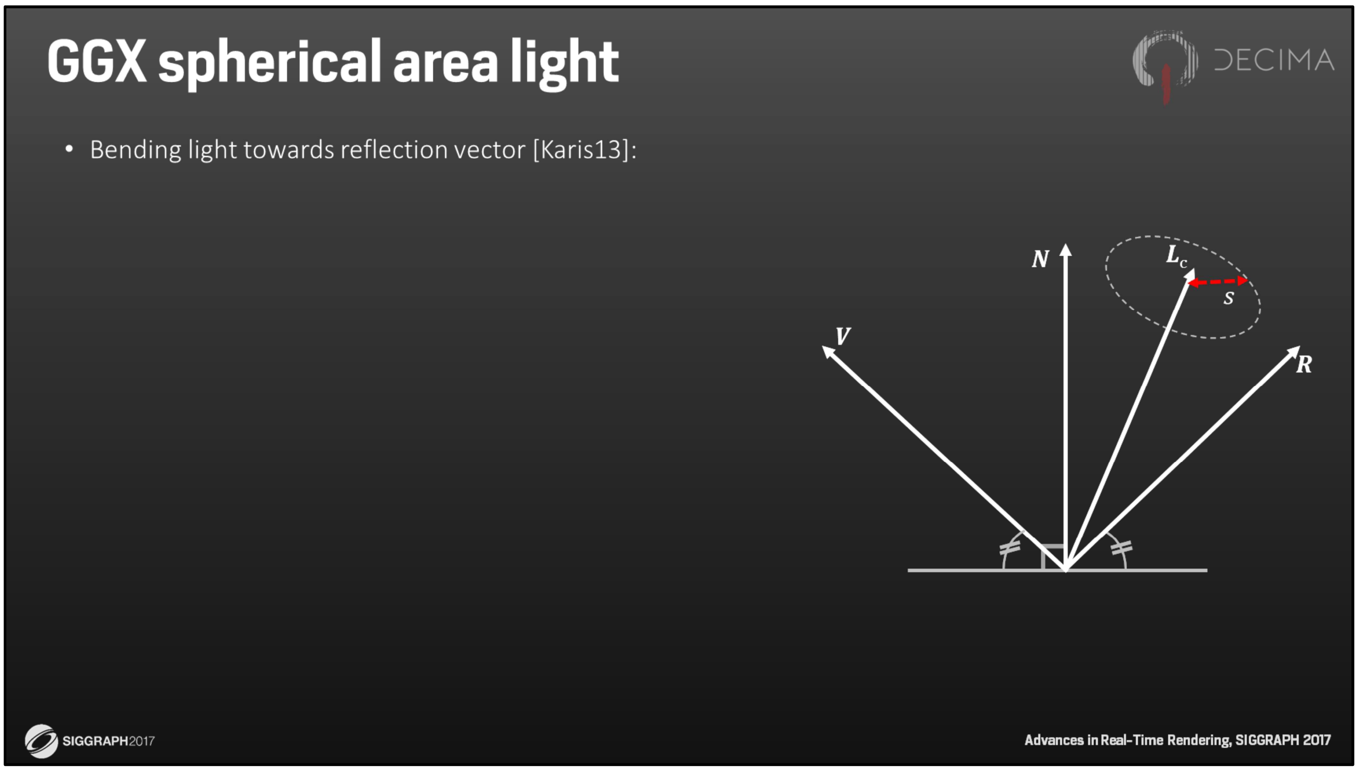
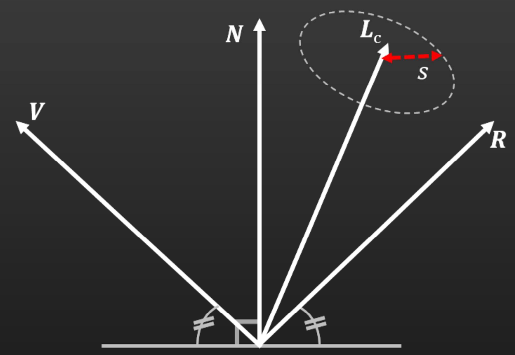
What we want to do instead is to move the point light to a different position on the perimeter of the area light.
And we choose that position such that the point light will light the pixel the most. Ignoring the Fresnel term, the Geometry term, and the N dot L term, this happens when the normal N and the half vector H are the closest.

In other words, we want to look for the light vector that maximizes N dot H.



GGX spherical area light

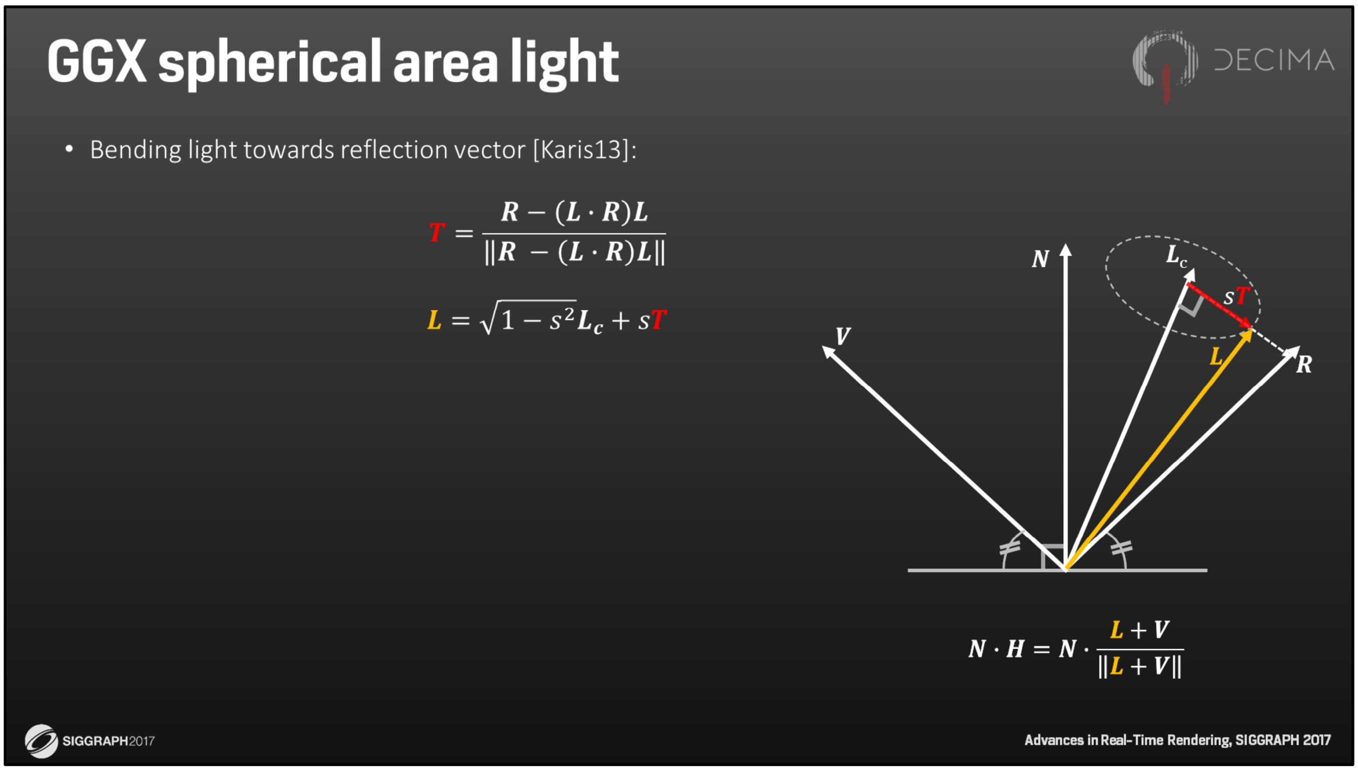
- Bending light towards reflection vector [Karis13]:



To solve this problem, we need a bit of math. And let's start by defining the necessary variables.

Suppose we have the normal N, the view vector V and the reflection vector R.
And suppose we have an spherical area light.

Now let's assume that the center of this light is in the unit direction Lc.
And let's define the spherical SHAPE by the sine s, which is equal to the perimeter's radius over its distance.

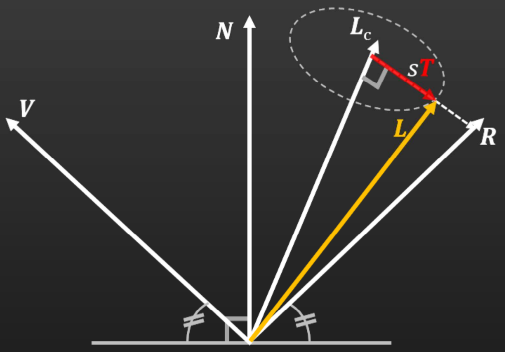


GGX spherical area light

- Bending light towards reflection vector [Karis13]:

$$T = \frac{R - (L \cdot R)L}{\|R - (L \cdot R)L\|}$$

$$L = \sqrt{1 - s^2} L_c + sT$$



$$N \cdot H = N \cdot \frac{L + V}{\|L + V\|}$$

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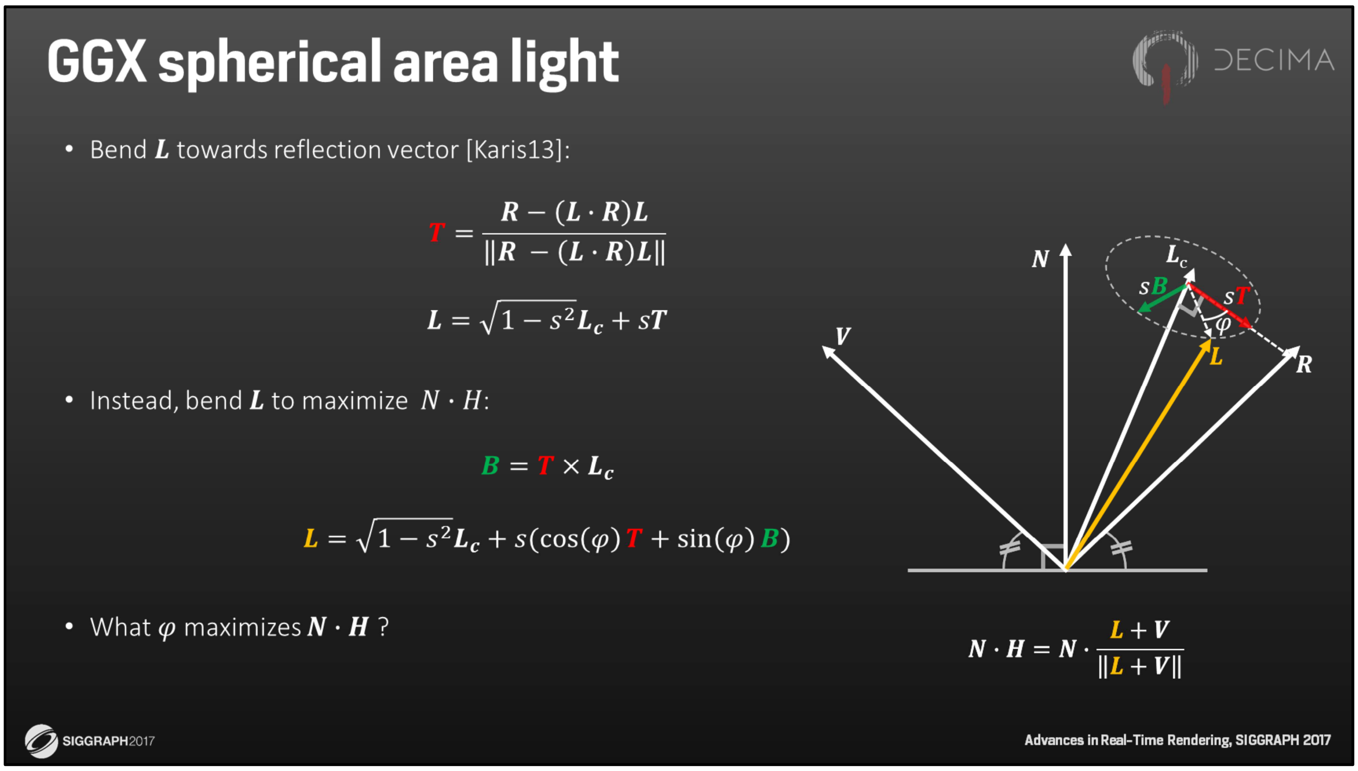
Now, let’s also define the unit vector T, which is the vector pointing towards R but made orthonormal to Lc.
That is, T is simply the reflection vector R that has projected on the plane perpendicular to Lc, and is then renormalized.

With this unit vector T, we can easily find the unit vector L that’s pointing to the perimeter of the light and is closest to the reflection vector R.
We do that by rotating Lc to L, using the sine S we already got, and the cosine we can calculate from S.

And this L can be used to calculate the half vector H.

This is exactly the half vector used in Karis’ approach.



GGX spherical area light

- Bend $\boldsymbol{L}$ towards reflection vector [Karis13]:

$$\boldsymbol{T} = \frac{\boldsymbol{R} - (\boldsymbol{L}\cdot\boldsymbol{R})\boldsymbol{L}}{\|\boldsymbol{R} - (\boldsymbol{L}\cdot\boldsymbol{R})\boldsymbol{L}\|}$$

$$\boldsymbol{L} = \sqrt{1-s^2}\boldsymbol{L_c} + s\boldsymbol{T}$$

- Instead, bend $\boldsymbol{L}$ to maximize $N\cdot H$:

$$\boldsymbol{B} = \boldsymbol{T}\times\boldsymbol{L_c}$$

$$\boldsymbol{L} = \sqrt{1-s^2}\boldsymbol{L_c} + s(\cos(\varphi)\boldsymbol{T} + \sin(\varphi)\boldsymbol{B})$$

- What φ maximizes $\boldsymbol{N}\cdot\boldsymbol{H}$?

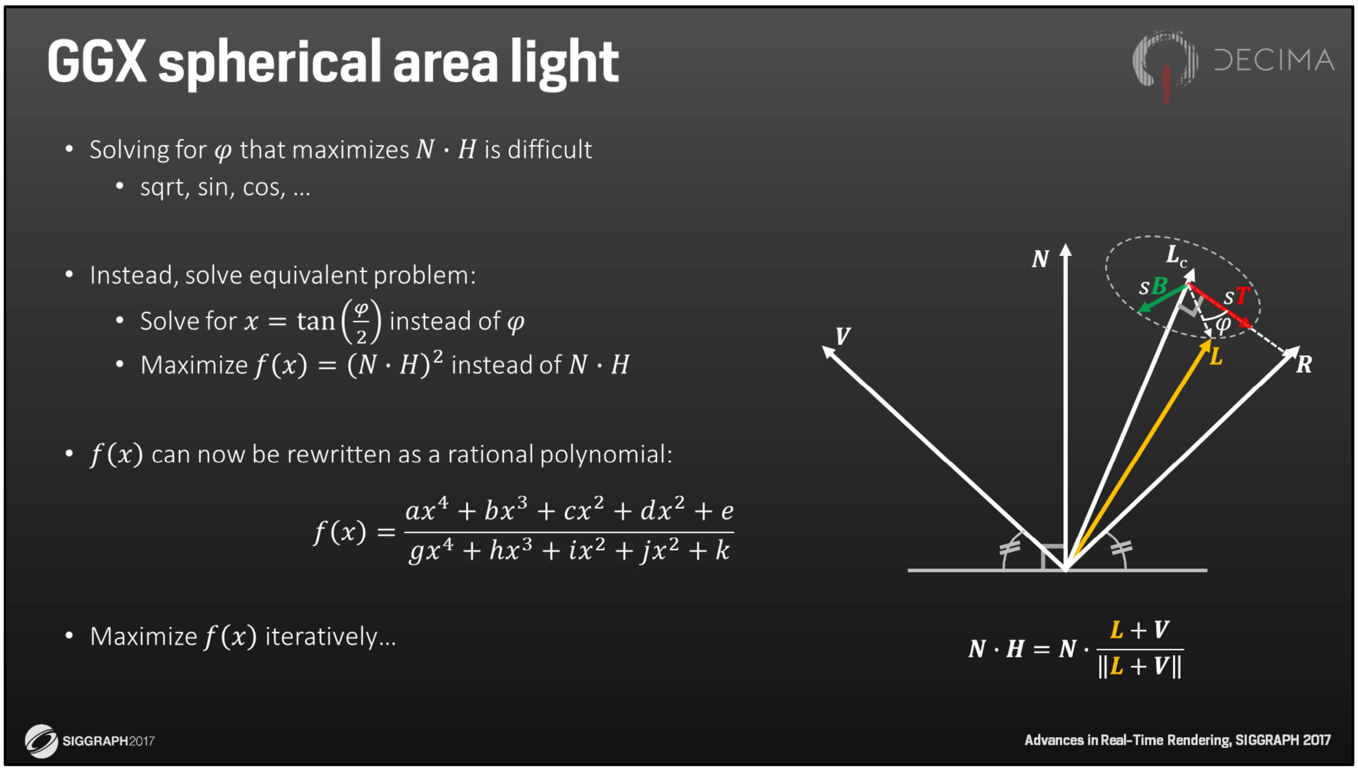
$$\boldsymbol{N}\cdot\boldsymbol{H} = \boldsymbol{N}\cdot\frac{\boldsymbol{L}+\boldsymbol{V}}{\|\boldsymbol{L}+\boldsymbol{V}\|}$$

We can easily extend this idea by introducing another vector called B.

B is a bi-tangent, and together, Lc, T and B create an orthonormal basis.
We can use that to define a normalized light direction L that points to any point on the perimeter of the area light…

…Including one that's rotated around on the perimeter by some angle phi.

And, going back to our original problem, the trick is to now find the phi leads to the largest N dot H.
That way, we'll find a more dominant specular response for the pixel we want to shade.
And, in turn, that leads a better approximation to the area light.

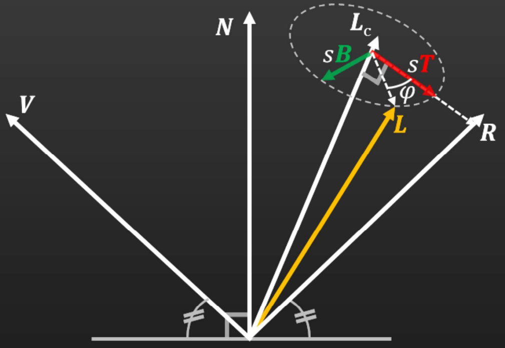


GGX spherical area light

- Solving for φ that maximizes $N \cdot H$ is difficult
  - sqrt, sin, cos, …
- Instead, solve equivalent problem:
  - Solve for $x = \tan\left(\frac{\varphi}{2}\right)$ instead of φ
  - Maximize $f(x) = (N \cdot H)^2$ instead of $N \cdot H$
- $f(x)$ can now be rewritten as a rational polynomial:

$$f(x) = \frac{ax^4 + bx^3 + cx^2 + dx^2 + e}{gx^4 + hx^3 + ix^2 + jx^2 + k}$$

- Maximize $f(x)$ iteratively…



$$N \cdot H = N \cdot \frac{L + V}{\|L + V\|}$$

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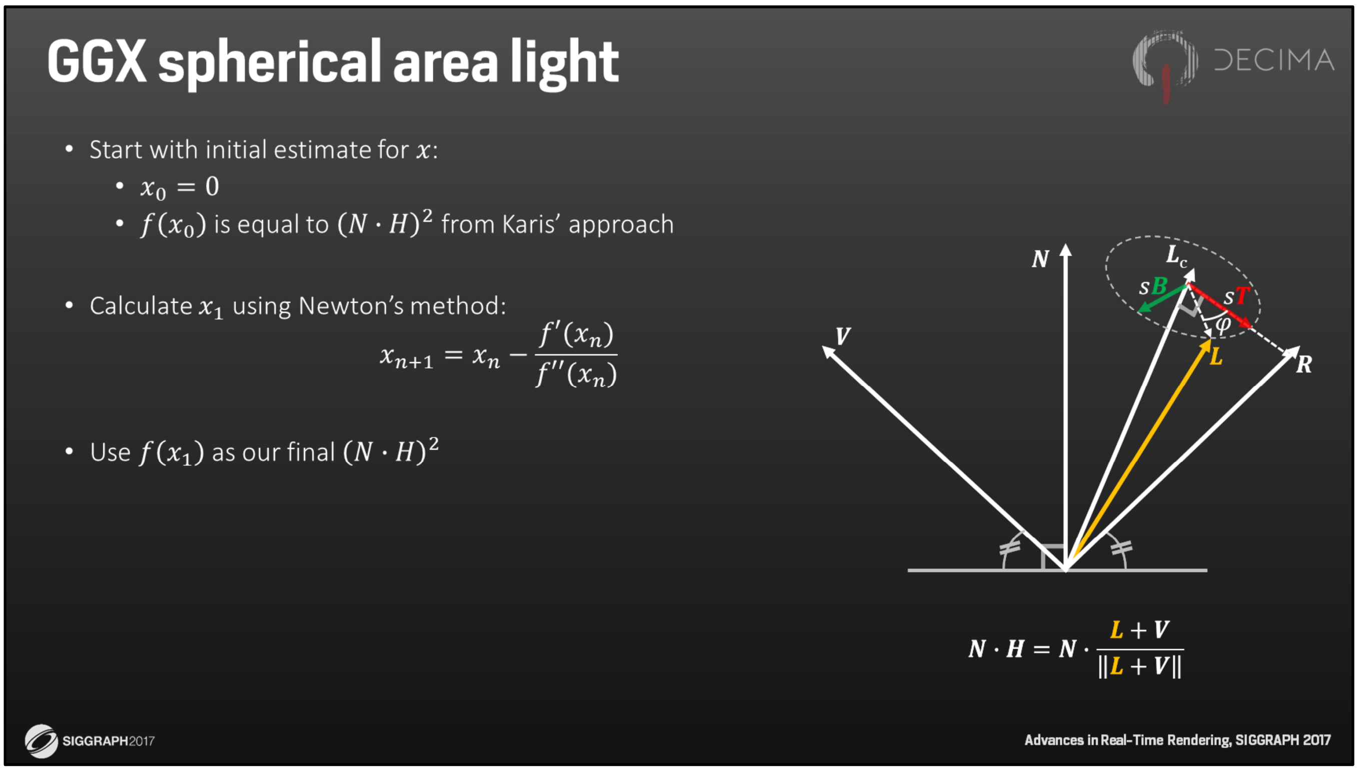
But solving for phi directly is rather hard.
That's because there's a bunch of square roots, sines and cosines involved.

But we can reformulate that problem to an equivalent problem that's easier to solve.
For example, instead of solving for the angle phi, we can solve for x, where x is the TANGENT of half phi.
This derivation is a bit tedious to show here, but it will allow us to get rid of all the sines and cosines using common mathematical half-angle identities.
And we can do more. We can try to maximize N dot H squared instead of N dot H. This will free us from the remaining square roots.

And what we end up with is a relatively simple rational polynomial called f of x.

And all we need to do now is find x that maximizes this f of x, and thus maximizes N dot H squared.
Sadly, that's is still a non-trivial problem to solve analytically.
But we can still solve this numerically using an iterative approach.



GGX spherical area light

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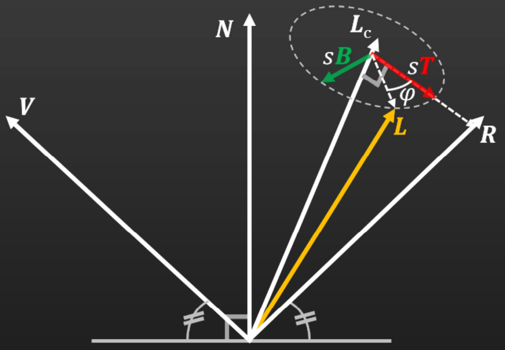
- Start with initial estimate for x:
  - $x_0 = 0$
  - $f(x_0)$ is equal to $(N \cdot H)^2$ from Karis' approach
- Calculate x_1 using Newton's method:

$$x_{n+1} = x_n - \frac{f'(x_n)}{f''(x_n)}$$

- Use $f(x_1)$ as our final $(N \cdot H)^2$



$$N \cdot H = N \cdot \frac{L+V}{\|L+V\|}$$

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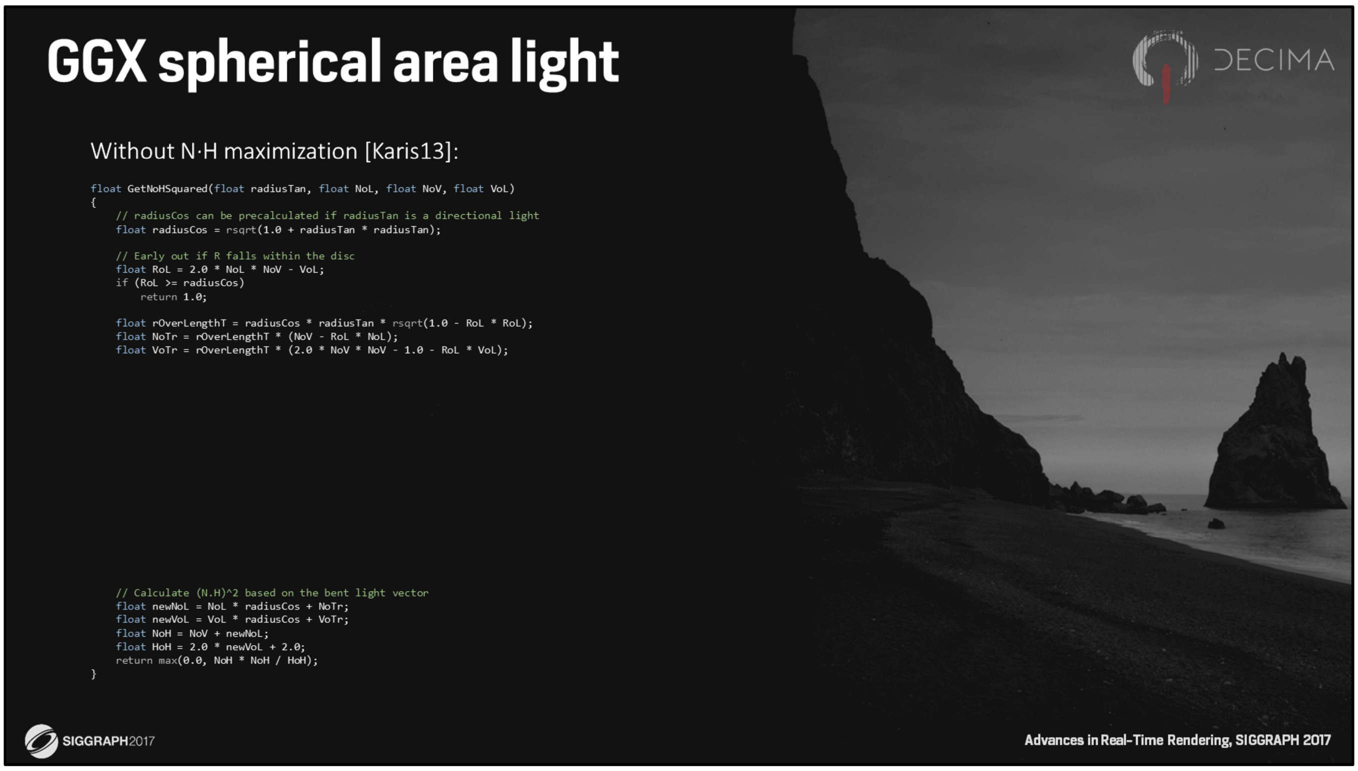
An iterative approach starts with a guess and tries to improve that.
So we start with Karis' approach, which is equivalent to starting with x is 0.

And we then apply a single iteration of Newton's method to get x1.
This brings us already a lot closer to the maximum, and we'll simply take that as our final estimate.

Plugging x1 into f of x gives us the N dot H squared that we were looking for, and we use that directly as input to the GGX function.

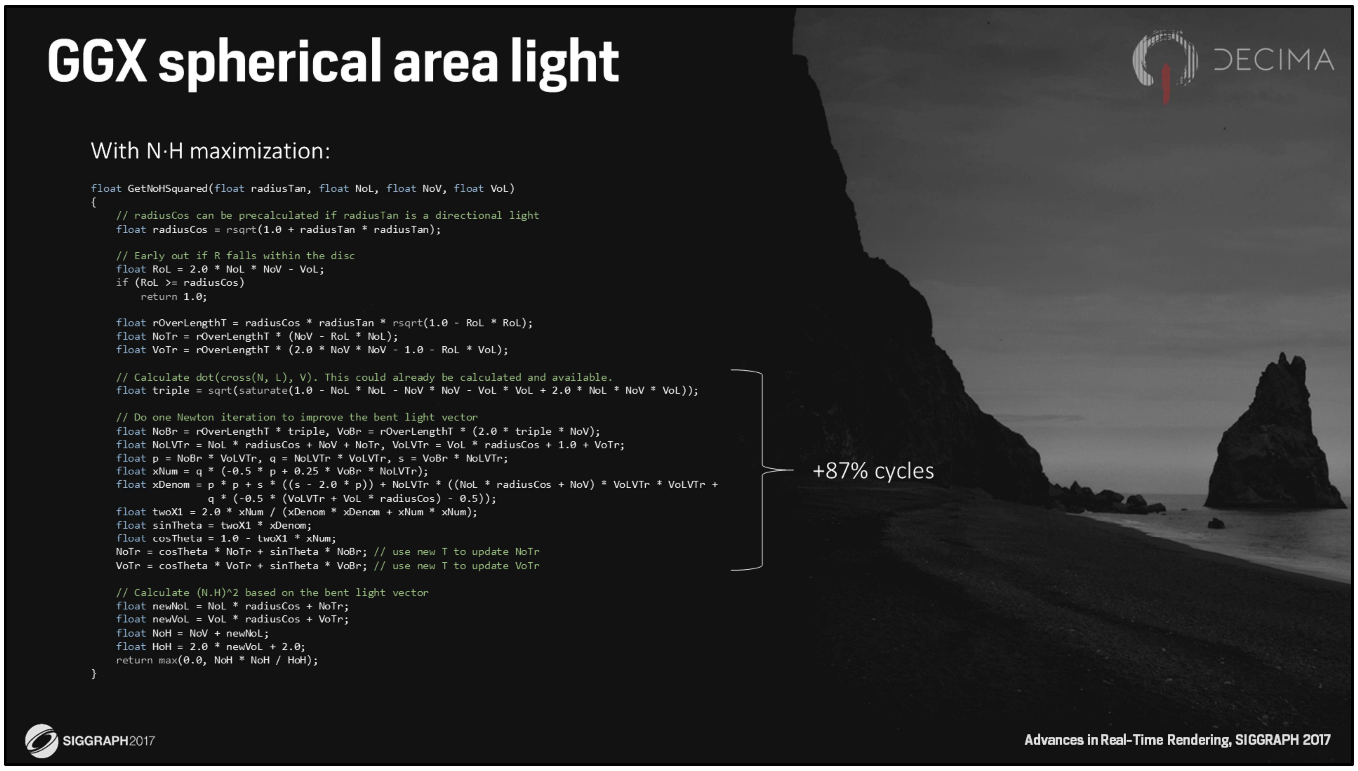


GGX spherical area light

Without N·H maximization [Karis13]:

```
float GetNoHSquared(float radiusTan, float NoL, float NoV, float VoL)
{
    // radiusCos can be precalculated if radiusTan is a directional light
    float radiusCos = rsqrt(1.0 + radiusTan * radiusTan);

    // Early out if R falls within the disc
    float RoL = 2.0 * NoL * NoV - VoL;
    if (RoL >= radiusCos)
        return 1.0;

    float rOverLengthT = radiusCos * radiusTan * rsqrt(1.0 - RoL * RoL);
    float NoTr = rOverLengthT * (NoV - RoL * NoL);
    float VoTr = rOverLengthT * (2.0 * NoV * NoV - 1.0 - RoL * VoL);










    // Calculate (N.H)^2 based on the bent light vector
    float newNoL = NoL * radiusCos + NoTr;
    float newVoL = VoL * radiusCos + VoTr;
    float NoH = NoV + newNoL;
    float HoH = 2.0 * newVoL + 2.0;
    return max(0.0, NoH * NoH / HoH);
}
```

To get a feel for how complex that is to implement, here’s what that looks like in HLSL. This is an implementation of Karis’ approach, all in scalar math.



GGX spherical area light

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With N·H maximization:

```
float GetNoHSquared(float radiusTan, float NoL, float NoV, float VoL)
{
    // radiusCos can be precalculated if radiusTan is a directional light
    float radiusCos = rsqrt(1.0 + radiusTan * radiusTan);

    // Early out if R falls within the disc
    float RoL = 2.0 * NoL * NoV - VoL;
    if (RoL >= radiusCos)
        return 1.0;

    float rOverLengthT = radiusCos * radiusTan * rsqrt(1.0 - RoL * RoL);
    float NoTr = rOverLengthT * (NoV - RoL * NoL);
    float VoTr = rOverLengthT * (2.0 * NoV * NoV - 1.0 - RoL * VoL);

    // Calculate dot(cross(N, L), V). This could already be calculated and available.
    float triple = sqrt(saturate(1.0 - NoL * NoL - NoV * NoV - VoL * VoL + 2.0 * NoL * NoV * VoL));

    // Do one Newton iteration to improve the bent light vector
    float NoBr = rOverLengthT * triple, VoBr = rOverLengthT * (2.0 * triple * NoV);
    float NoLVTr = NoL * radiusCos + NoV + NoTr, VoLVTr = VoL * radiusCos + 1.0 + VoTr;
    float p = NoBr * VoLVTr, q = NoLVTr * VoLVTr, s = VoBr * NoLVTr;
    float xNum = q * (-0.5 * p + 0.25 * VoBr * NoLVTr);
    float xDenom = p * p + s * ((s - 2.0 * p)) + NoLVTr * ((NoL * radiusCos + NoV) * VoLVTr * VoLVTr +
                   q * (-0.5 * (VoLVTr + VoL * radiusCos) - 0.5));
    float twoX1 = 2.0 * xNum / (xDenom * xDenom + xNum * xNum);
    float sinTheta = twoX1 * xDenom;
    float cosTheta = 1.0 - twoX1 * xNum;
    NoTr = cosTheta * NoTr + sinTheta * NoBr; // use new T to update NoTr
    VoTr = cosTheta * VoTr + sinTheta * VoBr; // use new T to update VoTr

    // Calculate (N.H)^2 based on the bent light vector
    float newNoL = NoL * radiusCos + NoTr;
    float newVoL = VoL * radiusCos + VoTr;
    float NoH = NoV + newNoL;
    float HoH = 2.0 * newVoL + 2.0;
    return max(0.0, NoH * NoH / HoH);
}
```

+87% cycles

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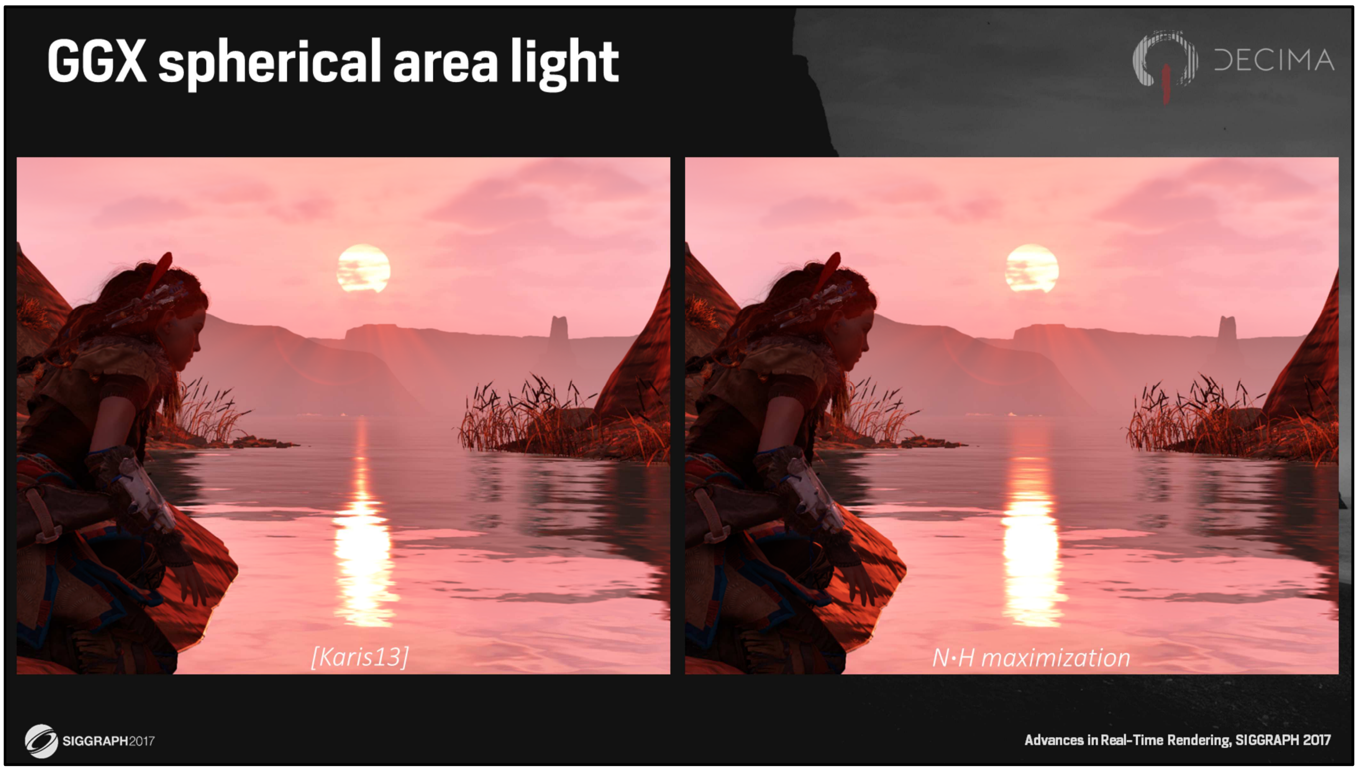
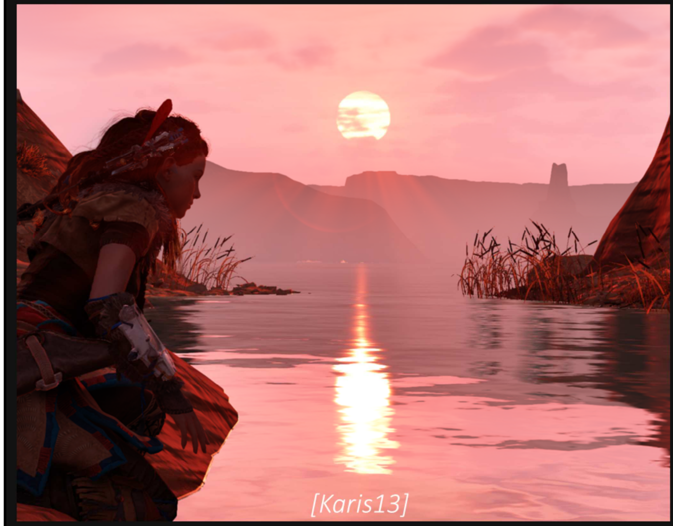
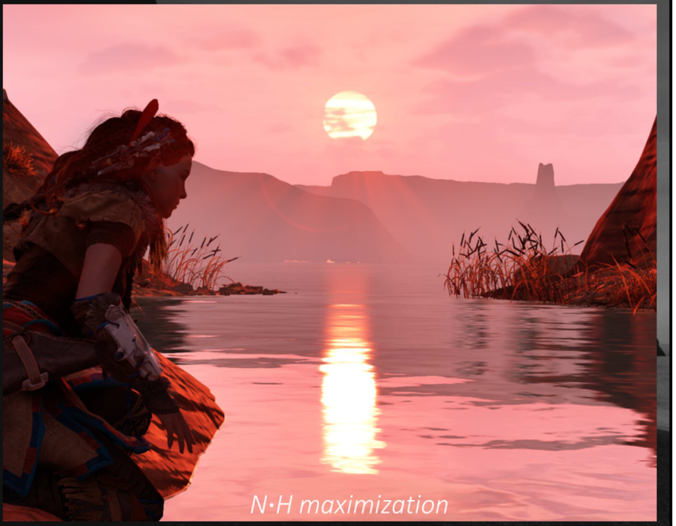
And this is what it looks like when we add one Newton iteration.
As you can see, this does add quite a few instructions, but compared the whole light shader, this may be a relative small change.
So depending on how this is used, the difference in performance might be noticeable, or it might be virtually free.



GGX spherical area light





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So is it worth it?
Well, here you see the sun's reflection with and without the N.H maximization.
And as you can see, it works quite nicely, as it gets you a more natural looking reflection at low angles.

I should mention though, than even though these screenshots have been made in Horizon Zero Dawn,
the technique was only finished after Horizon shipped.
But it has been retro-fitted for internal use, and is ready for use for other titles.

Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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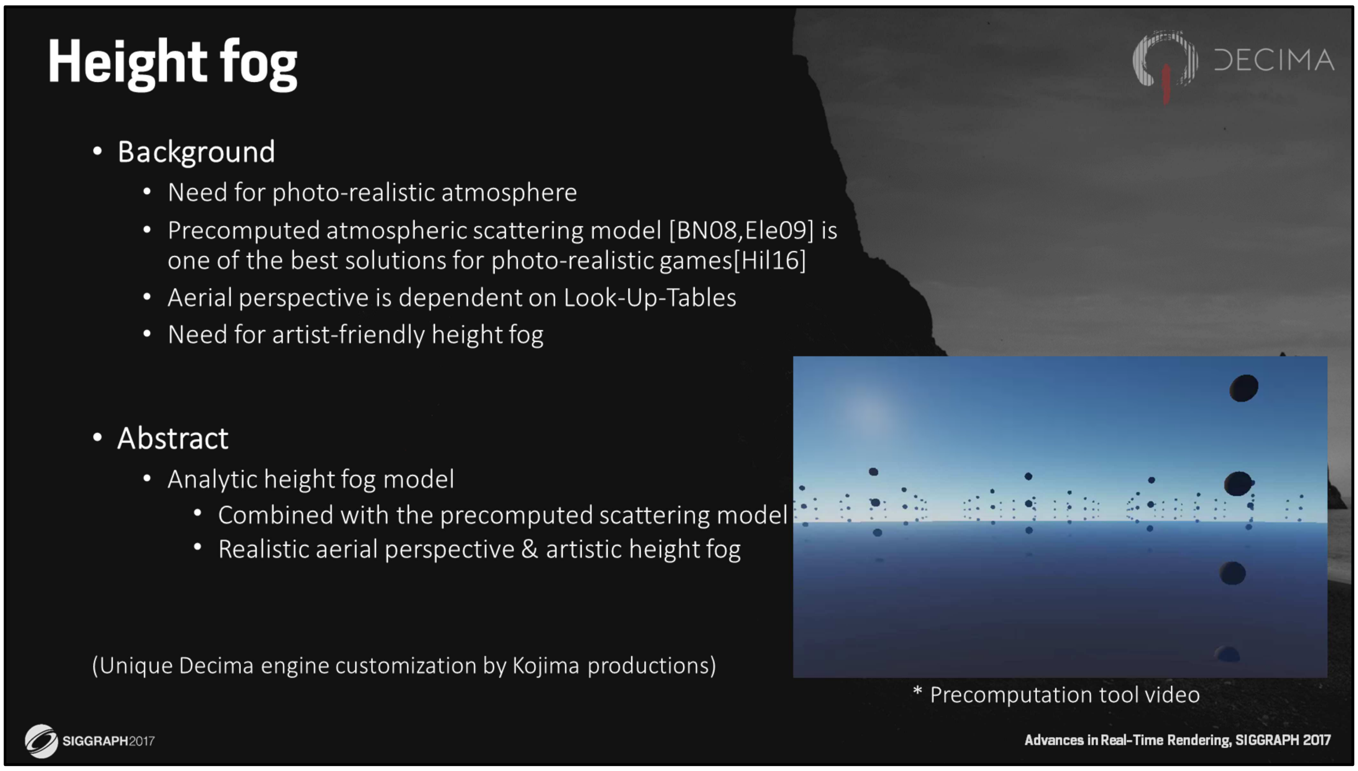
The next topic is about height fog and will be covered by Kohei.



Height fog

- Background
  - Need for photo-realistic atmosphere
  - Precomputed atmospheric scattering model [BN08,Ele09] is one of the best solutions for photo-realistic games[Hil16]
  - Aerial perspective is dependent on Look-Up-Tables
  - Need for artist-friendly height fog
- Abstract
  - Analytic height fog model
    - Combined with the precomputed scattering model
    - Realistic aerial perspective & artistic height fog

(Unique Decima engine customization by Kojima productions)

* Precomputation tool video

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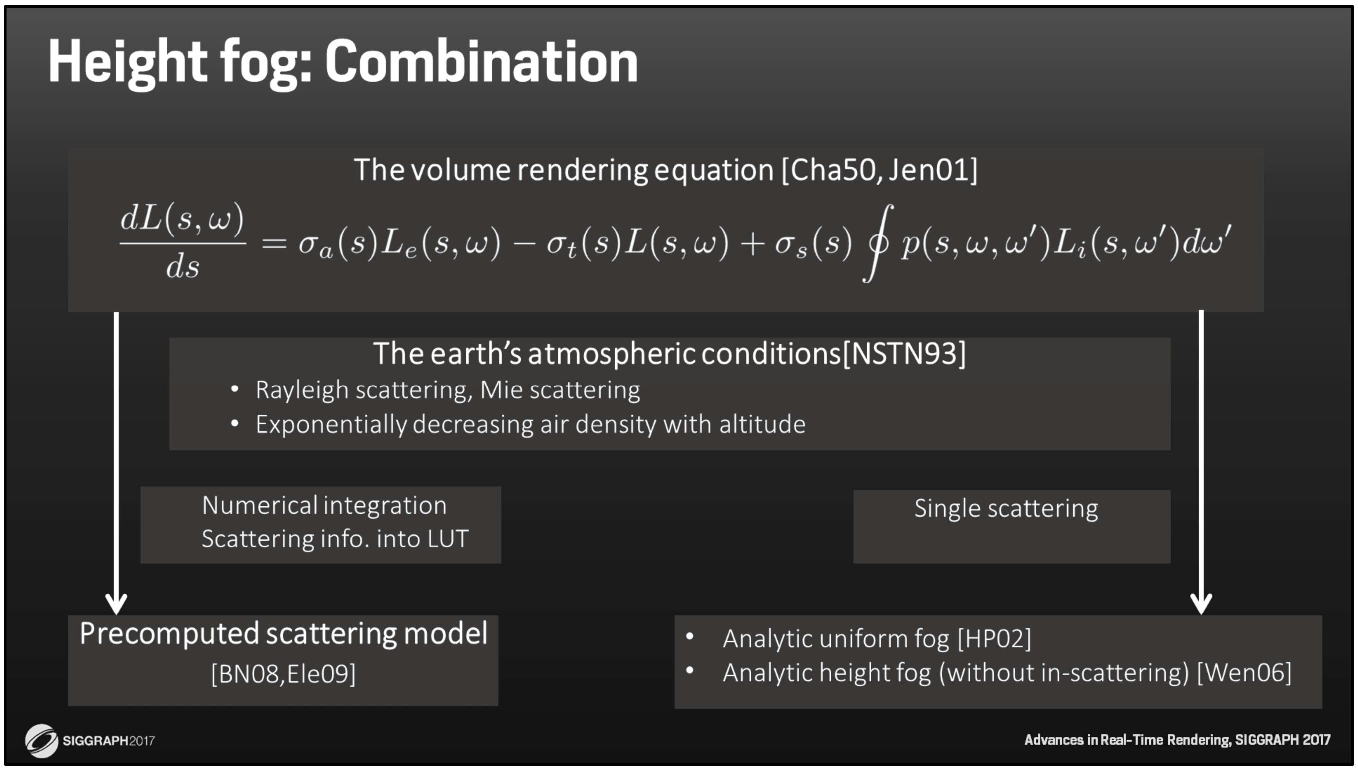
In this section I will introduce our height fog model, which is a unique Decima Engine customization created by Kojima Productions.

First of all, please let me explain why this optimization was necessary.
Decima Engine has a flexible atmospheric scattering system linked with clouds and outdoor lighting.
However, at Kojima Productions, there was a request for an atmospheric scattering system optimized for photo-realistic rendering.
Precomputed atmospheric scattering is one of the best methods for photo-realistic games.
In this model, the aerial perspective is strongly dependent on the precomputed Look Up Tables.
It works well for the photo-realistic atmosphere, but we often need to express artistic quantities such as dense fog and colored fog in the actual game.

So, it would be nice if we can express the photo-realistic aerial perspective and the artistic height fog with a single height fog model. To achieve this, we introduced an analytic height fog model, and combined with a precomputed atmospheric scattering model. Let's take a look at how this combination works.



Height fog: Combination

The volume rendering equation [Cha50, Jen01]

$$\frac{dL(s,\omega)}{ds} = \sigma_a(s)L_e(s,\omega) - \sigma_t(s)L(s,\omega) + \sigma_s(s)\oint p(s,\omega,\omega')L_i(s,\omega')d\omega'$$

The earth's atmospheric conditions[NSTN93]
- Rayleigh scattering, Mie scattering
- Exponentially decreasing air density with altitude

Numerical integration
Scattering info. into LUT

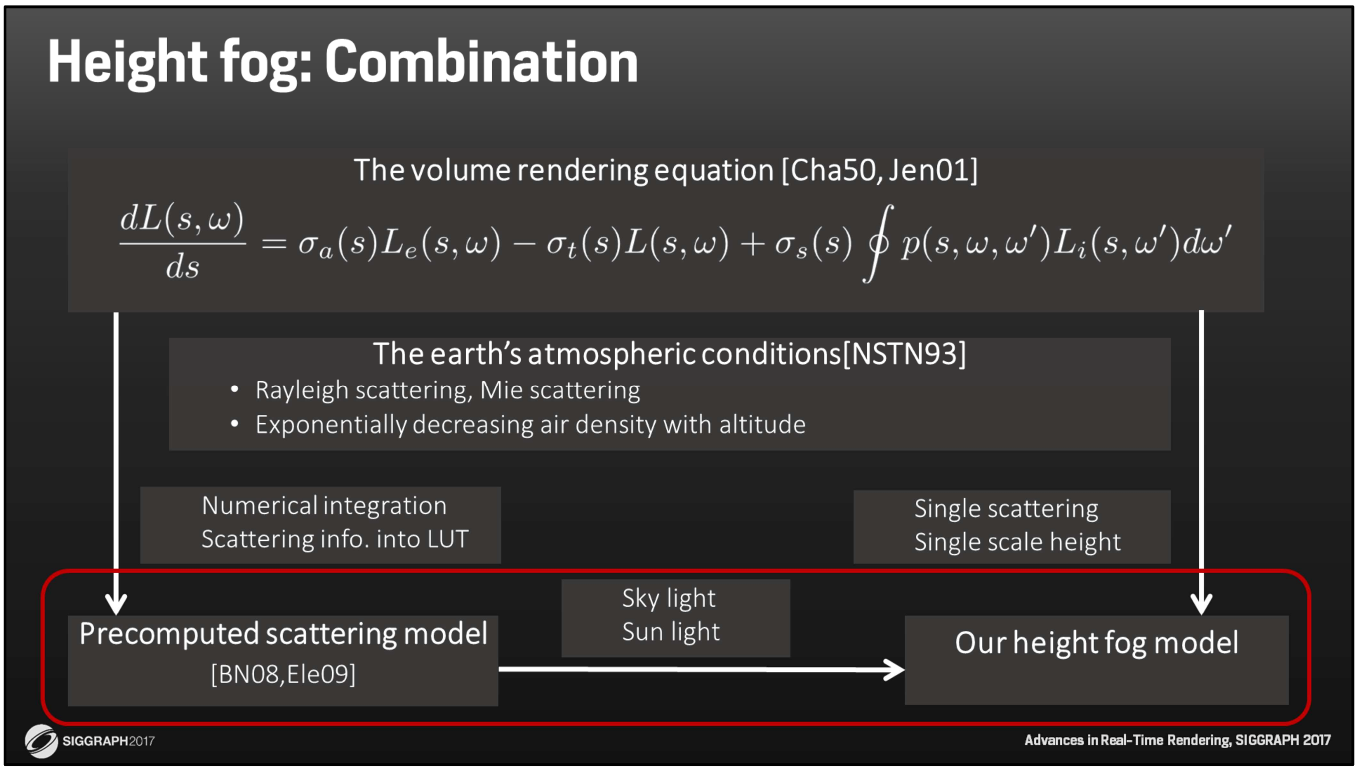
Single scattering

Precomputed scattering model
[BN08,Ele09]

- Analytic uniform fog [HP02]
- Analytic height fog (without in-scattering) [Wen06]

This is an overview of our approach.

* The volume rendering equation
The starting point is the volume rendering equation, and the earth's atmospheric conditions.
The earth's atmospheric conditions are described by the Rayleigh scattering and the Mie scattering, and the participating media with exponentially decreasing air density with altitude.
Both of the precomputed model and the analytic model share these conditions.
* Precomputed atmospheric scattering model
The precomputed atmospheric scattering model performs numerical integration, and stores the in-scattering and transmittance information into Look-Up-Tables.
* Height fog model
On the other hand, the height fog model calculates the fog directly when we render the scene.
This calculation is an analytic solution of the volume rendering equation with assuming the single scattering.
This kind of analytic solution is known for the uniform fog model[HP02], but we couldn't find a satisfactory solution for the height fog model.



Height fog: Combination

The volume rendering equation [Cha50, Jen01]

$$\frac{dL(s,\omega)}{ds} = \sigma_a(s)L_e(s,\omega) - \sigma_t(s)L(s,\omega) + \sigma_s(s)\oint p(s,\omega,\omega')L_i(s,\omega')d\omega'$$

The earth's atmospheric conditions[NSTN93]

- Rayleigh scattering, Mie scattering
- Exponentially decreasing air density with altitude

Numerical integration
Scattering info. into LUT
Single scattering
Single scale height
Sky light
Sun light
Precomputed scattering model [BN08,Ele09]
Our height fog model
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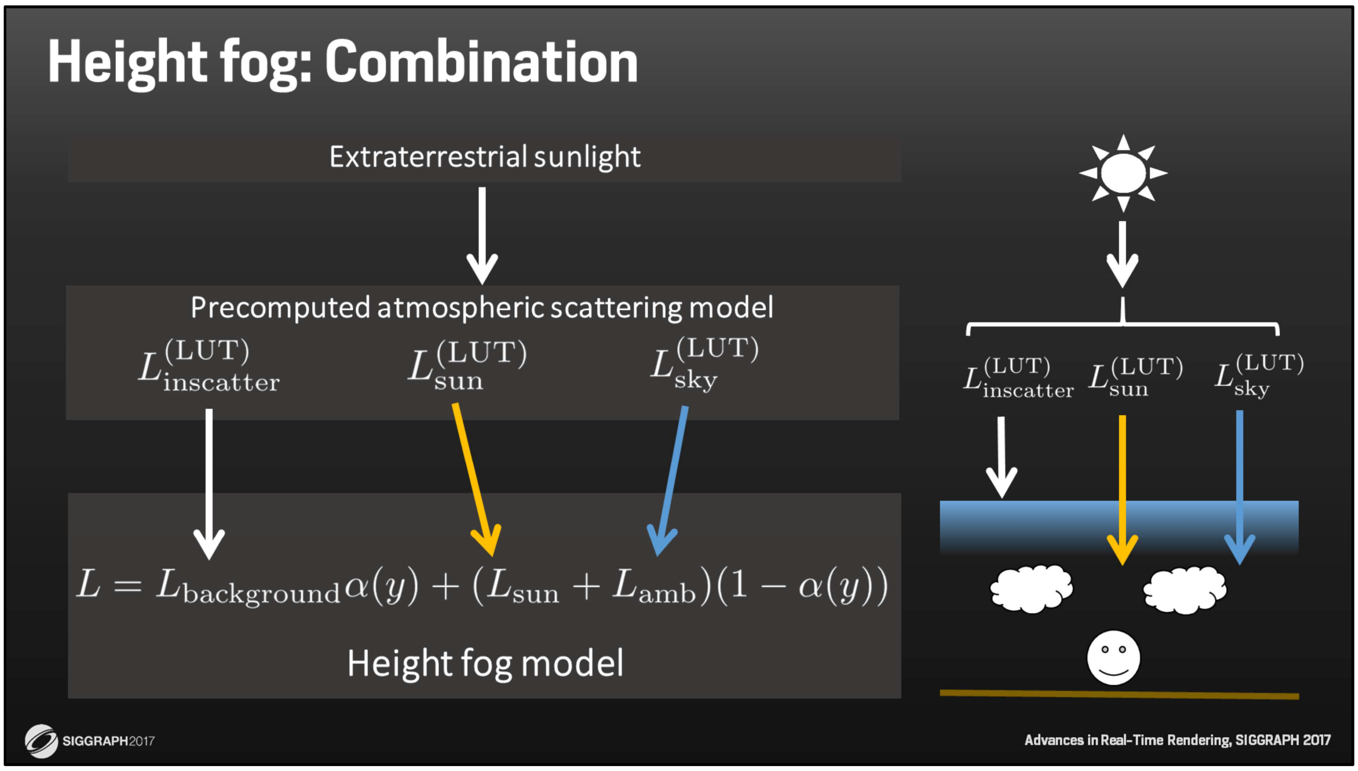
* Height fog model
So, we derived it independently.
In order to derive it, we assumed single scattering and single scale-height.
Here, the scale height is a parameter to describe how decreases the fog density with altitude.

* Combination
In our approach, we supplied the skylight and the sunlight information from the precomputed atmospheric scattering model to the height fog model.

That concludes the basic overview.
In the next slide, we will focus on this combination.



Height fog: Combination

Extraterrestrial sunlight

Precomputed atmospheric scattering model

$L^{(\mathrm{LUT})}_{\mathrm{inscatter}}$ $L^{(\mathrm{LUT})}_{\mathrm{sun}}$ $L^{(\mathrm{LUT})}_{\mathrm{sky}}$

$$L = L_{\mathrm{background}}\alpha(y) + (L_{\mathrm{sun}} + L_{\mathrm{amb}})(1 - \alpha(y))$$

Height fog model

The combination we are assuming is a hierarchy approximation of the volume rendering equation.

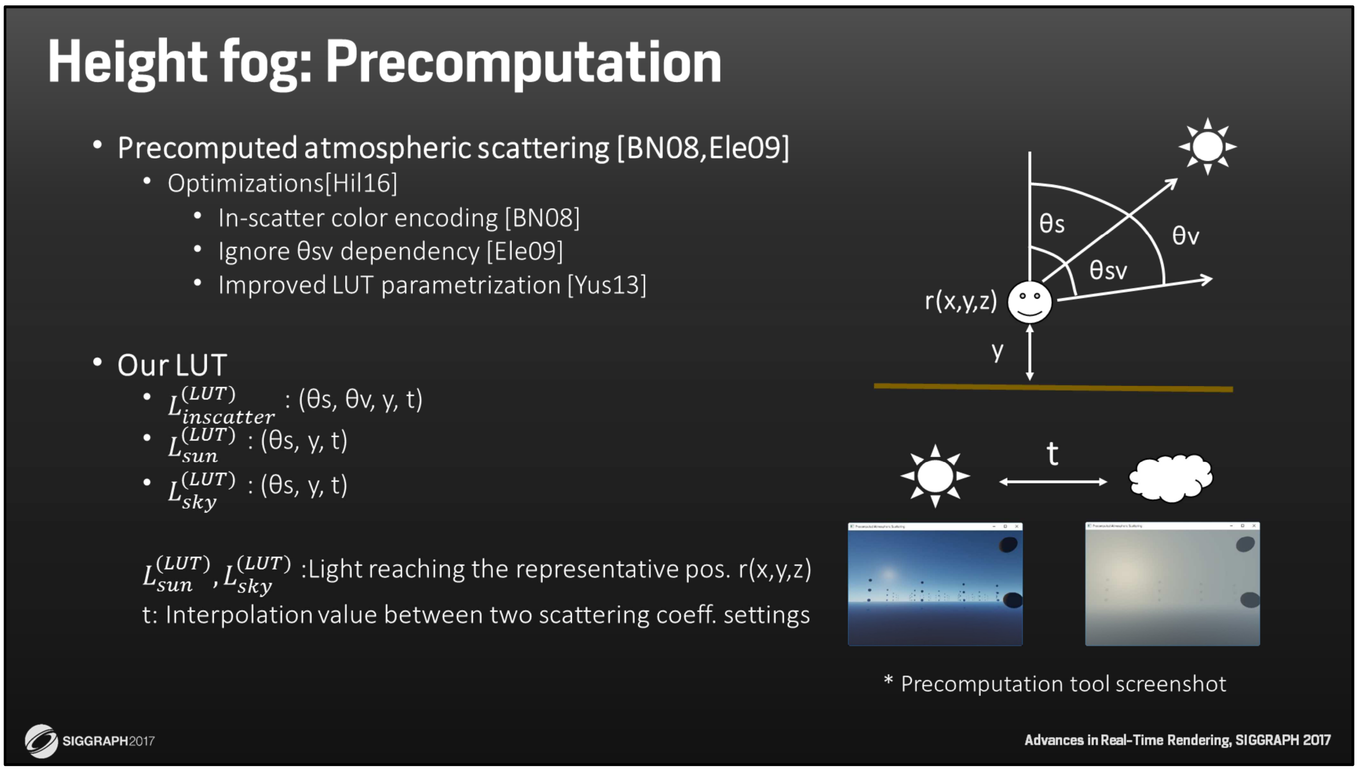
First, let us assume there is sunlight.

This extraterrestrial sunlight is incident into the earth, and interacts with the air.
Our precomputed model generates its multiple scattering information, and stores it as the LUT Linscatter, Lsun and Lsky.

The height fog model receives the background radiation, the sunlight and the skylight from the precomputed LUT.

It seems a trivial task to achieve this type of LUT if we develop the precomputation tool appropriately.
However, the problem is whether such a height fog solution can be obtained or not, especially for non-uniform fog.

In the following slides, I will explain the precomputed model and the height fog model in detail.



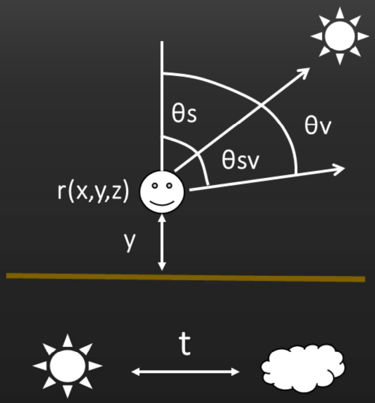
Height fog: Precomputation

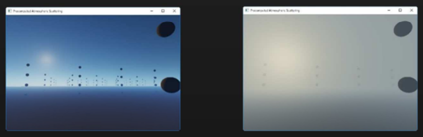
- Precomputed atmospheric scattering [BN08,Ele09]
  - Optimizations[Hil16]
    - In-scatter color encoding [BN08]
    - Ignore θsv dependency [Ele09]
    - Improved LUT parametrization [Yus13]

- Our LUT
  - $L_{inscatter}^{(LUT)}$: (θs, θv, y, t)
  - $L_{sun}^{(LUT)}$: (θs, y, t)
  - $L_{sky}^{(LUT)}$: (θs, y, t)

$L_{sun}^{(LUT)}, L_{sky}^{(LUT)}$:Light reaching the representative pos. r(x,y,z)

t: Interpolation value between two scattering coeff. settings





* Precomputation tool screenshot

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Our precomputed atmospheric scattering model is nothing special, but the LUT is different from the typical model.
Our implementation is mainly based on Bruneton's[BN08] and Elek's model[EK10] with some optimizations[Hil16].
For details of the precomputation algorithm, please refer to the references shown on this slide.

A typical precomputed atmospheric Model has an In-scatter and Transmittance LUT.
But we replace the transmittance LUT with Sunlight and Skylight LUTs, because we want to give the Sunlight and Skylight information directly to the Analytic Height Fog model.

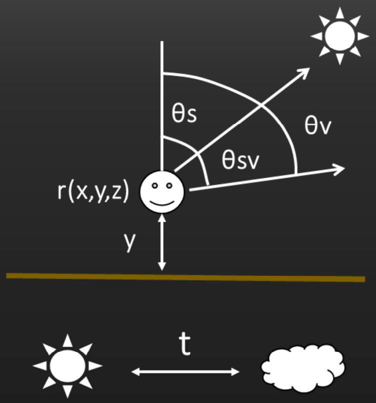
By the way, we precomputed the two weather types into the LUT.
Here, "two weather types" means two different scattering settings.
This is because we found that we can express the various weather conditions with no runtime precomputation if there are sunny and dense fog weather conditions as a base.

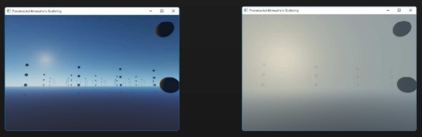
Height fog: Precomputation

- Precomputed atmospheric scattering [BN08,Ele09]
  - Optimizations[Hil16]
    - In-scatter color encoding [BN08]
    - Ignore θsv dependency [Ele09]
    - Improved LUT parametrization [Yus13]
- Our LUT (an example)
  - $L_{inscatter}^{(LUT)}$: (θs, θv, y, t) - (8, 64, 8, 4), 128KB

  - $L_{sun}^{(LUT)}$: (θs, y, t) - (64, 1, 4), 4KB

  - $L_{sky}^{(LUT)}$: (θs, y, t) - (64, 1, 4), 4KB

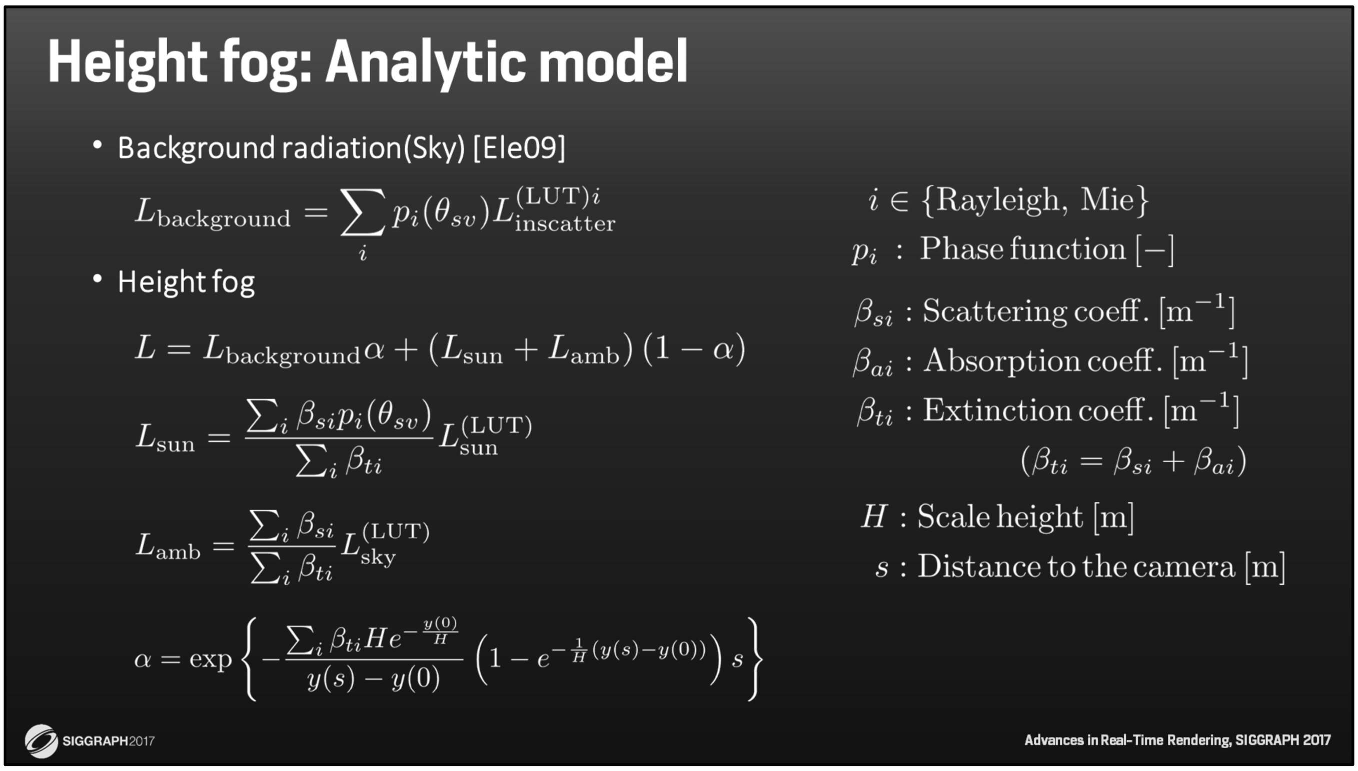




* Precomputation tool screenshot

This is an example of our LUT.
These sizes are optimized for games on the ground or near the ground.

Now we have the scattering information as 3 LUTs.
Let's see how these LUTs are used in the height fog model on the next slide.



Height fog: Analytic model

- Background radiation(Sky) [Ele09]

$$L_{\text{background}} = \sum_i p_i(\theta_{sv}) L^{(\text{LUT})i}_{\text{inscatter}}$$

- Height fog

$$L = L_{\text{background}}\alpha + (L_{\text{sun}} + L_{\text{amb}})(1-\alpha)$$

$$L_{\text{sun}} = \frac{\sum_i \beta_{si} p_i(\theta_{sv})}{\sum_i \beta_{ti}} L^{(\text{LUT})}_{\text{sun}}$$

$$L_{\text{amb}} = \frac{\sum_i \beta_{si}}{\sum_i \beta_{ti}} L^{(\text{LUT})}_{\text{sky}}$$

$$\alpha = \exp\left\{ -\frac{\sum_i \beta_{ti} H e^{-\frac{y(0)}{H}}}{y(s)-y(0)} \left(1 - e^{-\frac{1}{H}(y(s)-y(0))}\right) s \right\}$$

$i \in \{\text{Rayleigh},\ \text{Mie}\}$

p_i : Phase function $[-]$

β_{si} : Scattering coeff. $[\text{m}^{-1}]$

β_{ai} : Absorption coeff. $[\text{m}^{-1}]$

β_{ti} : Extinction coeff. $[\text{m}^{-1}]$

$(\beta_{ti} = \beta_{si} + \beta_{ai})$

H : Scale height $[\text{m}]$

s : Distance to the camera $[\text{m}]$

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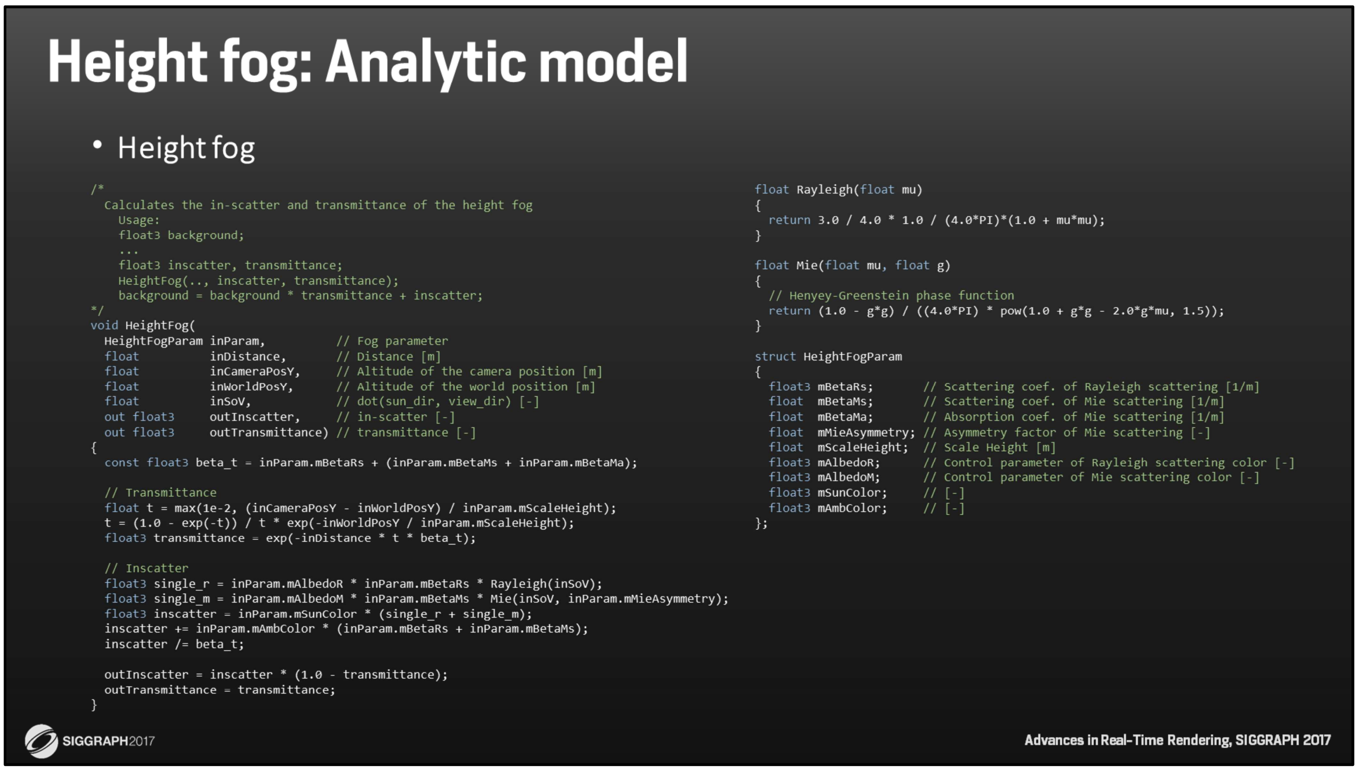
Before getting into the height fog model, one comment about the sky.
Background radiation, namely the sky is made with In-scatter LUT and the phase function.
This is the same as the Elek's model[EK10].

OK, let's take a look at the analytic height fog model.
The model has a form of blending background and sunlight + ambient with α.
Lbackground means the background radiation, sky.
Lsun describes single scattering component of sunlight.
And Lamb is constant ambient light component from the sky.
α is a blending factor with the background. The decreasing fog density with altitude is expressed here.
At first glance, this alpha blending structure looks like a model that has been adjusted for the game.
However we can derive it from the volume rendering equation directly.
If you are interested in the derivation of this model, please contact me after this session.



Height fog: Analytic model

- Height fog

```
/*
  Calculates the in-scatter and transmittance of the height fog
    Usage:
    float3 background;
    ...
    float3 inscatter, transmittance;
    HeightFog(.., inscatter, transmittance);
    background = background * transmittance + inscatter;
*/
void HeightFog(
  HeightFogParam inParam,          // Fog parameter
  float          inDistance,       // Distance [m]
  float          inCameraPosY,     // Altitude of the camera position [m]
  float          inWorldPosY,      // Altitude of the world position [m]
  float          inSoV,            // dot(sun_dir, view_dir) [-]
  out float3     outInscatter,     // in-scatter [-]
  out float3     outTransmittance) // transmittance [-]
{
  const float3 beta_t = inParam.mBetaRs + (inParam.mBetaMs + inParam.mBetaMa);

  // Transmittance
  float t = max(1e-2, (inCameraPosY - inWorldPosY) / inParam.mScaleHeight);
  t = (1.0 - exp(-t)) / t * exp(-inWorldPosY / inParam.mScaleHeight);
  float3 transmittance = exp(-inDistance * t * beta_t);

  // Inscatter
  float3 single_r = inParam.mAlbedoR * inParam.mBetaRs * Rayleigh(inSoV);
  float3 single_m = inParam.mAlbedoM * inParam.mBetaMs * Mie(inSoV, inParam.mMieAsymmetry);
  float3 inscatter = inParam.mSunColor * (single_r + single_m);
  inscatter += inParam.mAmbColor * (inParam.mBetaRs + inParam.mBetaMs);
  inscatter /= beta_t;

  outInscatter = inscatter * (1.0 - transmittance);
  outTransmittance = transmittance;
}
```

```
float Rayleigh(float mu)
{
  return 3.0 / 4.0 * 1.0 / (4.0*PI)*(1.0 + mu*mu);
}

float Mie(float mu, float g)
{
  // Henyey-Greenstein phase function
  return (1.0 - g*g) / ((4.0*PI) * pow(1.0 + g*g - 2.0*g*mu, 1.5));
}

struct HeightFogParam
{
  float3 mBetaRs;       // Scattering coef. of Rayleigh scattering [1/m]
  float  mBetaMs;       // Scattering coef. of Mie scattering [1/m]
  float  mBetaMa;       // Absorption coef. of Mie scattering [1/m]
  float  mMieAsymmetry; // Asymmetry factor of Mie scattering [-]
  float  mScaleHeight;  // Scale Height [m]
  float3 mAlbedoR;      // Control parameter of Rayleigh scattering color [-]
  float3 mAlbedoM;      // Control parameter of Mie scattering color [-]
  float3 mSunColor;     // [-]
  float3 mAmbColor;     // [-]
};
```

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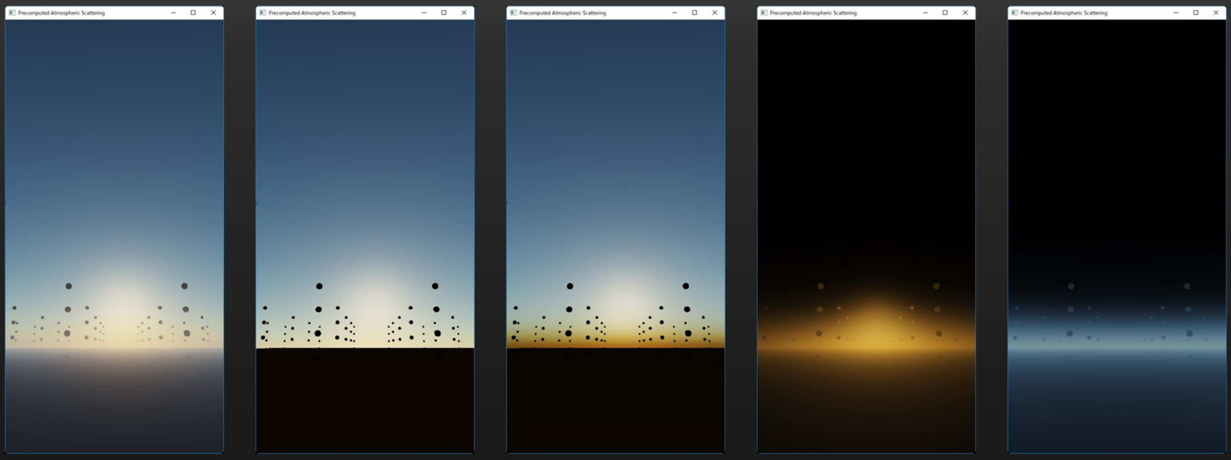
This is a sample code of our height fog model.

Height fog: Results



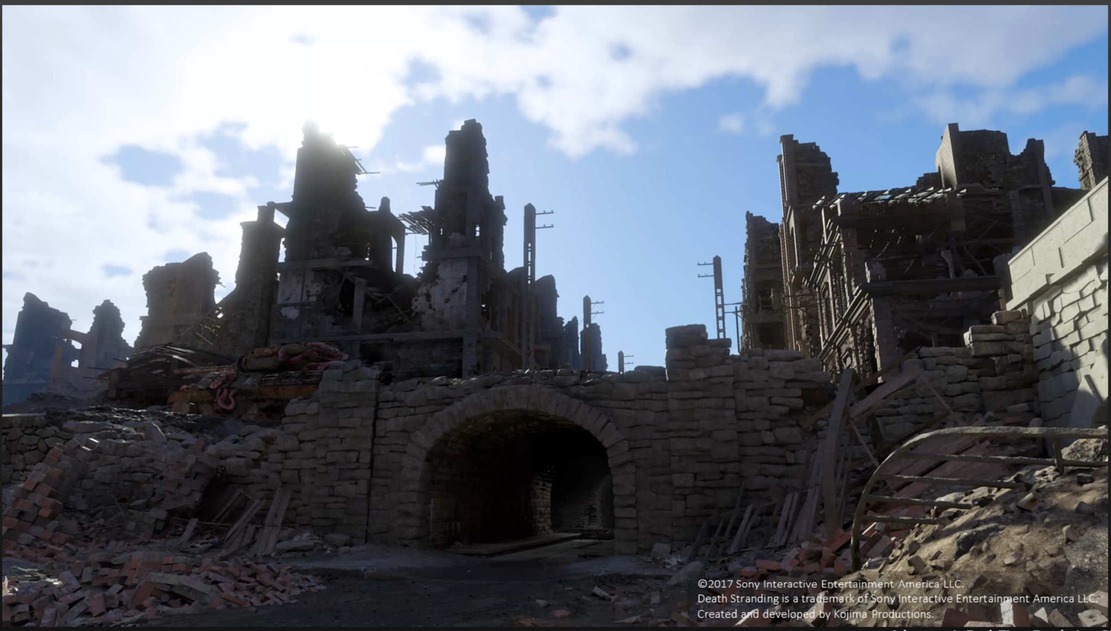
Result $L_{\text{background}}$ $L_{\text{background}}\,\alpha$ $L_{\text{sun}}(1-\alpha)$ $L_{\text{amb}}(1-\alpha)$

*Precomputation tool screenshots

This is the result.
I will explain these in order from the left end.
The left end is the final result.
Next is the background radiation.
Next is the background radiation multiplied by the alpha. We can see how the transmittance alpha is causing the color of the sunset as well.
The next is the sunlight component.
The right end is the ambient component.

When we sum up the three on the right, we get the result on the left.

Height fog: Results


©2017 Sony Interactive Entertainment America LLC.
Death Stranding is a trademark of Sony Interactive Entertainment America LLC.
Created and developed by Kojima Productions.

This is a sample scene from the Decima Engine.
We can see an aerial perspective from sunny to cloudy weather with the inclusion of an artistic atmosphere.

So, with this result, we achieve both a realistic aerial perspective and an artistic height fog with a single height fog model.

Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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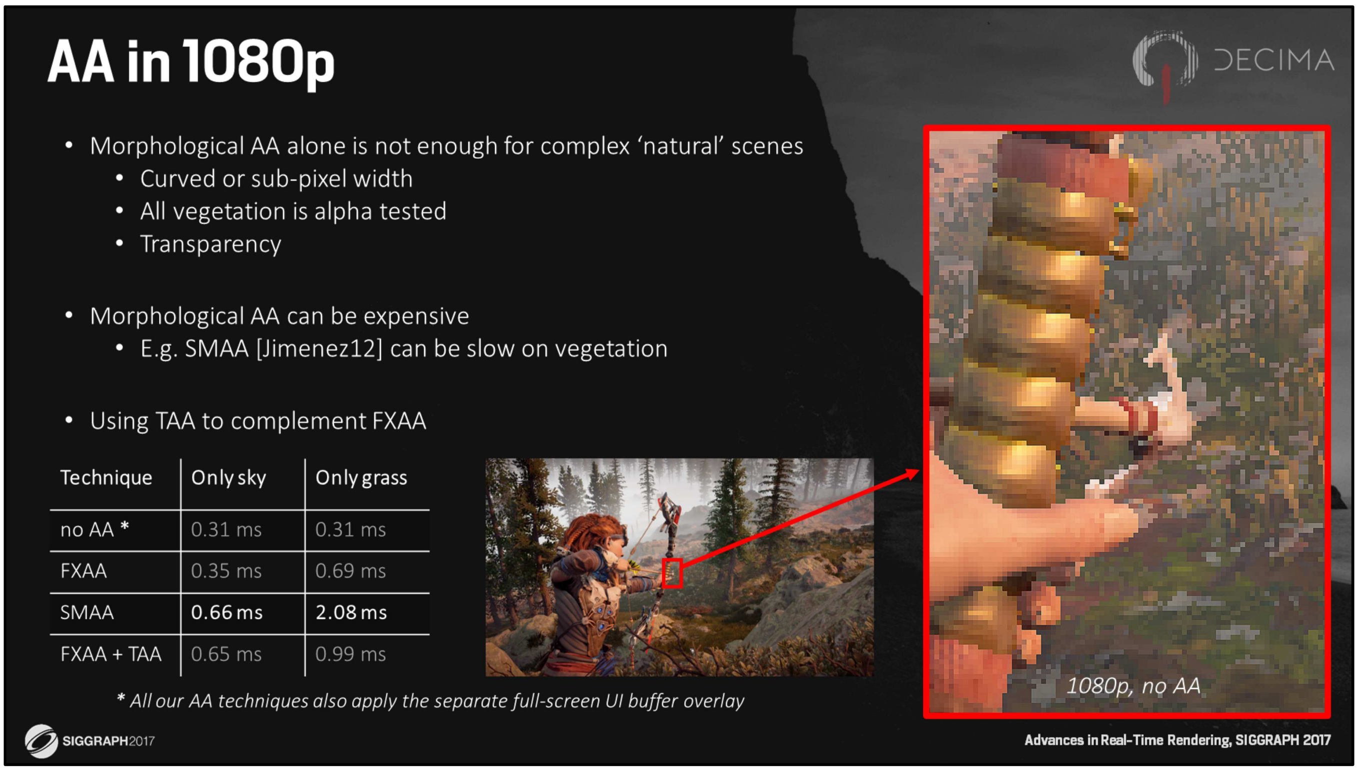
In the next section I'll be talking about our anti-aliasing solution.

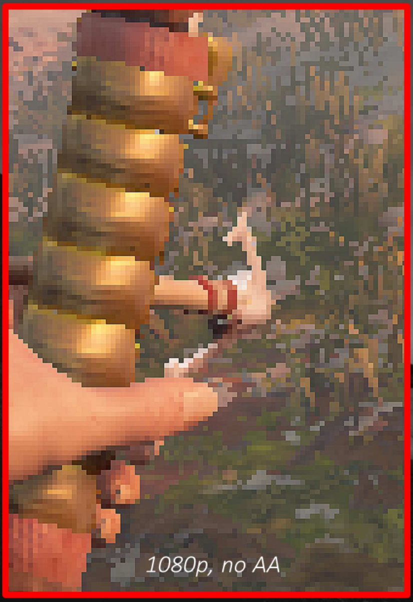


AA in 1080p

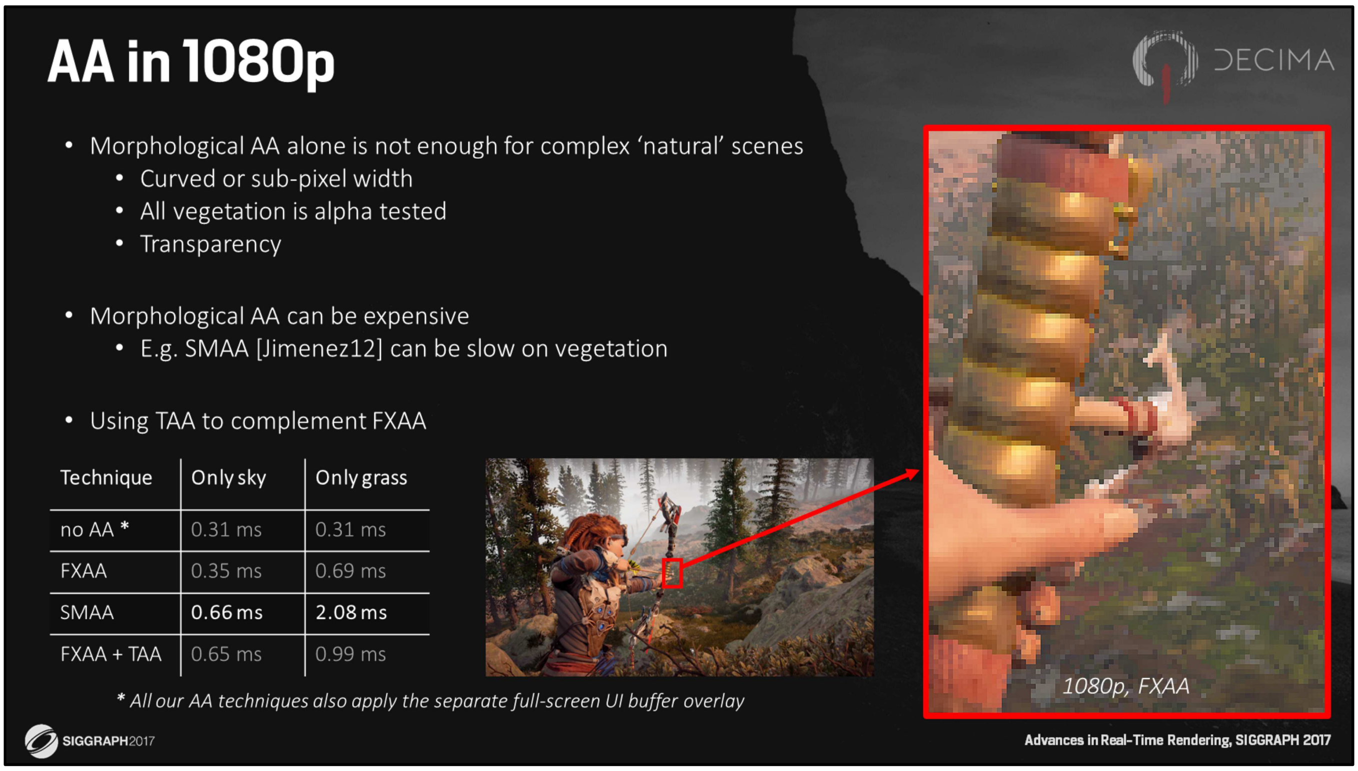
- Morphological AA alone is not enough for complex 'natural' scenes
  - Curved or sub-pixel width
  - All vegetation is alpha tested
  - Transparency
- Morphological AA can be expensive
  - E.g. SMAA [Jimenez12] can be slow on vegetation
- Using TAA to complement FXAA

Technique	Only sky	Only grass
no AA *	0.31 ms	0.31 ms
FXAA	0.35 ms	0.69 ms
SMAA	**0.66 ms**	**2.08 ms**
FXAA + TAA	0.65 ms	0.99 ms

** All our AA techniques also apply the separate full-screen UI buffer overlay*



There's many different ways to do anti-aliasing, including super-sampling, multi-sampling, post processing, and temporal AA.



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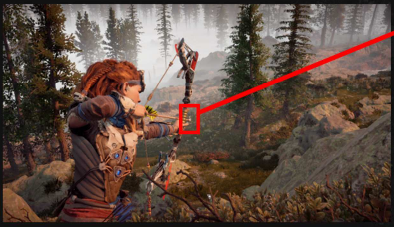

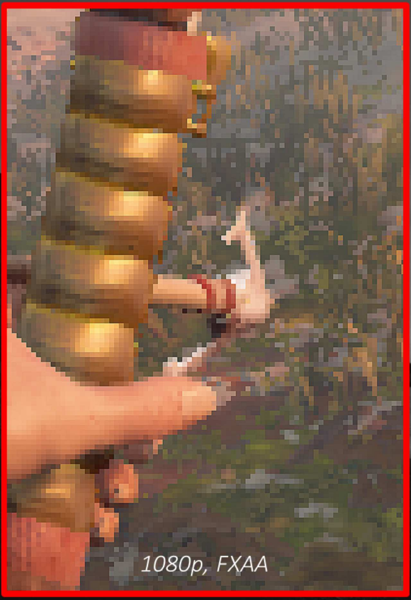

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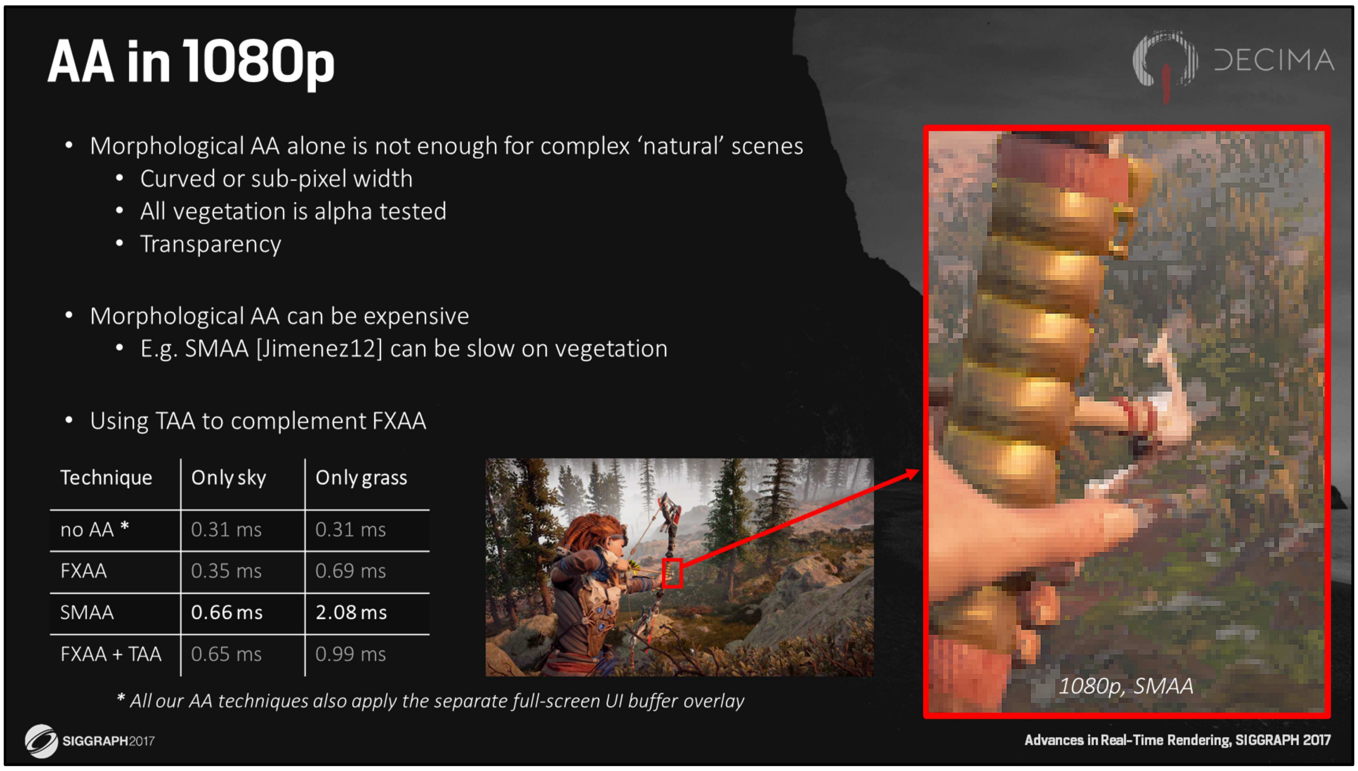
For Horizon, we tried to only use FXAA…



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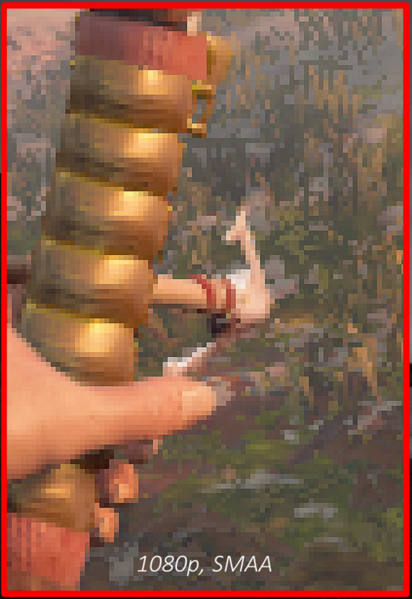
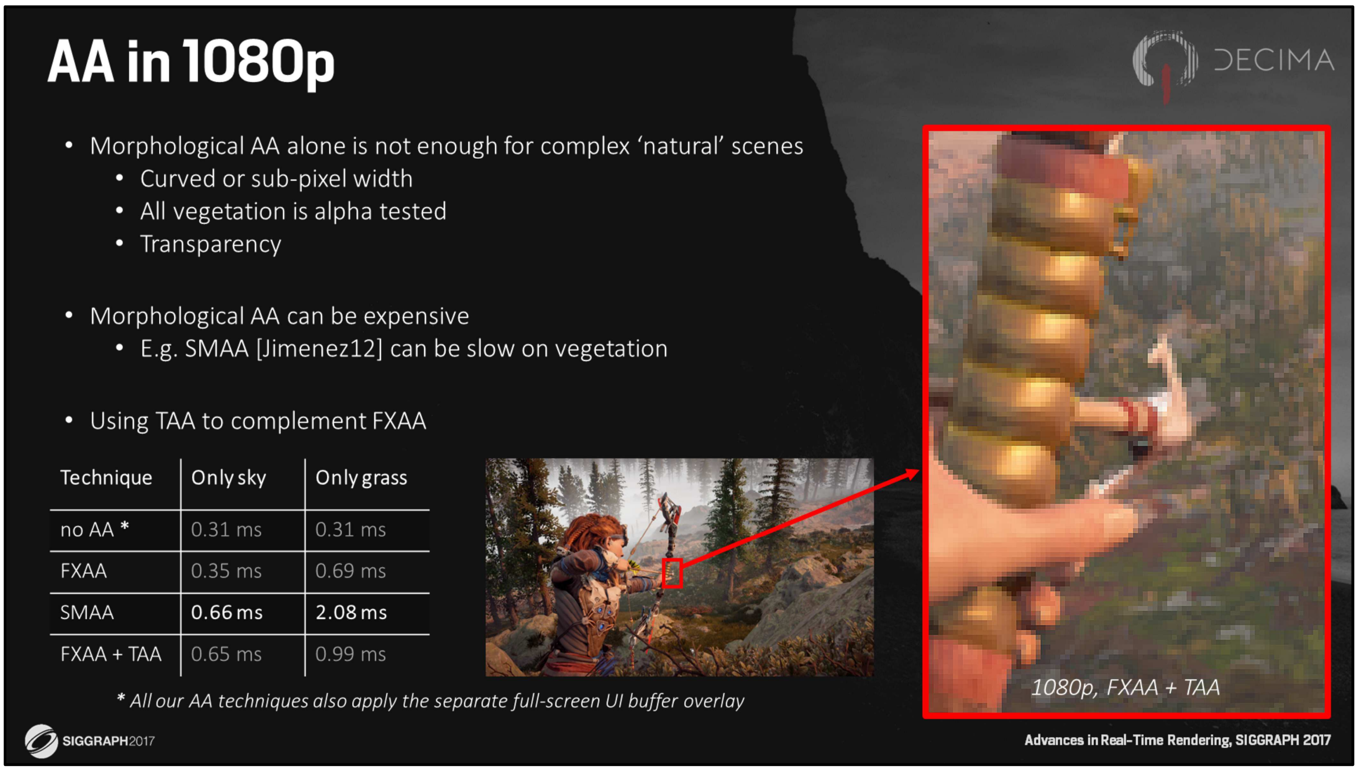


** All our AA techniques also apply the separate full-screen UI buffer overlay*

… and SMAA for some time, but it was clear that any technique purely based on post-processing wouldn't cut it.
These technique are pretty good at removing jaggies from clean and clear input, but we don't have a lot of that in Horizon.
Instead, our AA solution would need to cope with heavily curved, undersampled, ambiguous, alpha-tested and alpha-blended input.

But what's more is that post processing techniques can also be rather EXPENSIVE and scene dependent.
SMAA, for example, can takes up to 2 milliseconds when looking down at the grass in Horizon. And that's 3 times slower than just looking up at a clear sky.



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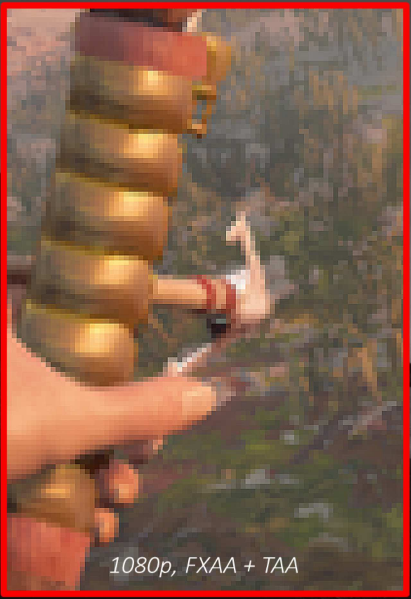
1080p, FXAA + TAA

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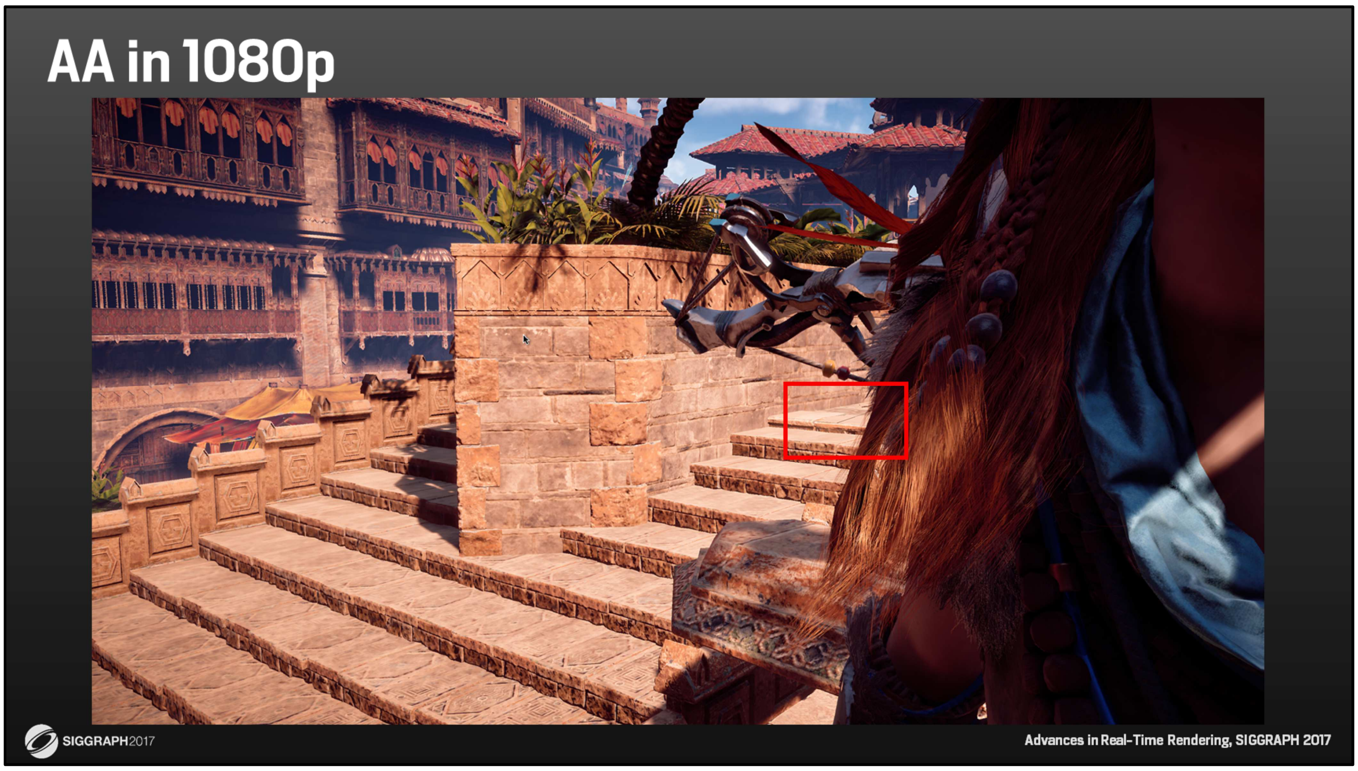
Obviously, instead of morphological post-processing techniques, we could have considered multi-sampling techniques or analytical techniques, for example.
But we simply couldn't afford the overhead in complexity and performance that that would have given us,
as we were looking for something that would cost less than 1 millisecond in total.

So, like many others, we turned to temporal anti-aliasing, which is effectively doing anti-aliasing over multiple frames.

And in the end, we settled on a combination of FXAA and our own variation on TAA, and use each of their strengths as effectively as possible. And using that, we get this..

And after the necessary optimizations, our FXAA plus TAA PLUS UI compositing system is now taking up at most 1 millisecond per frame on the PS4 in 1080p.



AA in 1080p

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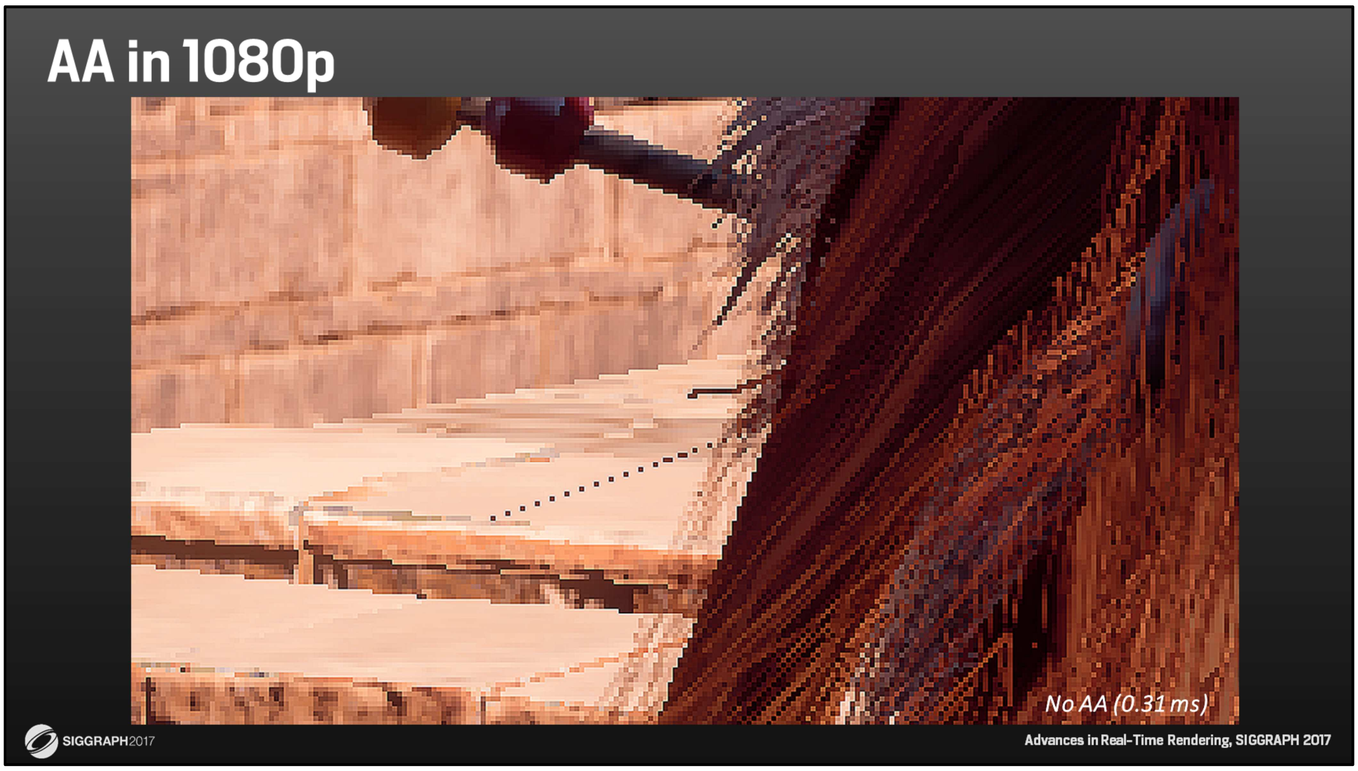
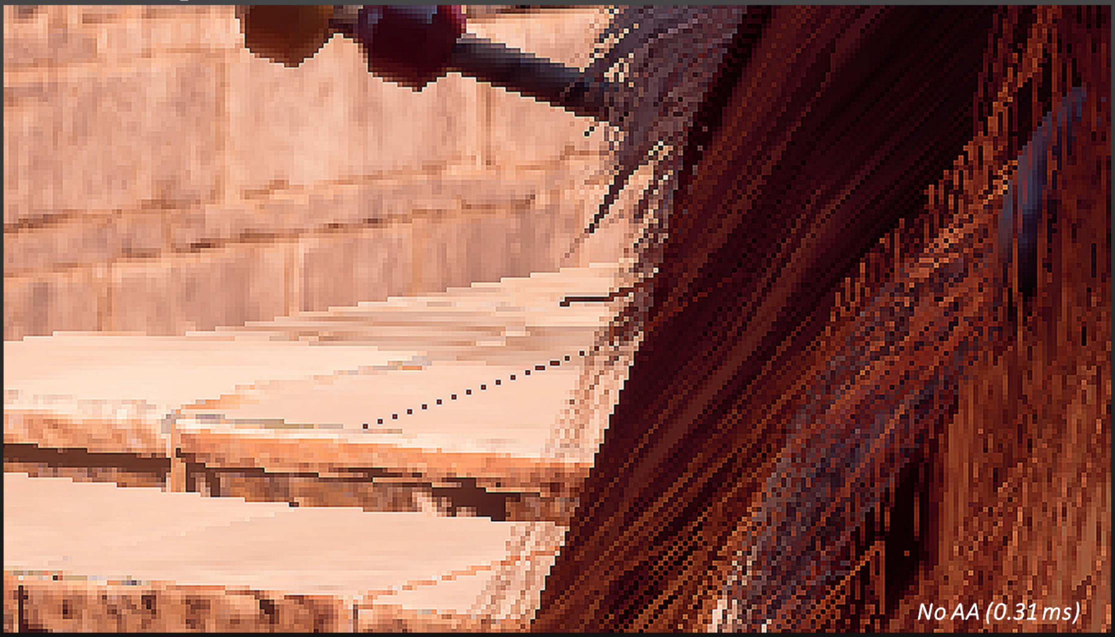
Let’s look at a more detailed comparison.

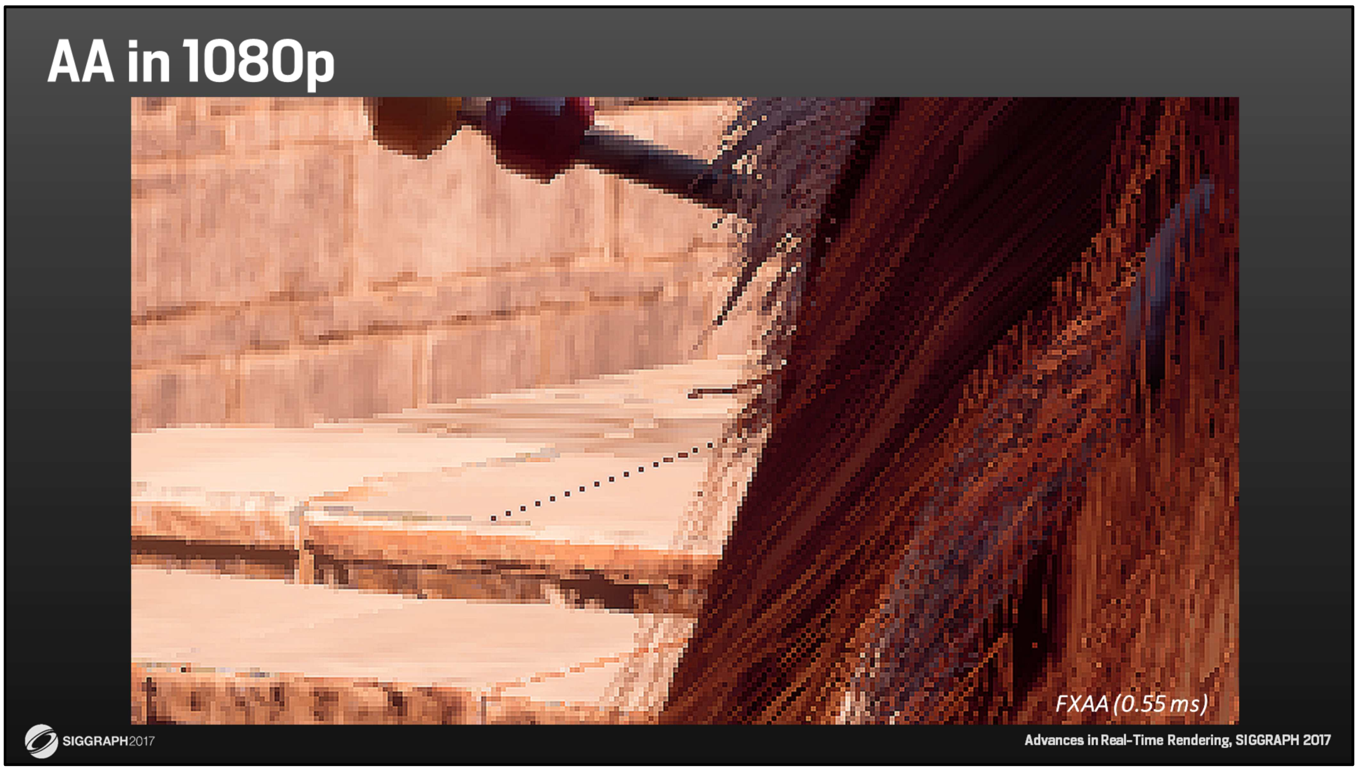
And focus on the highlighted area.



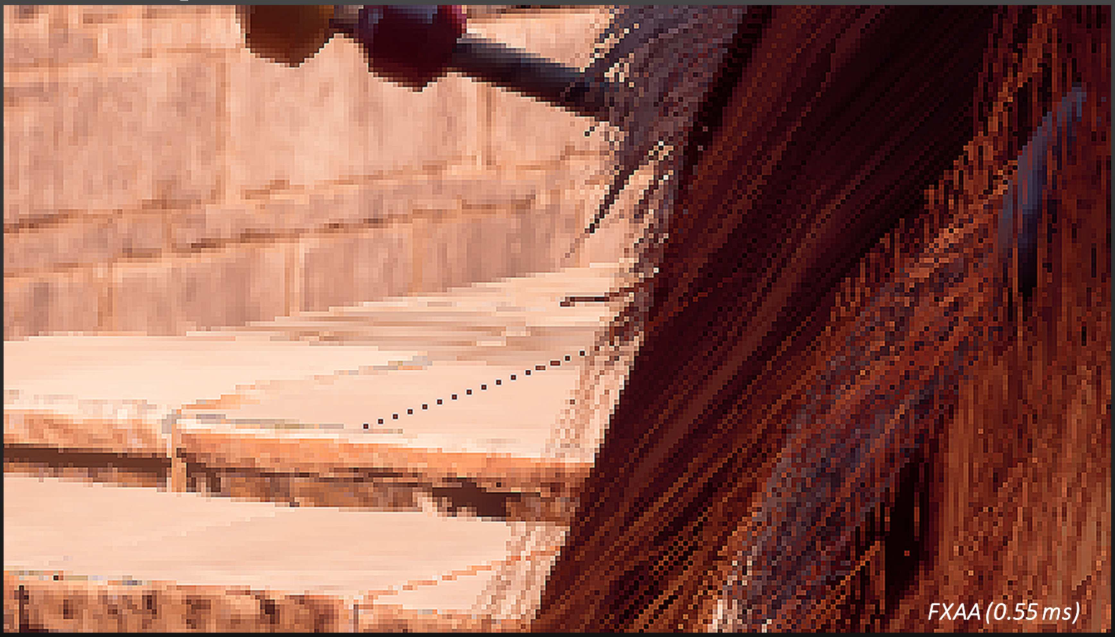
AA in 1080p



This is that zoomed-in area without any AA technique.
Here, you can clearly see the jaggies on the steps, the undersampling between the stones, and the rough look of the hair.



AA in 1080p



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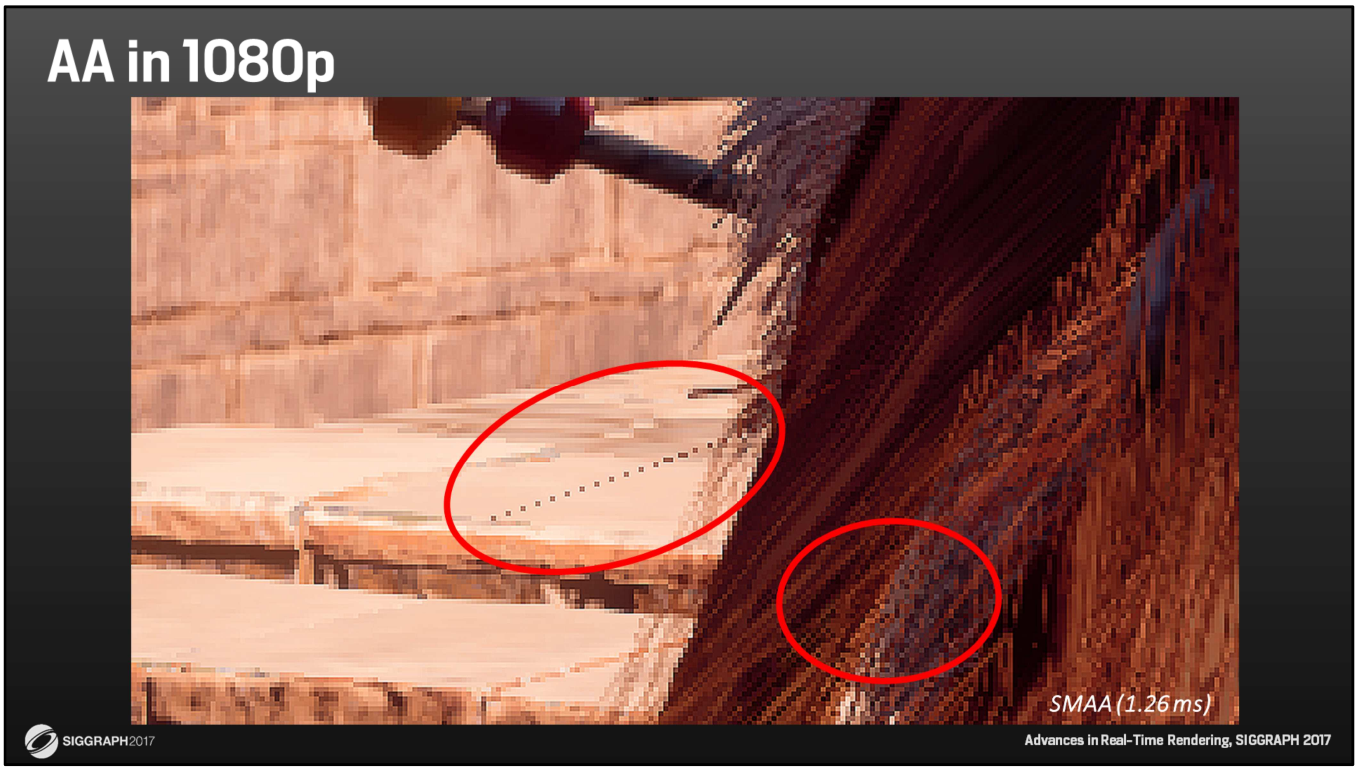
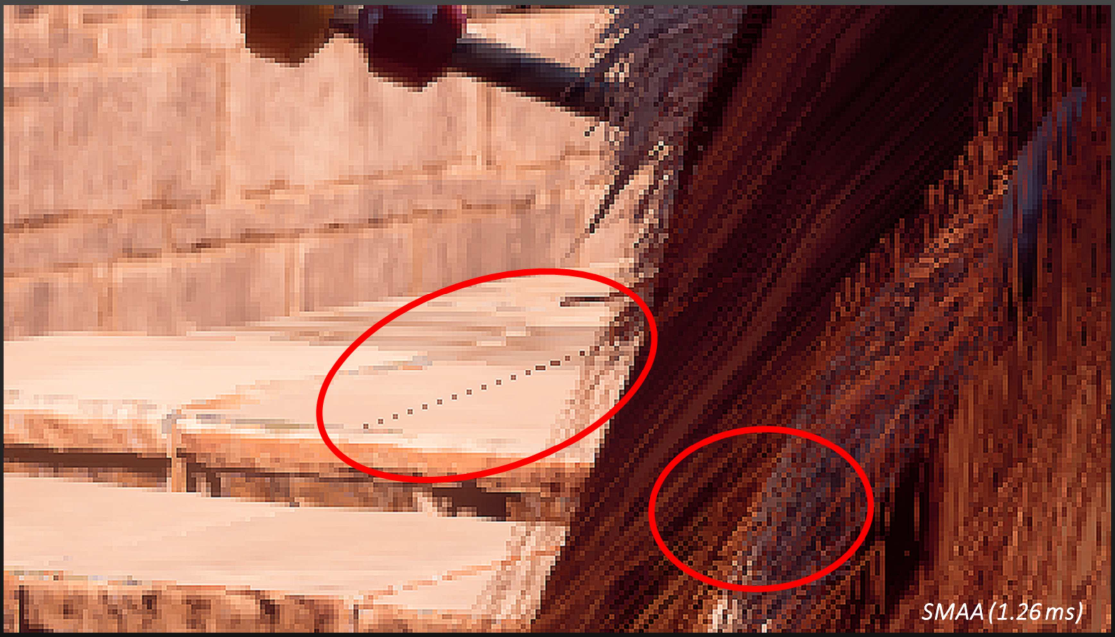
And this is with FXAA. And you can see, it does help a bit, but it only hides the jaggies in clear straight lines, like the horizontal lines between the stair steps.

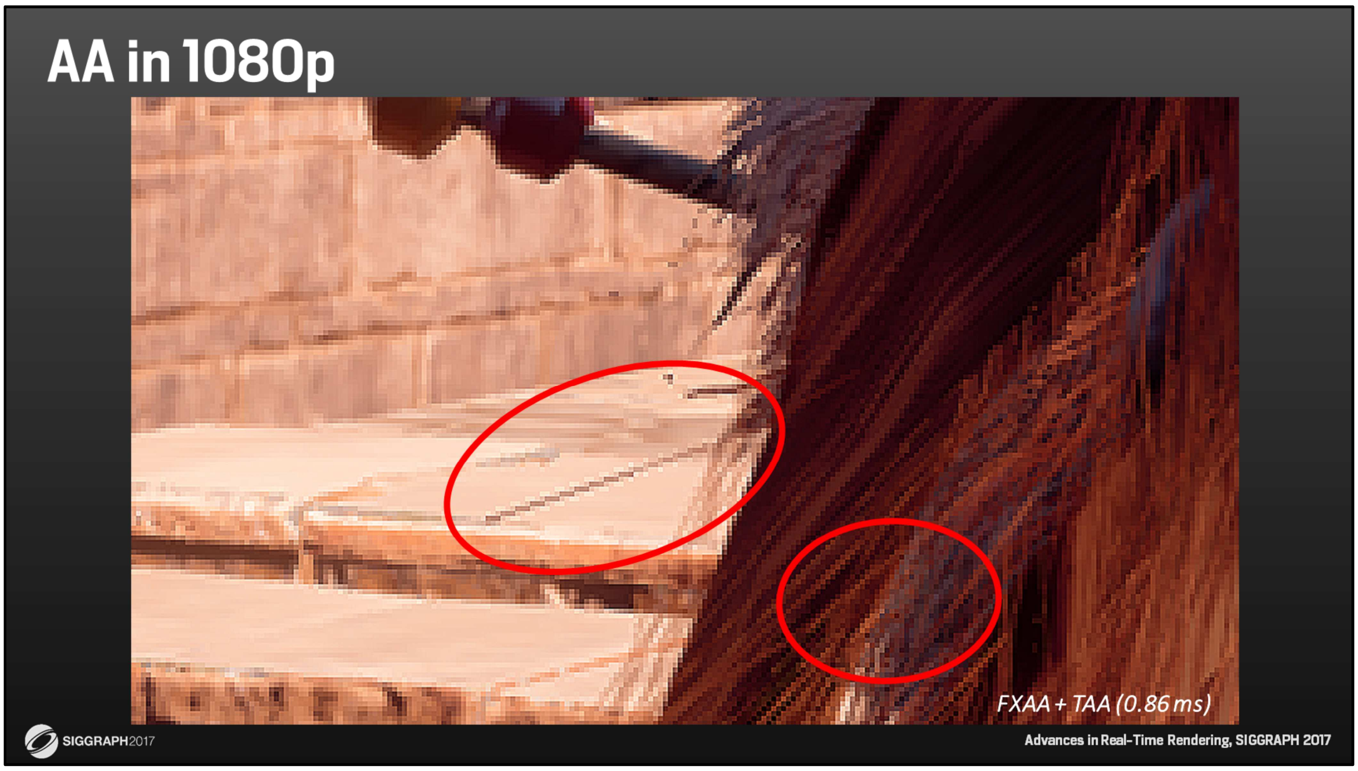


AA in 1080p

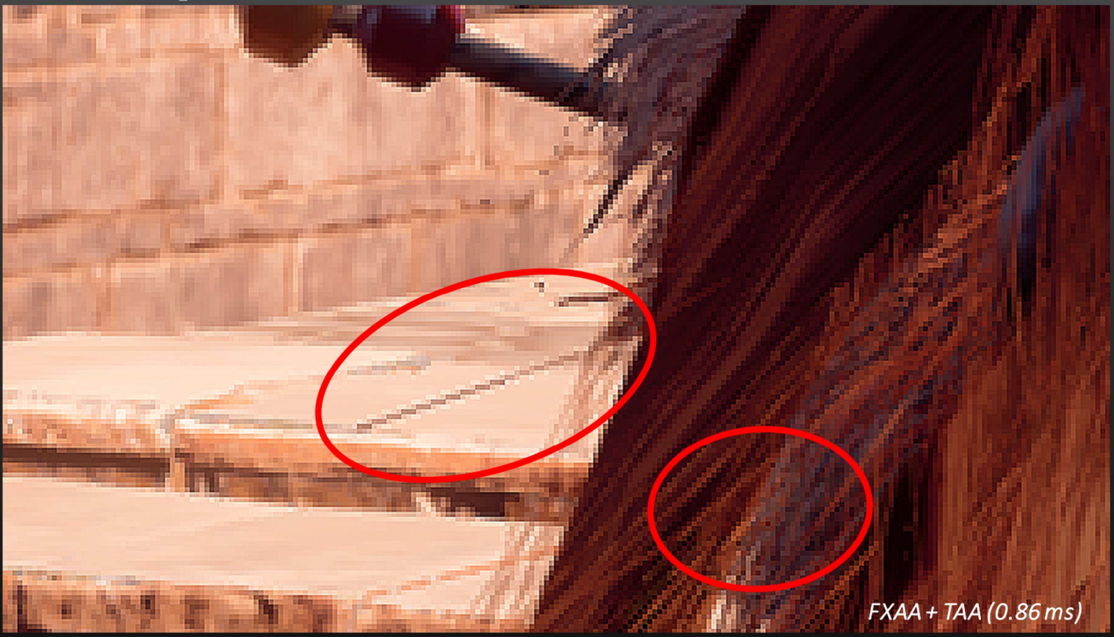


This is with SMAA. This again, is slightly better than the previous one,

But it still doesn't fix these areas.



AA in 1080p



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And this is with FXAA plus TAA. The TAA uses different sample positions for odd and even frames, and resolves to THIS after only two frames. Notice how the undersampled areas are now closed and a lot smoother.

You probably also notice the slight halo around the dark diagonal line. That’s because we also sharpen the output of the TAA a bit.

Not only does our TAA help with sampling more details.
But it also helps with temporal STABILITY.

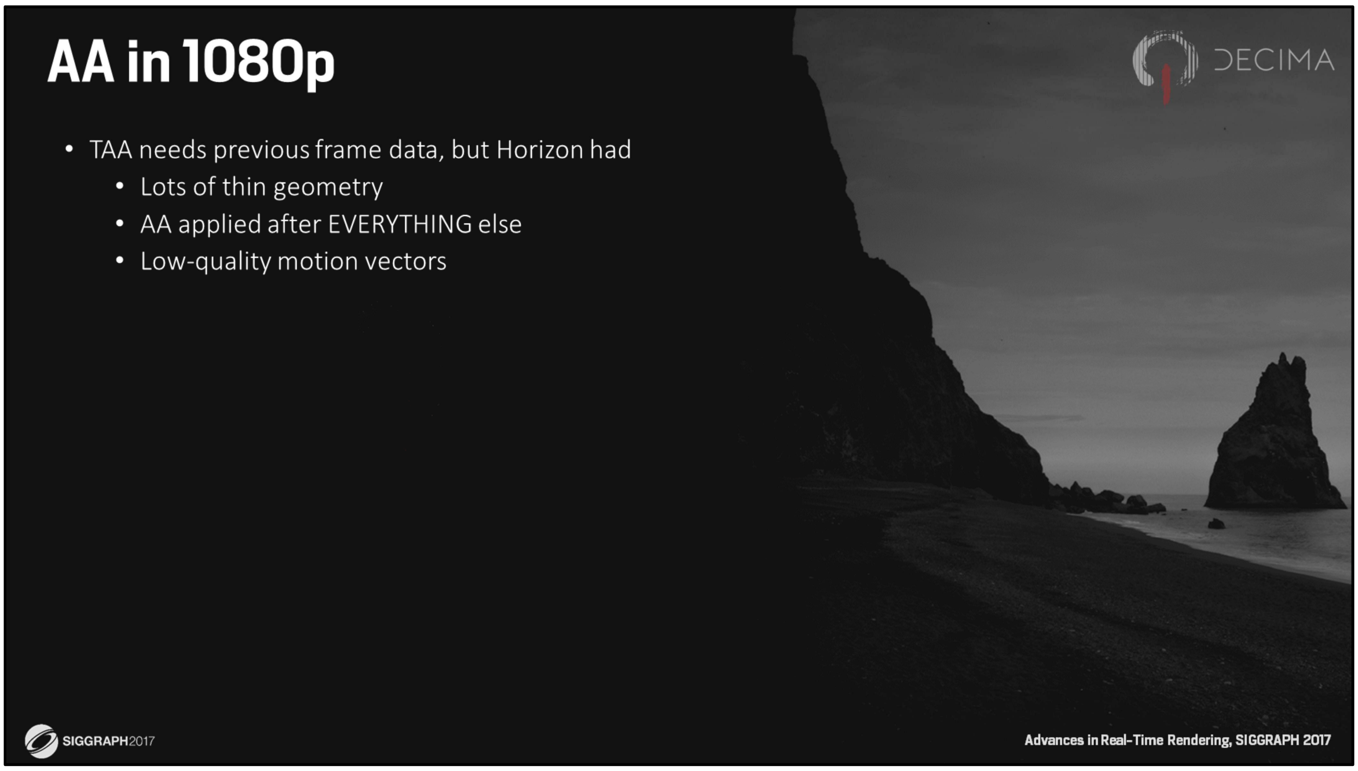
Here's a short clip of a typical environment in Horizon.

And let's zoom in a bit.

This is without any AA. Notice how noisy and flickery both the short and tail grass looks.

This is SMAA. It clearly helps, but it's still quite noisy.

This is TAA. Notice how much calmer everthing looks now.



AA in 1080p

- TAA needs previous frame data, but Horizon had
  - Lots of thin geometry
  - AA applied after EVERYTHING else
  - Low-quality motion vectors

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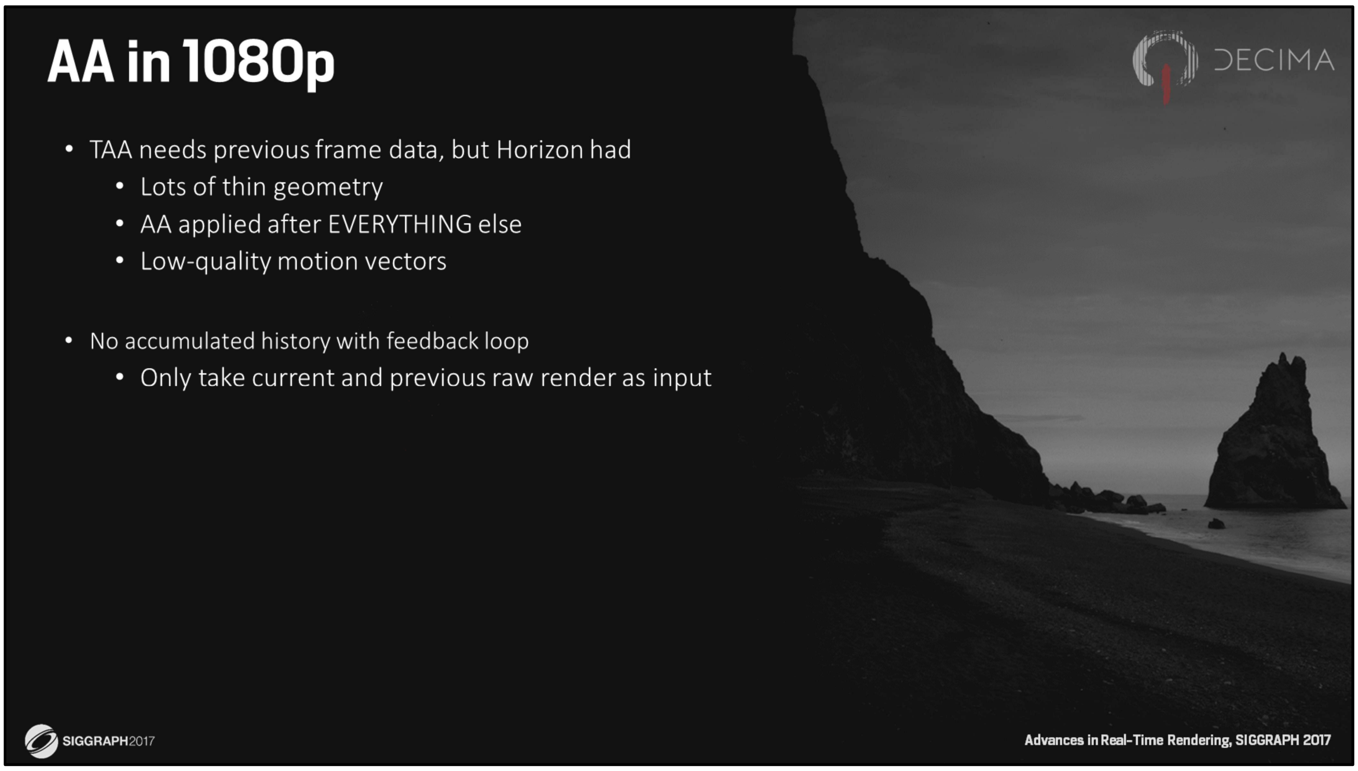
OK. So TAA helped us a lot. But getting that to work RELIABLY was somewhat of a challenge.

That's because all TAA implementations depend on some form of history reuse.
And this is typically done by accumulated many frames over times, and that CAN work great.
But doing that didn't work that well for Horizon.

The reason for that is that our AA is applied on often very thin geometry,
Plus we apply AA only AFTER we already overlayed a lot of visual FX and all post effects.
And that includes effects life Depth of Field and vignetting.

And lastly, we base our TAA reprojections on a HALF-RES motion buffer, which is probably not ideal.
And some types of objects don't even output motion vectors at all.



AA in 1080p

- TAA needs previous frame data, but Horizon had
  - Lots of thin geometry
  - AA applied after EVERYTHING else
  - Low-quality motion vectors
- No accumulated history with feedback loop
  - Only take current and previous raw render as input

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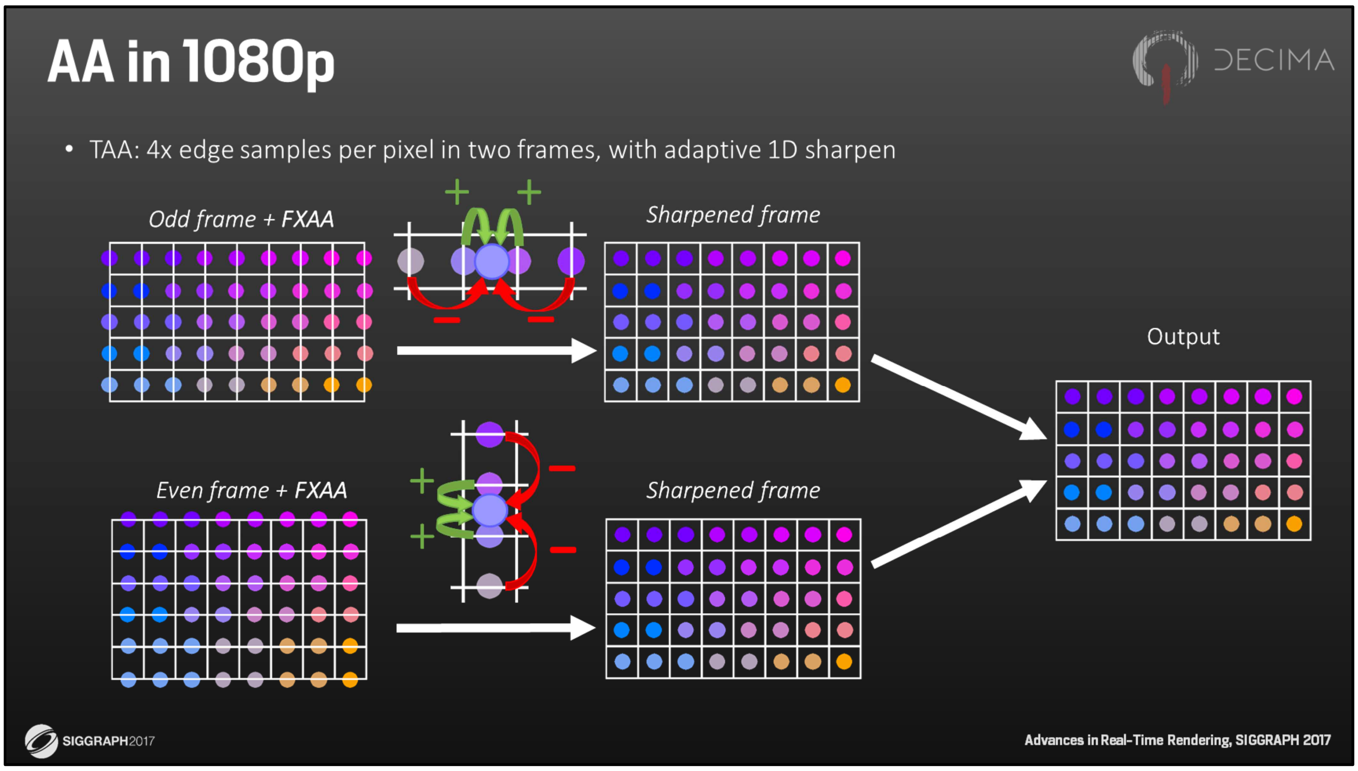
So, for those reasons, we prefer not to use any previous frame for too long.
And so, instead of somehow accumulating the output from previous frames,
we chose to only reuse the INPUT to the AA system from the previous frame, but not the previous output.

That is, we use the raw render of the previous frame and the current frame, but nothing more.
Thay way, we prevent any long ghosting trails caused failed rejects,
and we reach a stable and final result in only two frames, making our technique very responsive.



AA in 1080p

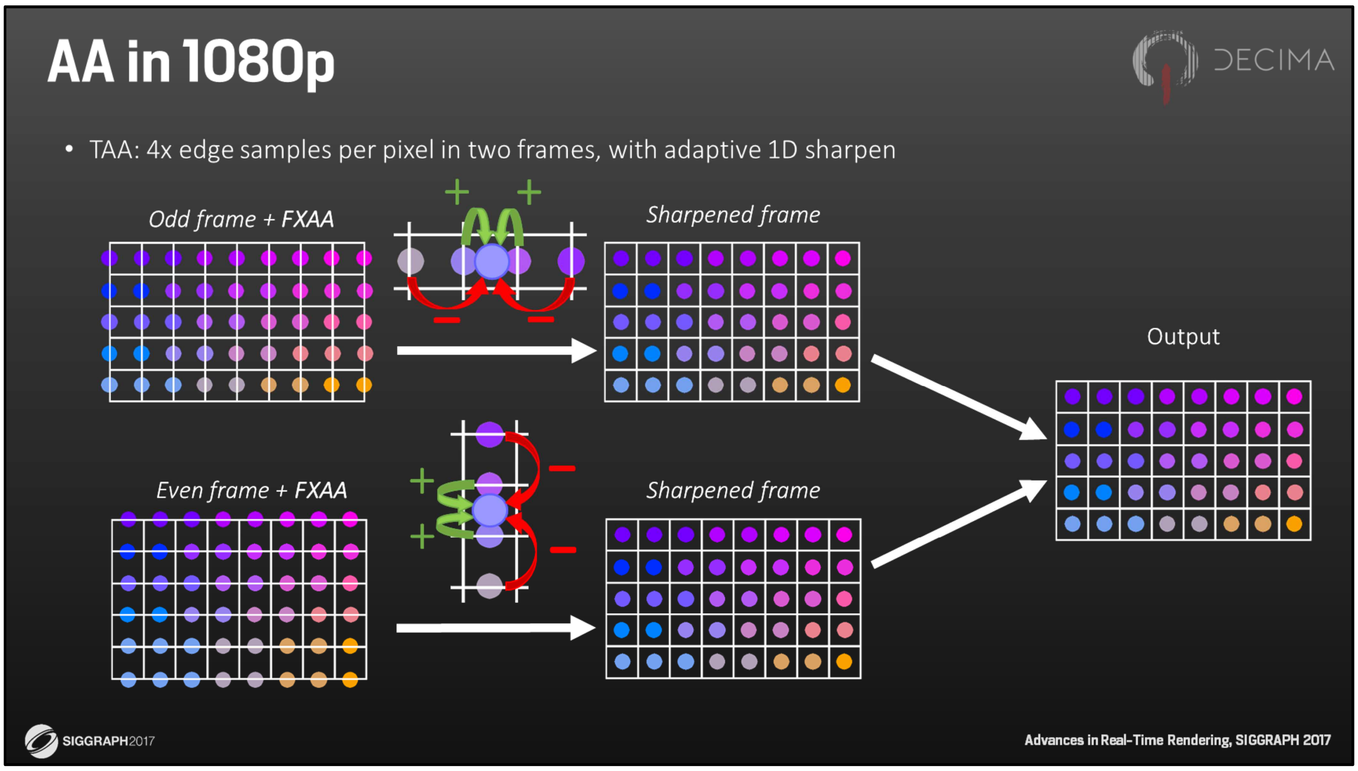
- TAA: 4x edge samples per pixel in two frames, with adaptive 1D sharpen

So let's dive into some the details of our solution.

For one, we never render at the pixel centers, but only on the pixel's edges.
In fact, we render HORIZONTALLY BETWEEN the pixel centers for odd frames, and VERTICALLY between pixel centers for even frames.
We do this by jittering the camera in this precise pattern, and we don't rely on any form of multi-sample hardware like EQAA.
And we don't have to process or output pixel shaders any differently.

After we've rendered the jittered frame, we apply all post effects, and run FXAA on these samples at the pixel's edges.
After the FXAA, the samples are then resampled from the pixel's edges to the pixel's centers.

You could do this by simply averaging the two samples closest to each pixel center.
But instead, we use a 4-tap resampling kernel with negative lobes to counter any texture blurring.
This is a bit like Catmull-Rom resampling, but cheaper, and the amount of sharpening is determined based on local contrast.



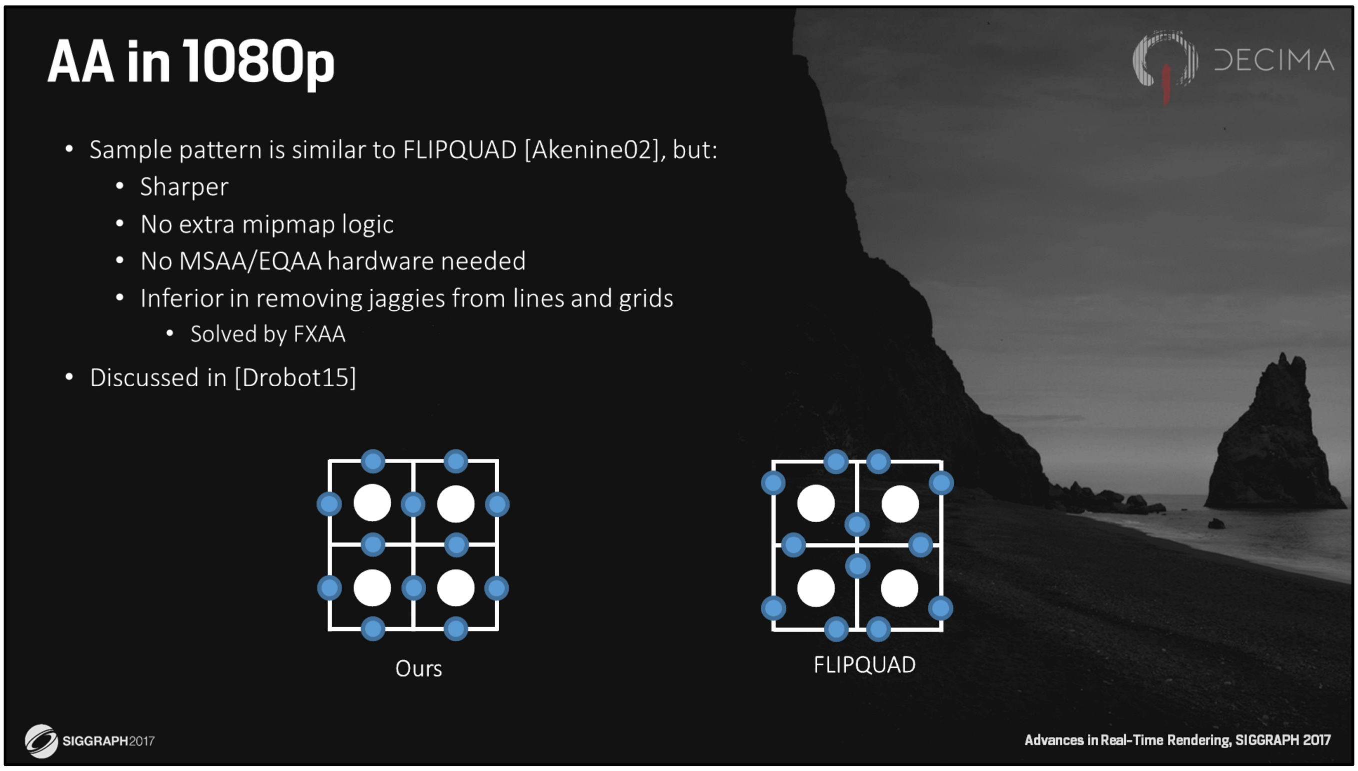
AA in 1080p

- TAA: 4x edge samples per pixel in two frames, with adaptive 1D sharpen

The final resolve tries to merge the previous sharpened frame with the current sharpened frame.
If history is accepted, this gives us effectively 4 samples of data per pixel.
And when history is rejected, we still get to use 2 samples per pixel that were already treated with FXAA.

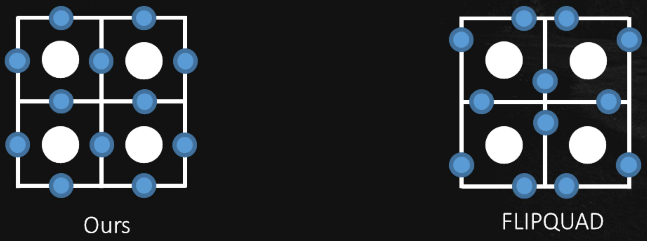
As an implementation detail, we actually only run two passes to do all this.
First, we run the FXAA pass.
And in the second pass, we sharpen the current frame, and OUTPUT that to one of the two history buffers.
In the meantime, from within the same shader, we also READ from the OTHER history buffer, which contains the sharpened version of the PREVIOUS frame, and we use that to either reject or reproject.

If a pixel from the history is reprojected, it's blended 50/50 with the current SHARPENED frame, and we output that to the final backbuffer.
But if the history sample is REJECTED, we simply output the CURRENT frame's pixel WITHOUT sharpening, to hide any potential aliasing as good as we can.



AA in 1080p

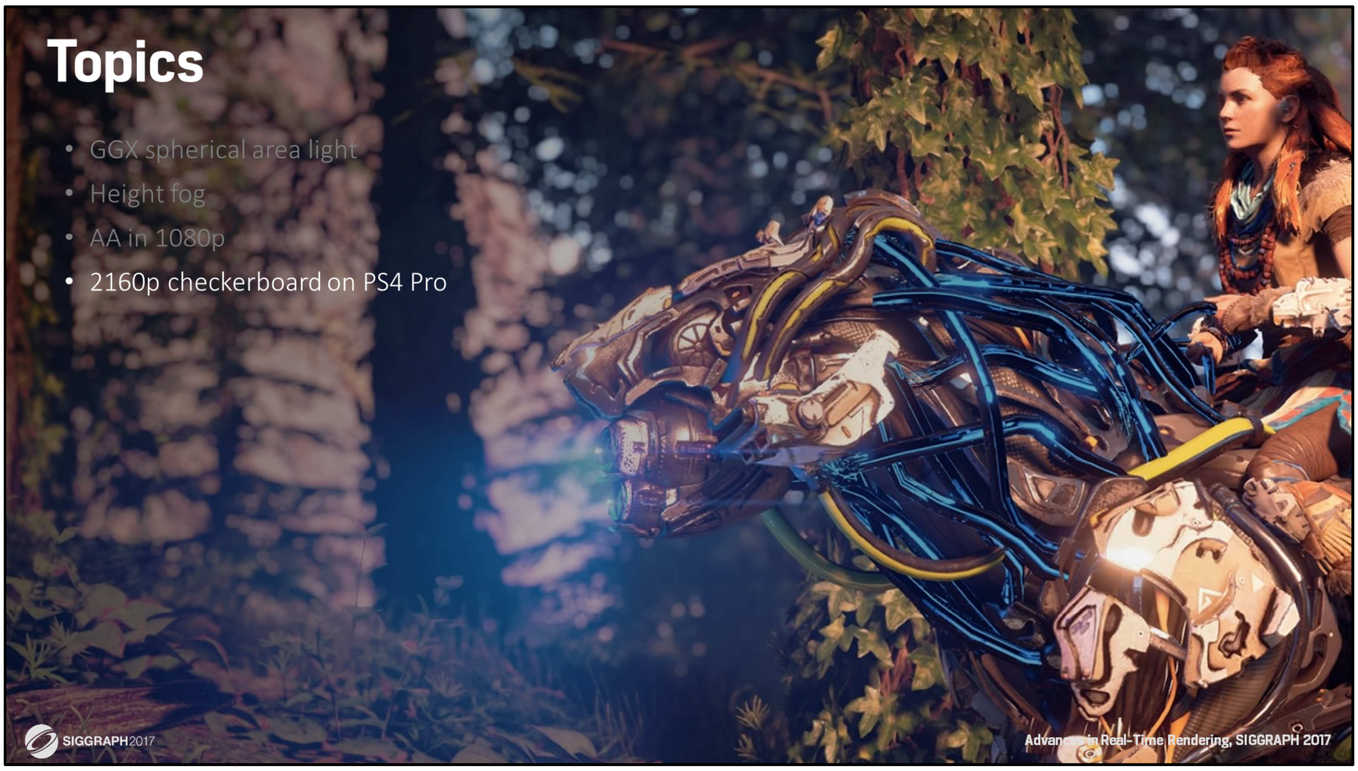
- Sample pattern is similar to FLIPQUAD [Akenine02], but:
  - Sharper
  - No extra mipmap logic
  - No MSAA/EQAA hardware needed
  - Inferior in removing jaggies from lines and grids
    - Solved by FXAA
- Discussed in [Drobot15]



You may have noticed that, if you'd succesfully merge two frames and ignore the sharpening, we effectively get the sampling pattern that you see on the left.

And in a way, this is a bit like the PATENTED FLIPQUAD technique, which also uses samples on the pixel's edge.
However:
- Our pattern is slightly sharper as the samples are closer to the center.
- And unlike rendering the FLIPQUAD pattern over two frames, we don't need any additional logic or features to get correct mipmap sampling, but this was already hinted at by Michal Drobot in 2015.
- Another nice thing about our pattern is that don't require any multi-sample features to render at the right sample positions. We only need to jitter the camera per frame.
- But the downside of all is that it's less good at removing jaggies from very regular straight patterns like lines and grids, but that's largely fixed by the FXAA pass we also apply.

OK. For other aspects of our TAA solution like temporal reprojection and neighborhood-based rejection criteria, we used some more traditional approaches, so we won't cover those here.



Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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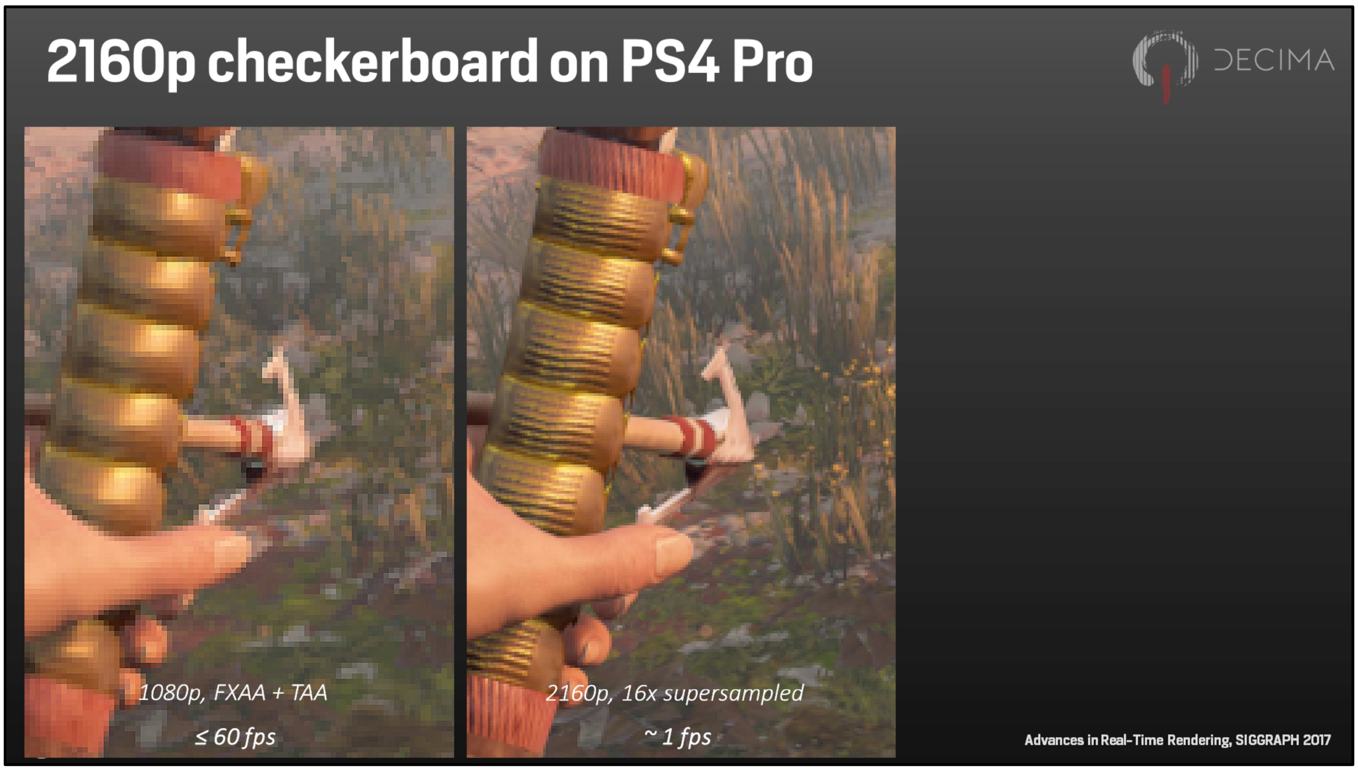
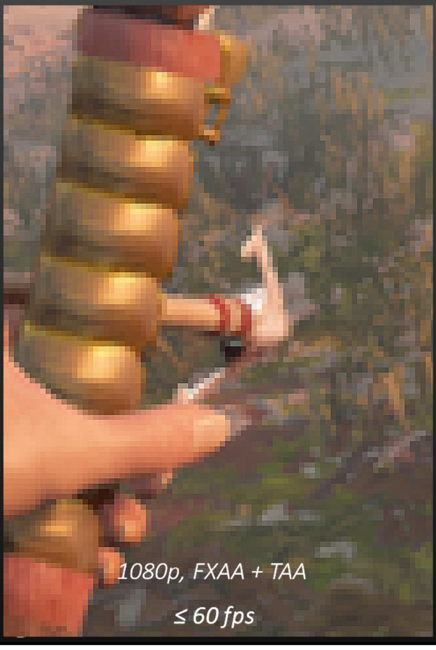
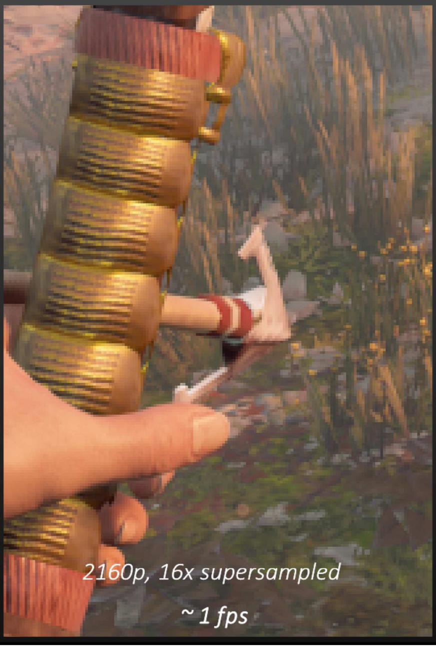
Instead, we'll jump to the next and last topic, which is about how we render for 2160p on the PS4 Pro using checkerboard rendering.



2160p checkerboard on PS4 Pro





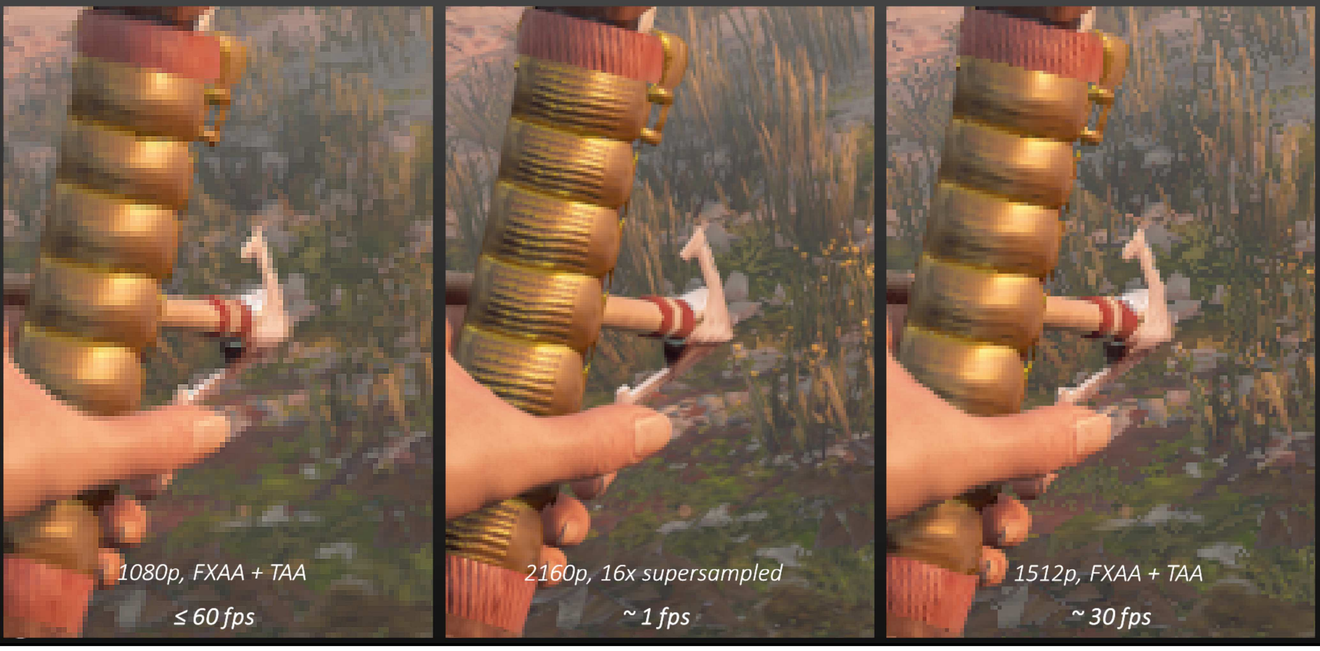
Let’s start with a comparison.

On the left you see the same image I’ve shown you before, which is a zoomed-in 1080p screenshot using our FXAA plus TAA solution.

In the middle, you see what you’d ideally get on 2160p. This wouldn’t run at 30fps on a PS4 Pro, especially when using 16 times supersampling.
But it does show what we’d ideally achieve if performance wasn’t a problem.

2160p checkerboard on PS4 Pro

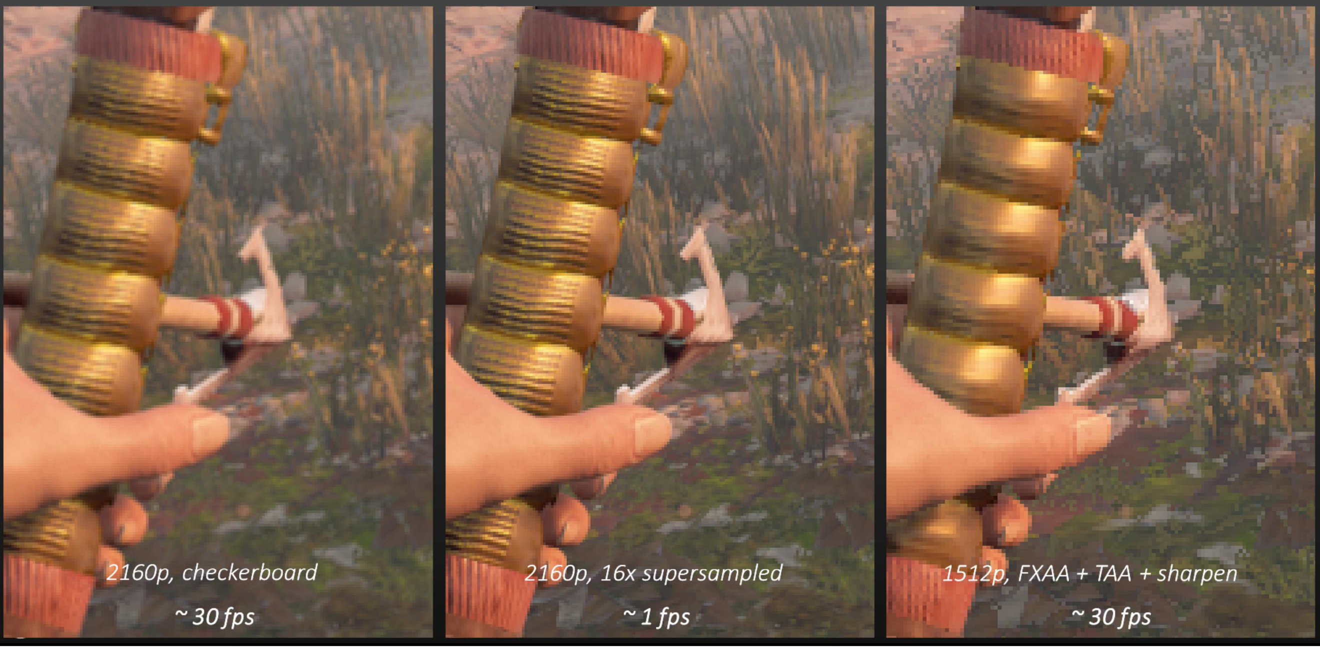
DECIMA



On the right, you now see what you COULD get at 30 fps on a PS4 Pro: A native 1512p image using the same AA technique as in 1080p.
Notice how it's clearly sharper than 1080p, but it still misses much of the detail that you DO see in the reference.

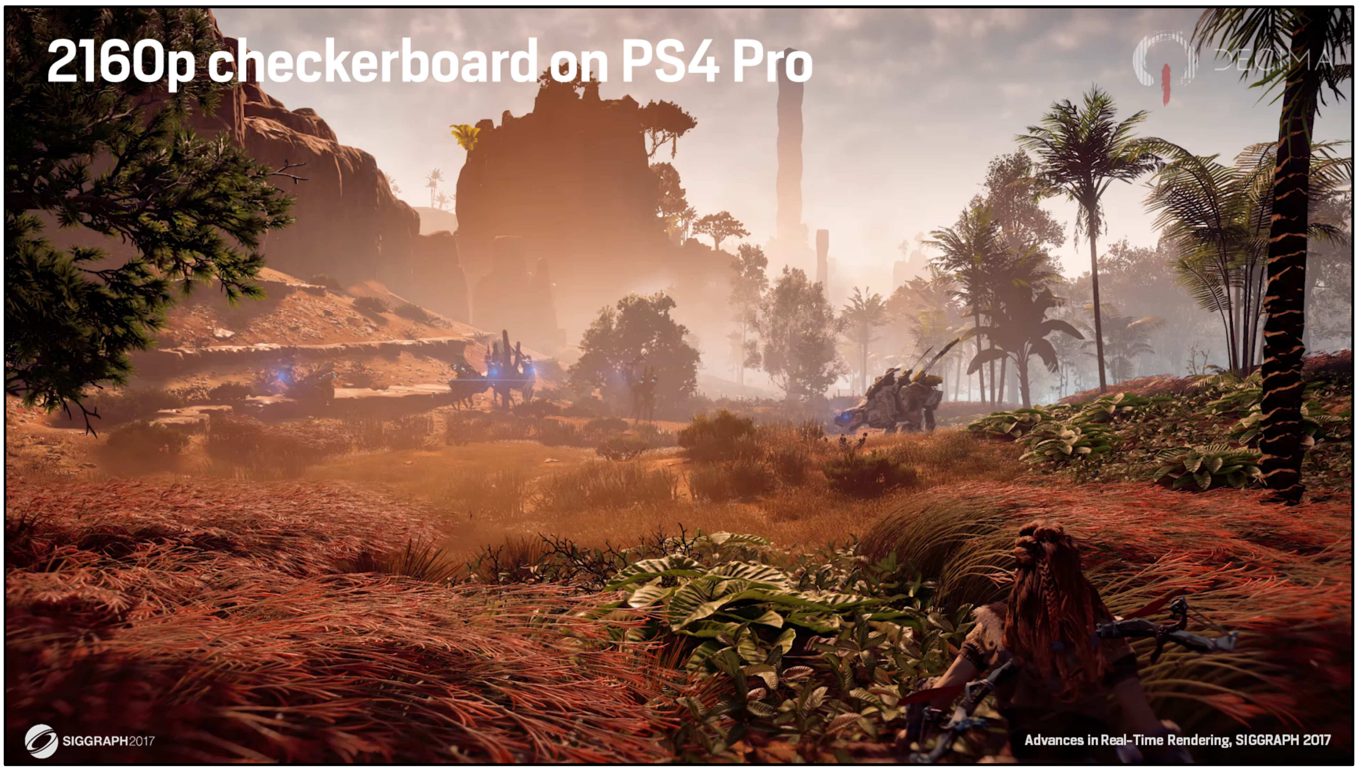
Ok, so how does this compare to our checkerboard rendering?

2160p checkerboard on PS4 Pro



Well, our checkerboard implementation (that you now see on the left) also runs at 30 fps, just like the native 1512p mode, but it's clearly more detailed.
In fact, it shows all the details that are also visible in the reference.

But when you compare the sharpness of our checkerboard result to the 16x supersampled reference, you do see a difference.
This is an inherent property of how we do checkerboard rendering:
It values more detail over more sharpness.
And we prefer it that way, if we're forced to choose between the two.
Sharpness is great when you're looking at imagery from close by.
But actual detail tends to be visible, or at least be hinted at, over a wider range of viewing distances,
And it also contributes more to the final image quality when having to downscale to a 1080p TV, for example.



2160p checkerboard on PS4 Pro

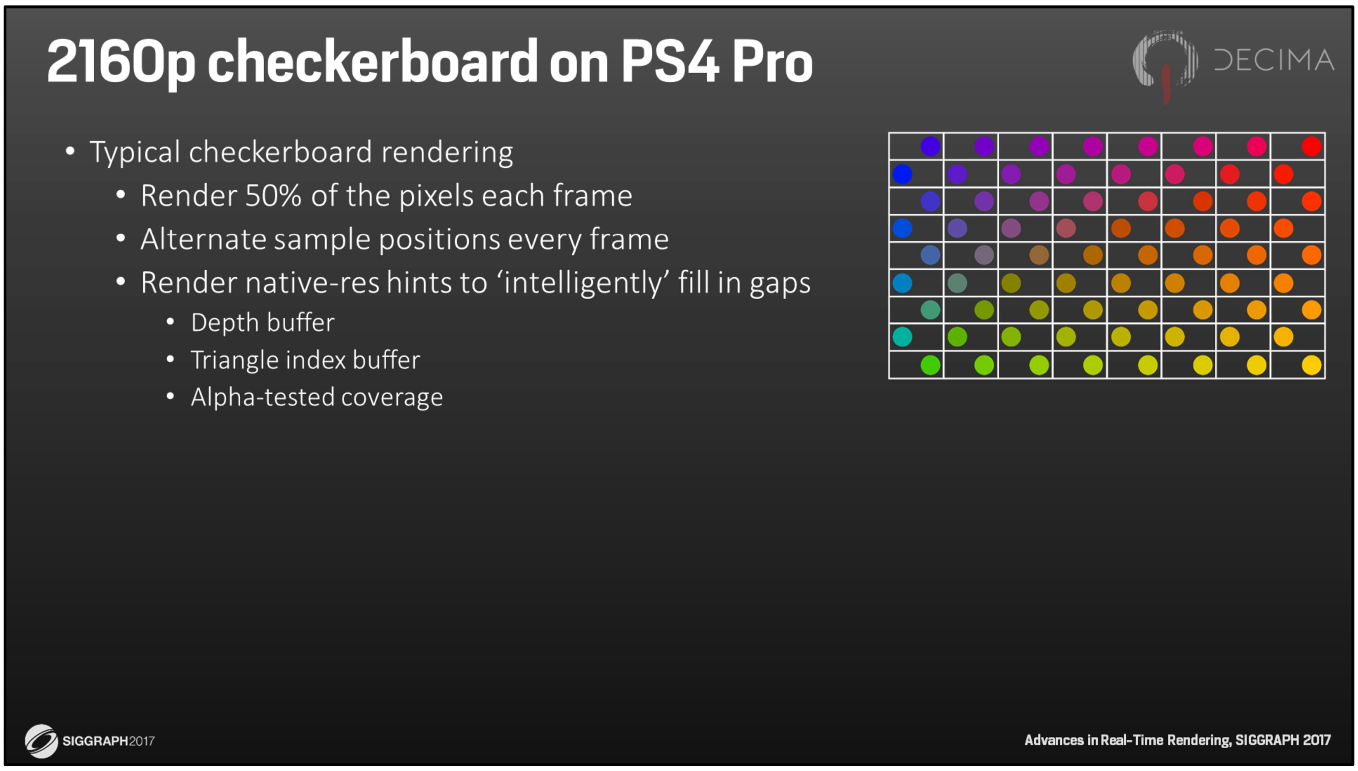
Our checkerboard solution is also quite stable TEMPORALLY.
Here's a quick comparison.

Let's start with the exact same scene as shown before, in 1080p with FXAA+TAA.

And this rendered with our 2160p checkerboard rendering.
And notice how similar it is in visual stability.

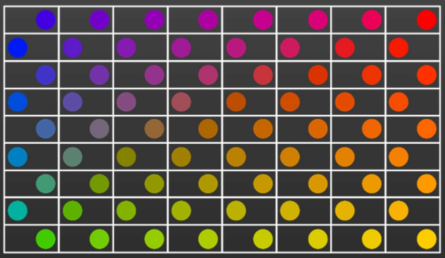
And again, 1080p.

And 2160p.



2160p checkerboard on PS4 Pro

- Typical checkerboard rendering
  - Render 50% of the pixels each frame
  - Alternate sample positions every frame
  - Render native-res hints to 'intelligently' fill in gaps
    - Depth buffer
    - Triangle index buffer
    - Alpha-tested coverage



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Alright, so how does this work?

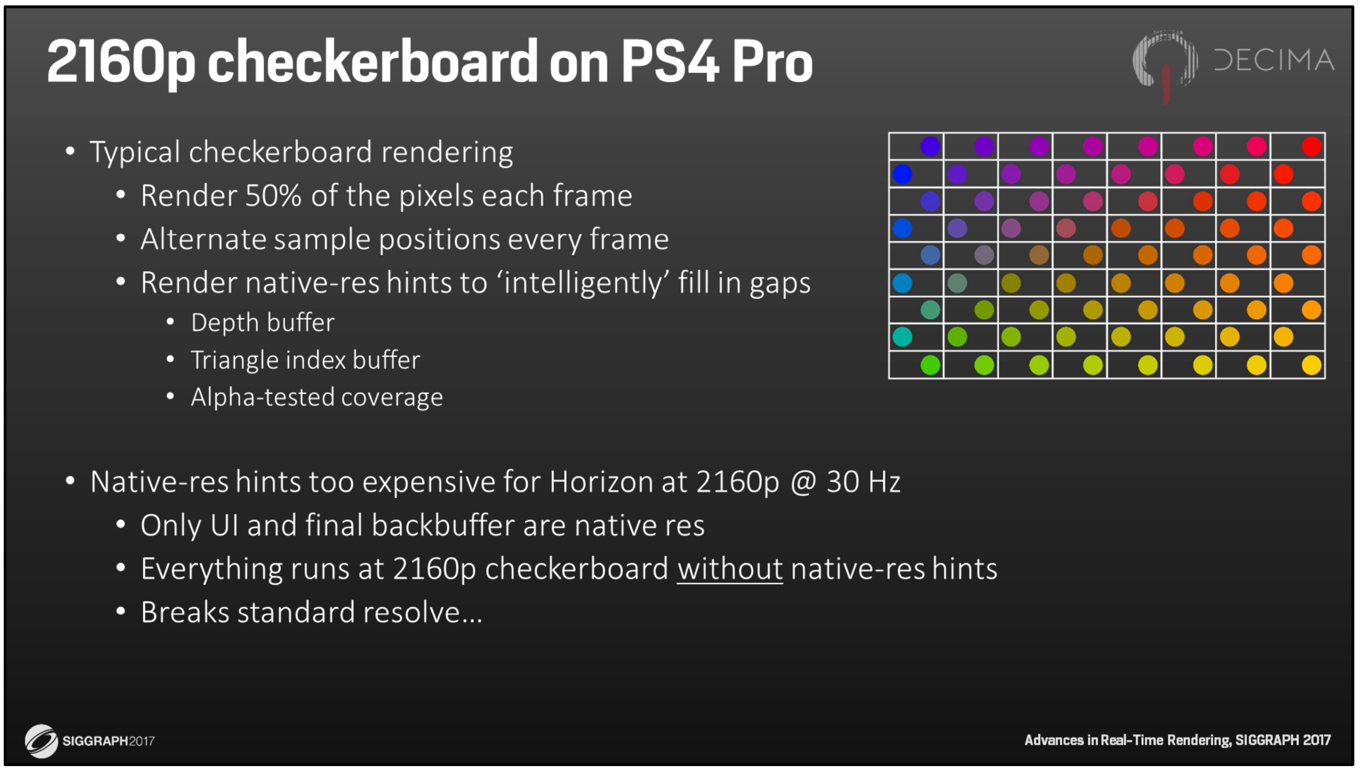
Well, with checkerboard rendering you typically SHADE only 50% of the pixels.

The other 50% is shaded next frame.

So, ideally, you get a native-res result after two frames.

However, dynamic scenes complicate this process quite a bit.

That's why you'd typically ALSO render NATIVE-res hints EACH FRAME.
Hints like depth, or PrimID.
And to complicate this even further:
Alpha-tested and alpha-blended objects may still need to be sampled and processed at native res, each frame.



2160p checkerboard on PS4 Pro

- Typical checkerboard rendering
  - Render 50% of the pixels each frame
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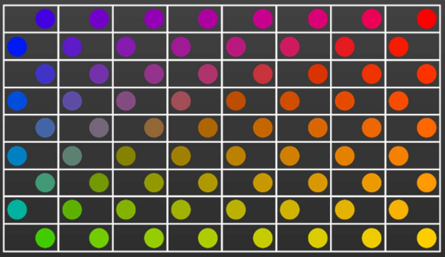
    - Depth buffer
    - Triangle index buffer
    - Alpha-tested coverage



- Native-res hints too expensive for Horizon at 2160p @ 30 Hz
  - Only UI and final backbuffer are native res
  - Everything runs at 2160p checkerboard without native-res hints
  - Breaks standard resolve…

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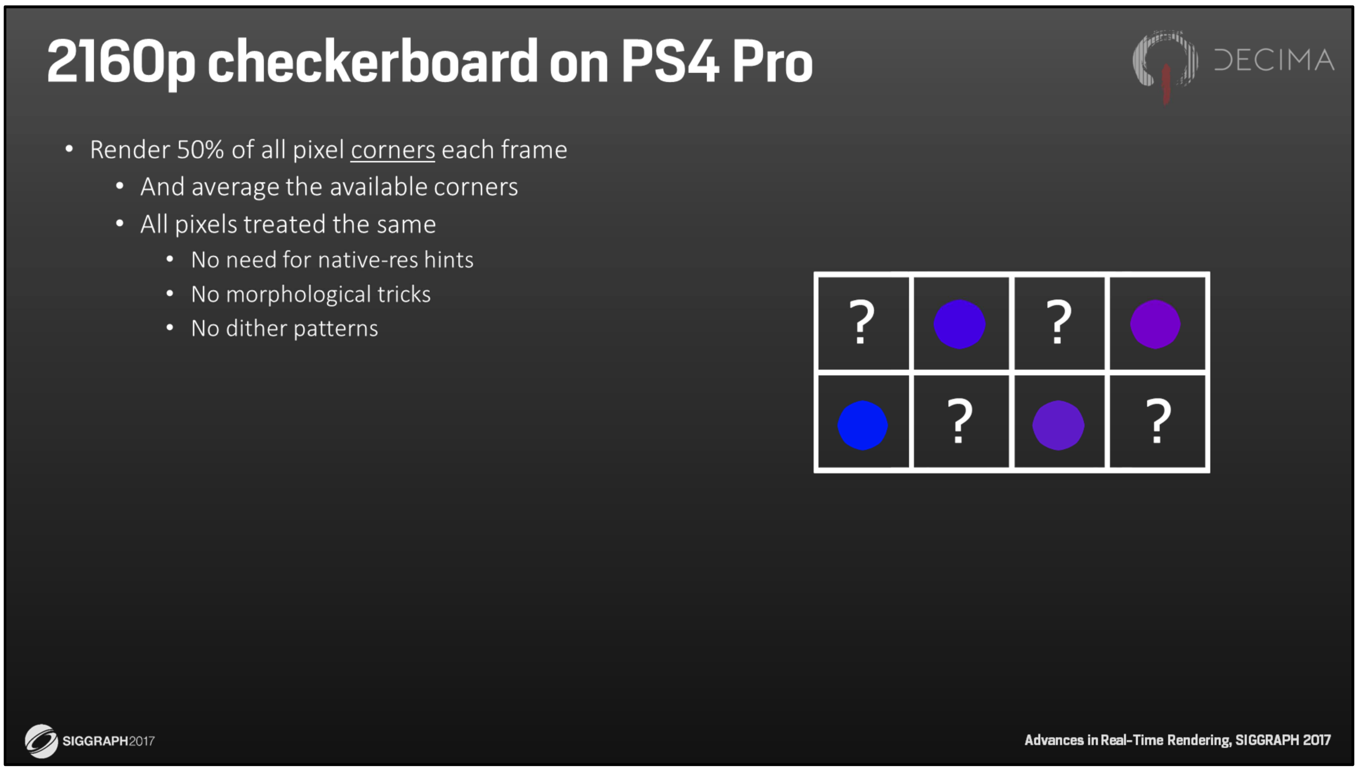
All that native-res overhead prevented us from running Horizon at 30 fps.

Obviously, we could have done what many other titles do, and that is to simply render at checkerboarded 1800p instead.
And maybe that would have given us a similar or even better sharpness, but the images would've been less detailed and would have gotten a more filtered look.
So instead, we chose to look for a way that still gave us the detail level of 2160p and would still run at 30 fps, but at the cost of sacrificing some of the potential sharpness.

We eventually found a way to do that, and we ended up removing all native-res hints, and only used native-res buffers for the UI and for the final backbuffer.
Everything else ran at checkerboard resolution, including alpha-tested objects, alpha-blended objects and post effects.
Well, except for some FXs that always ran at a lower resolution anyway.

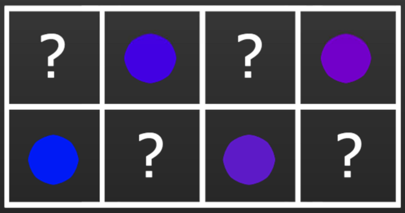
Doing all that took care of the performance problems. But we still had to find a way to resolve the checkerboard data without the typical native-res hints. And we found some inspiration in the way we do TAA in 1080p.



2160p checkerboard on PS4 Pro

DECIMA

- Render 50% of all pixel corners each frame
  - And average the available corners
  - All pixels treated the same
    - No need for native-res hints
    - No morphological tricks
    - No dither patterns



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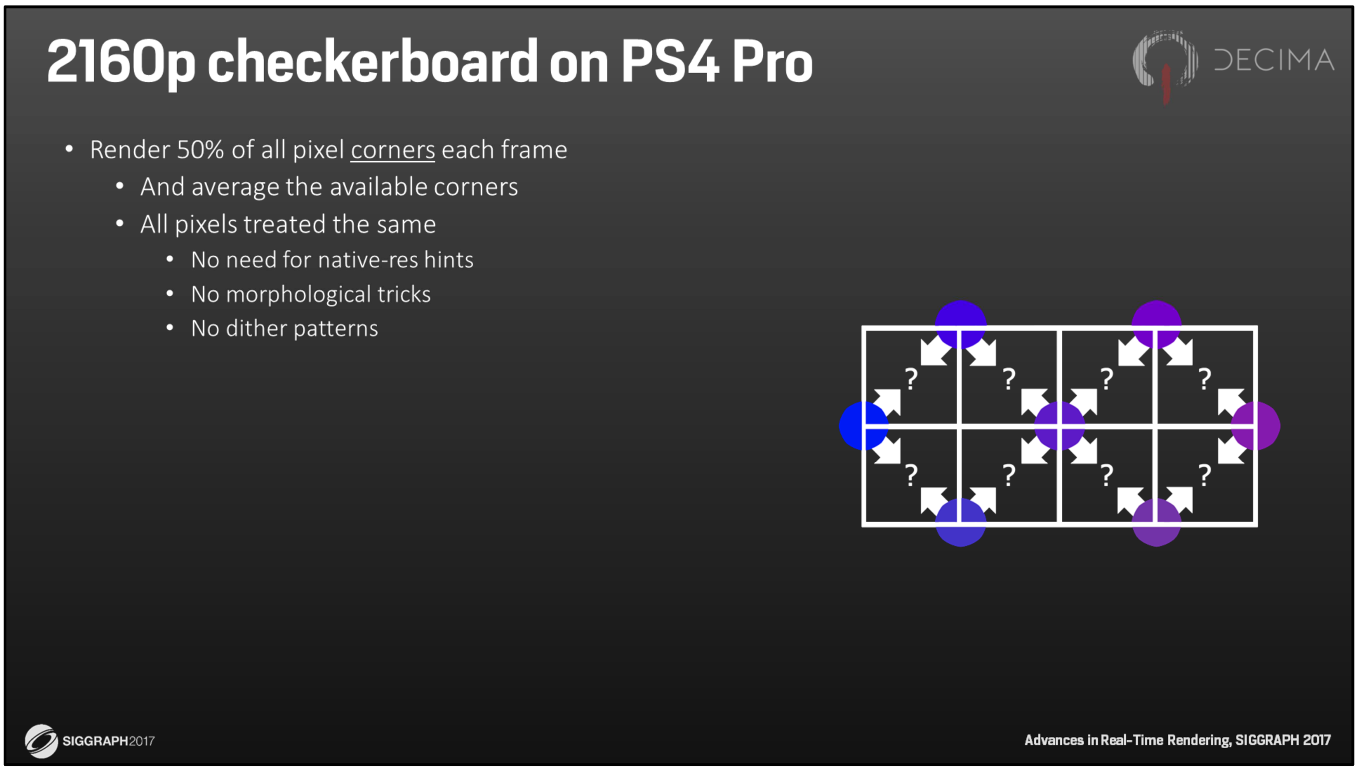
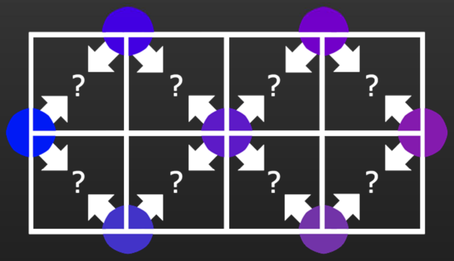
Normally, checkerboard rendering is used to render 50% of the pixel CENTERS.
And the other 50% procent is then guessed based on the native-res hints, the history buffer and the current checkerboard buffer.



2160p checkerboard on PS4 Pro

- Render 50% of all pixel corners each frame
  - And average the available corners
  - All pixels treated the same
    - No need for native-res hints
    - No morphological tricks
    - No dither patterns



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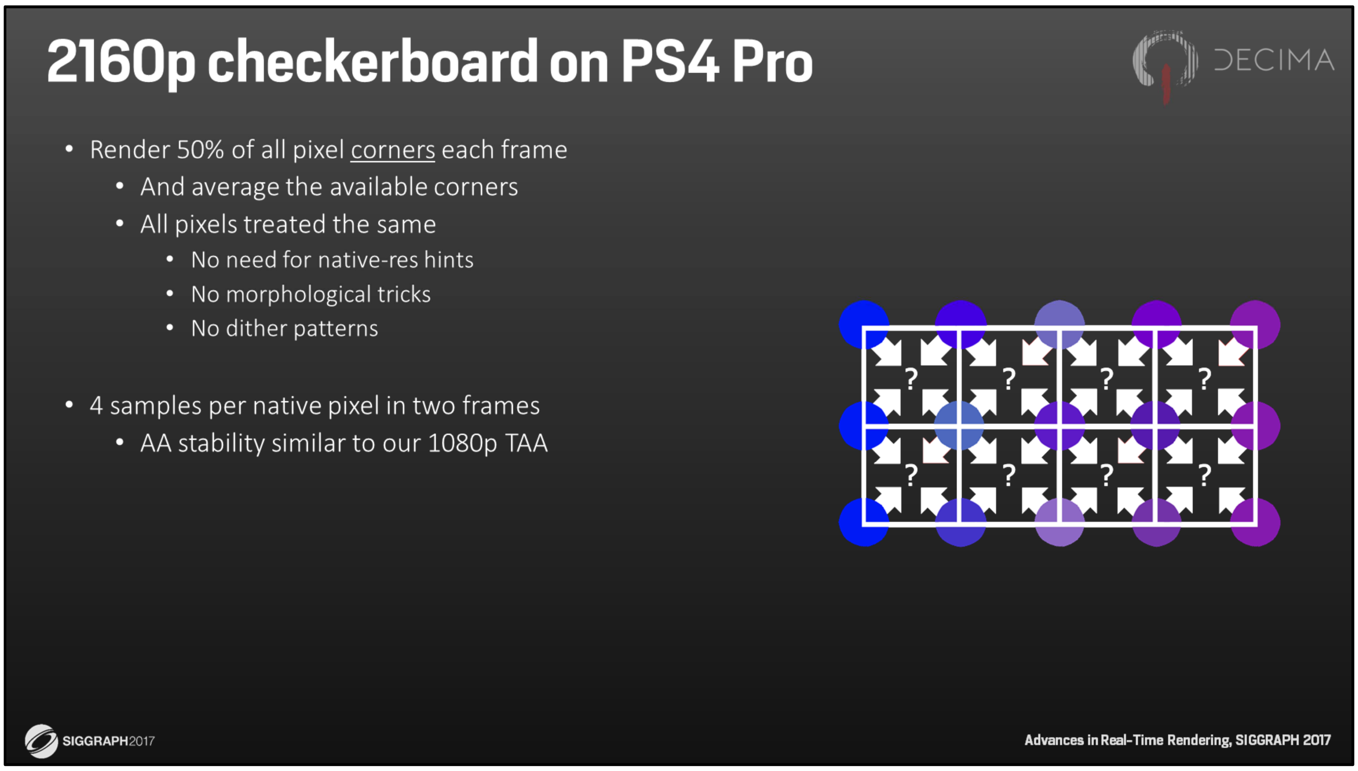
What we do instead is that we render 50% of the pixel CORNERS.

This gives us 2 samples for each pixel to work with, instead of only 1 sample per 2 pixels.
And so, we can simply average the two closest CORNER samples to get the value at the pixel CENTER.

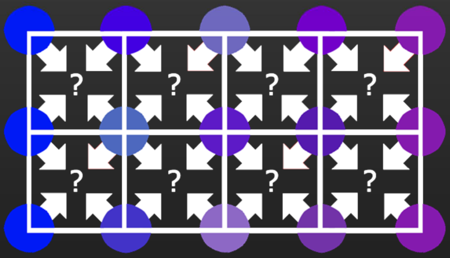
What's more is that this requires no native-res hints, and not even any morphological tricks.
And because every pixel is now treated with the same approach, we implicitly prevent the dither artefacts that are often associated with checkerboard rendering.

And after two frames, ...



2160p checkerboard on PS4 Pro

- Render 50% of all pixel corners each frame
  - And average the available corners
  - All pixels treated the same
    - No need for native-res hints
    - No morphological tricks
    - No dither patterns
- 4 samples per native pixel in two frames
  - AA stability similar to our 1080p TAA



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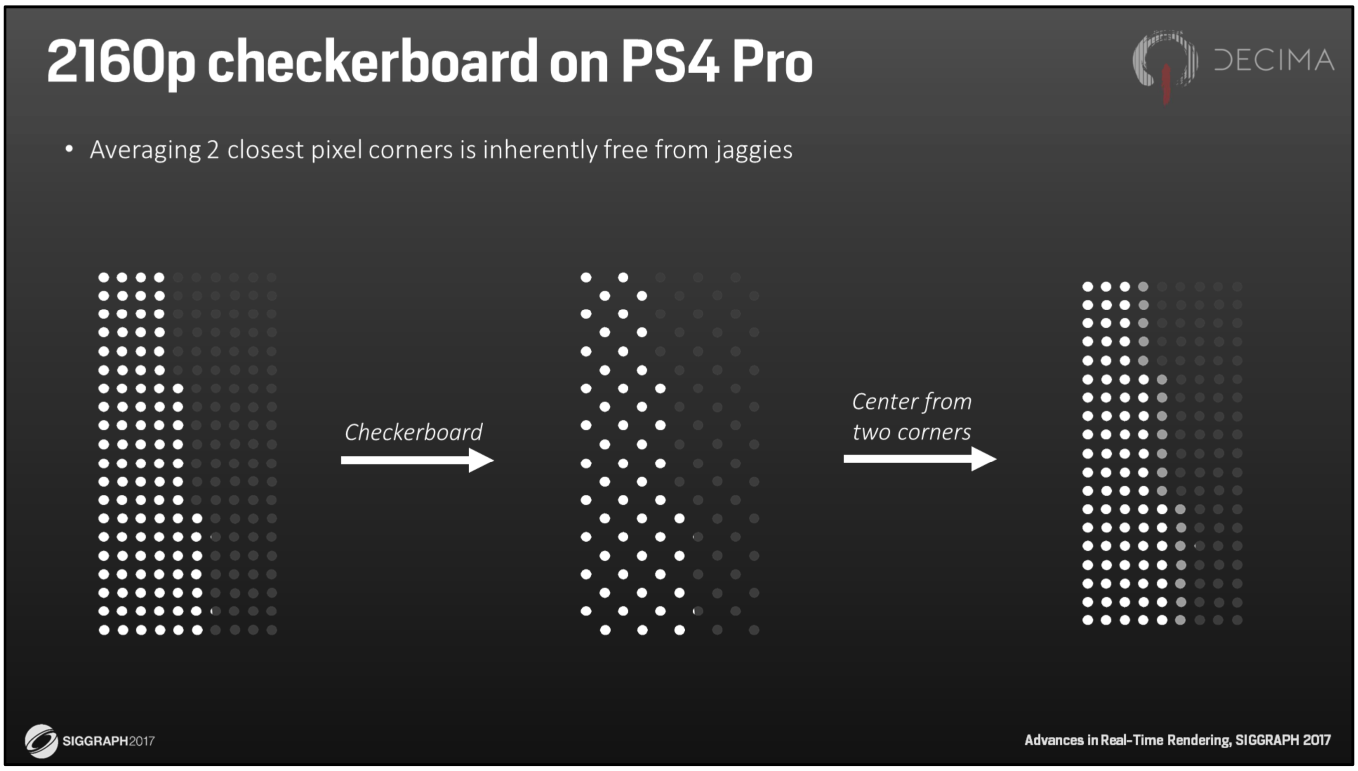
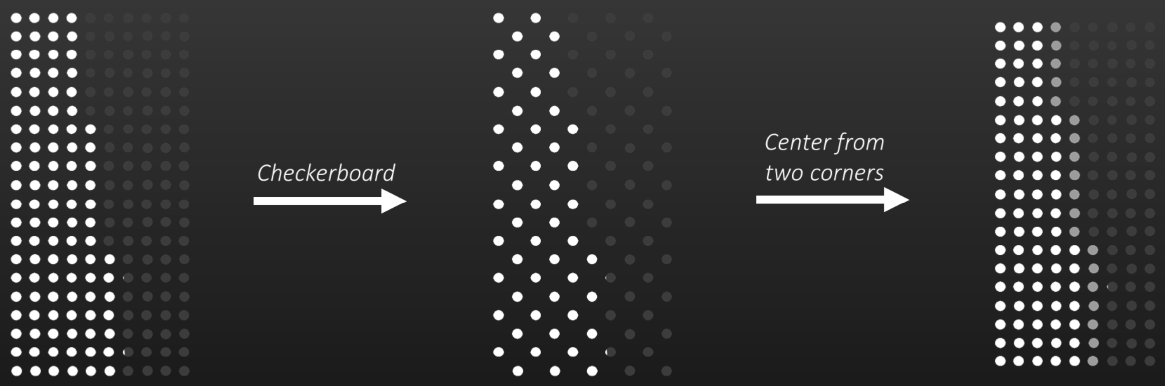
... it gives us 4 samples per pixel, resulting in the same AA STABILITY that our TAA gave us at 1080p.
One difference though, is that our TAA works with samples on the EDGES of pixels, while this works on the CORNERS.

Doing the checkerboard resolve like this is fast and clean, and after TWO frames, it contains all 2160p details you'd expect from a native 2160p render.
But even with only a single frame, the results are pretty decent.



2160p checkerboard on PS4 Pro

- Averaging 2 closest pixel corners is inherently free from jaggies



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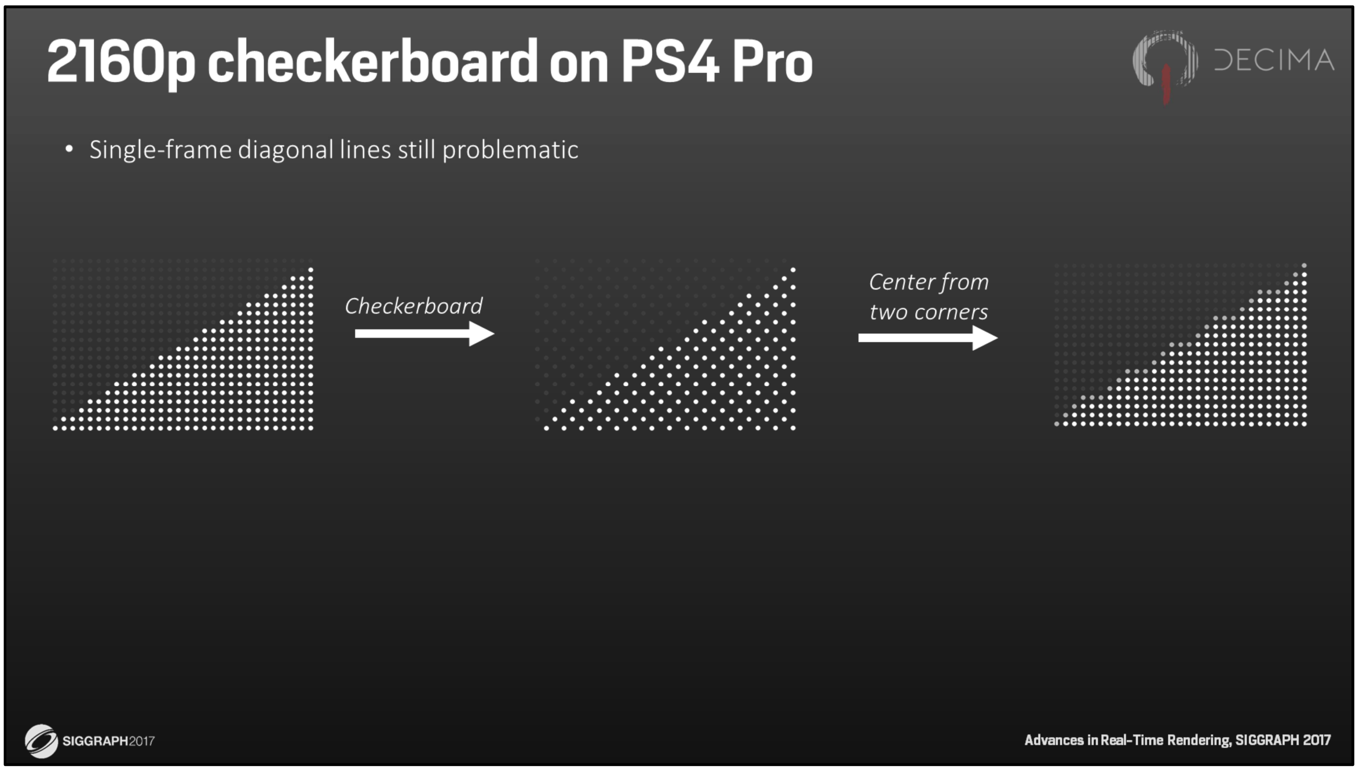
Here’s an example.

On the left, you see a near-vertical feature at native-res.

But with checkerboard rendering you actually only render what you see in the middle.

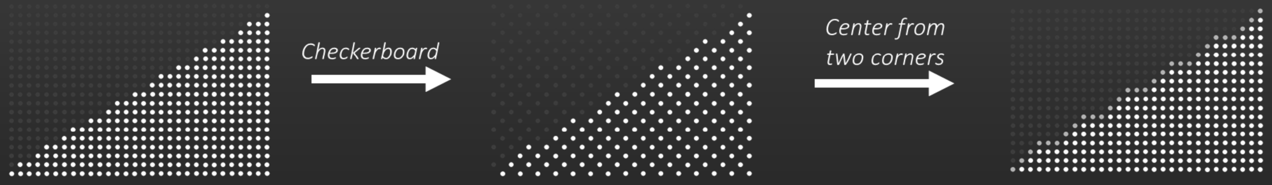
After resolving the pixel centers by averaging the two closest pixel corners, you get what you see on the right.
Notice that it’s pretty close to the one on left.

The only difference is that it’s slightly less sharp. But, again, that’s inherent to our technique.



2160p checkerboard on PS4 Pro

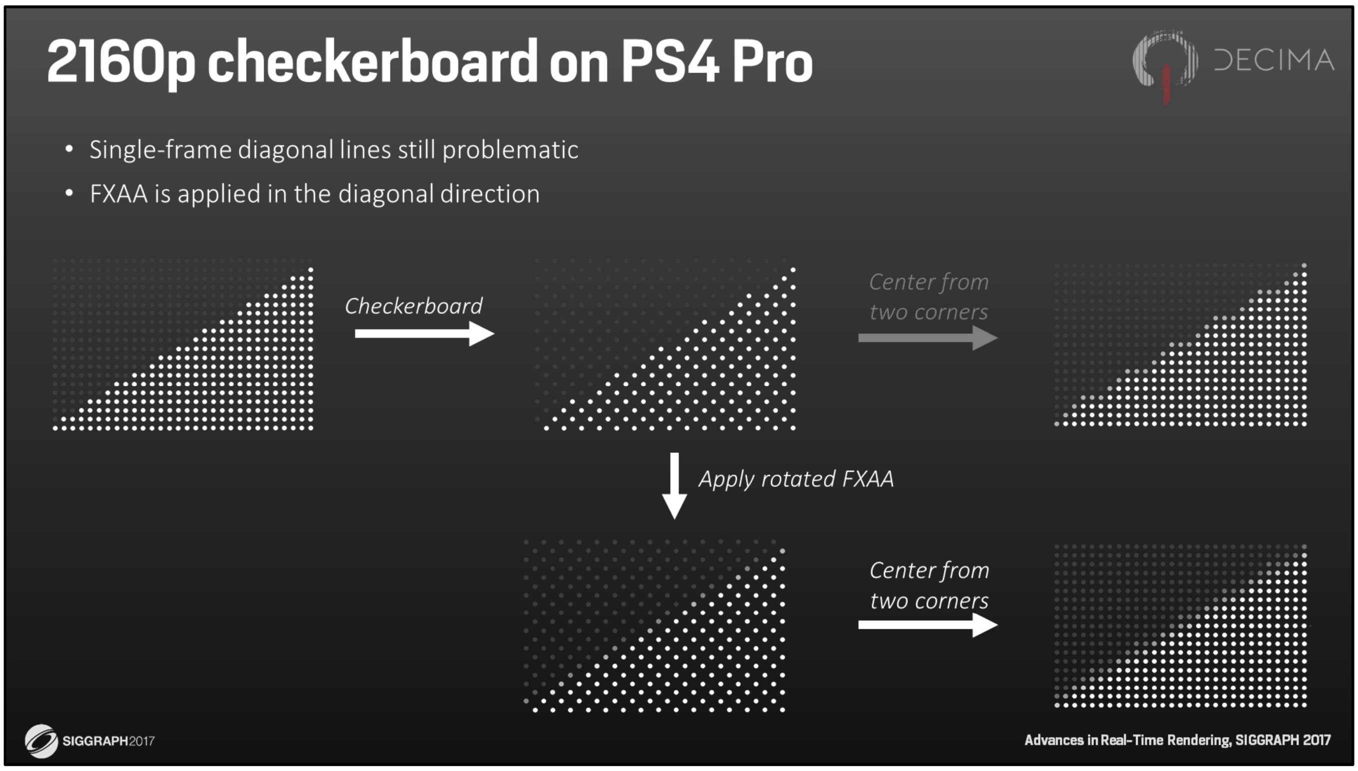
- Single-frame diagonal lines still problematic



In general, this trick already works pretty well.
And it's a clear step up compared to our 1080p solution.

But it can use some extra work on diagonal lines.
That's because the diagonal direction is the sparsest direction in checkerboard rendering.

In this example you see here, you clearly see that the 'corner resolve' can still lead to a somewhat jagged look of the diagonal line.



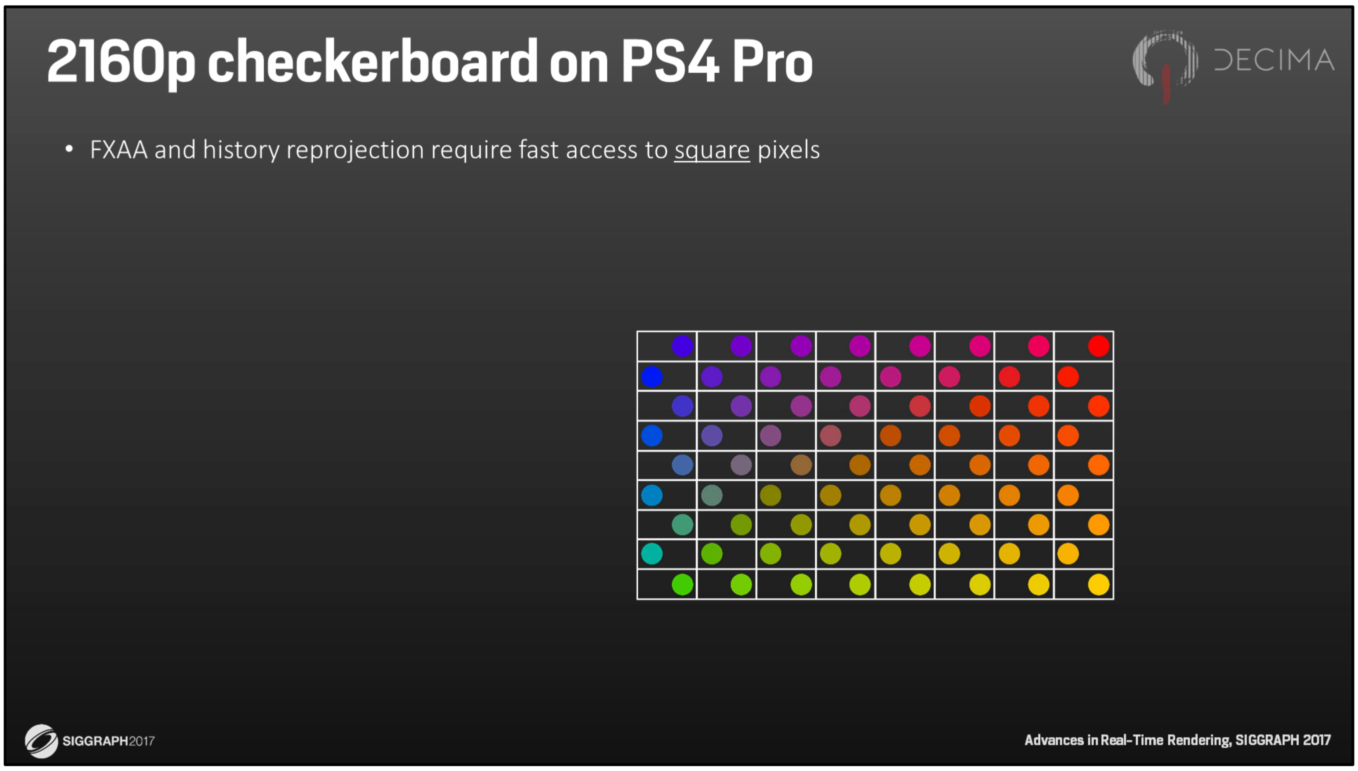
2160p checkerboard on PS4 Pro

- Single-frame diagonal lines still problematic
- FXAA is applied in the diagonal direction

To solve this, we run FXAA before we apply the corner resolve.
And looking at the bottom right, you can clearly see that this helps quite a bit.

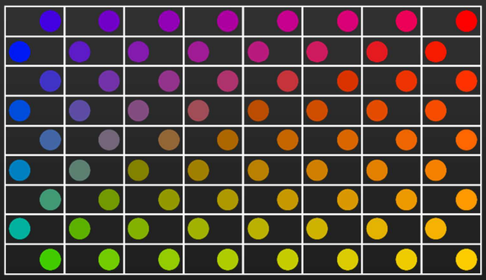
Notice that we apply FXAA on the checkerboard pixels, not on the resolved native-res pixels.
That's because it's twice as fast that way, but also because it works a lot better.
Especially because we also trick FXAA to focus on the diagonal lines instead of the more typical horizontal and vertical lines.

We do this by effectively rotating its input. And here's how.



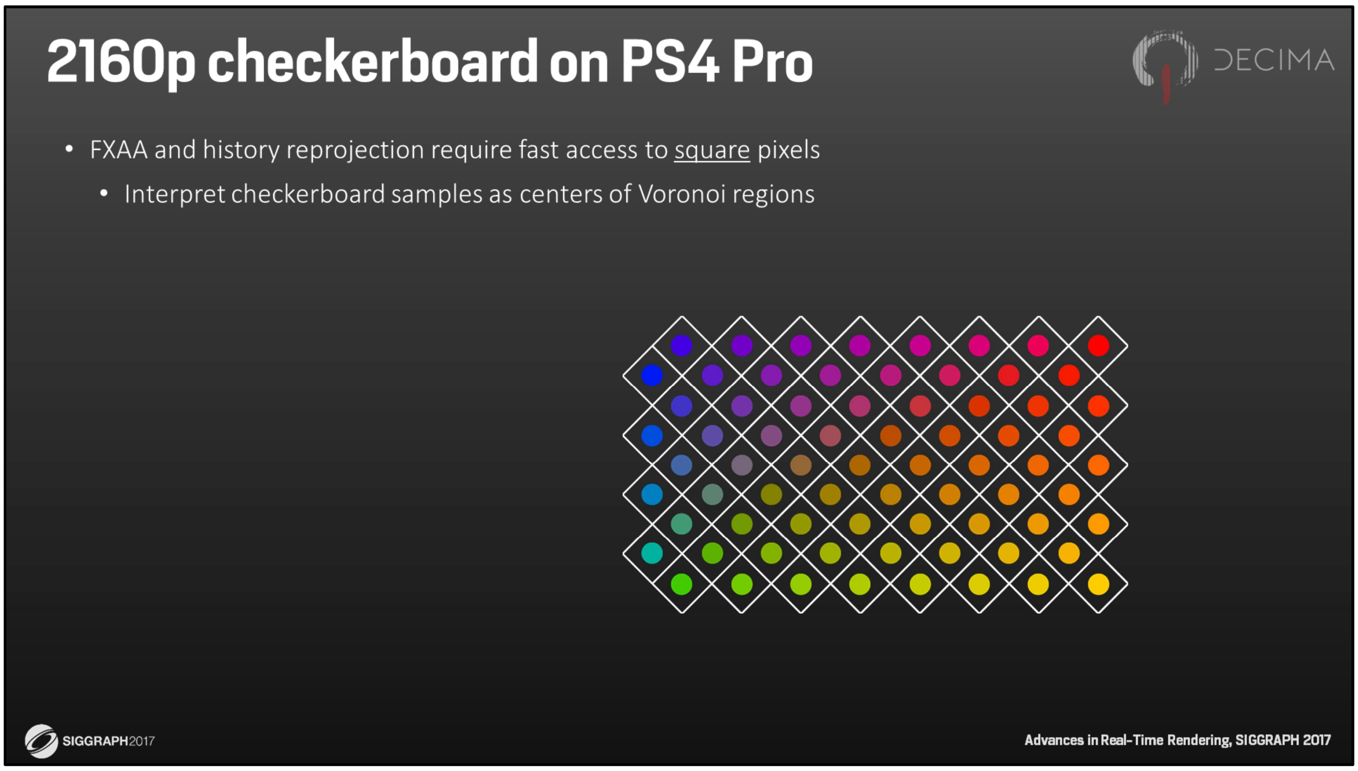
2160p checkerboard on PS4 Pro

- FXAA and history reprojection require fast access to square pixels



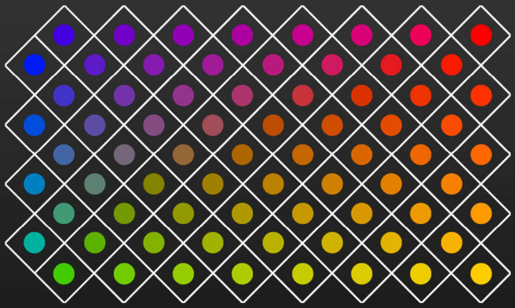
To apply FXAA, and to reproject the checkerboard render from the previous frame, we don't want to use the checkerboard data directly.
That's because pixels aren't square in checkerboard rendering. They're elongated and behave sort of zigzaggy.
But there is a trick we can use to interpret and interpolate this more meaningfully.

When we only look at the checkerboard sample positions and the Voronoi regions they create, ...



2160p checkerboard on PS4 Pro

- FXAA and history reprojection require fast access to square pixels
  - Interpret checkerboard samples as centers of Voronoi regions



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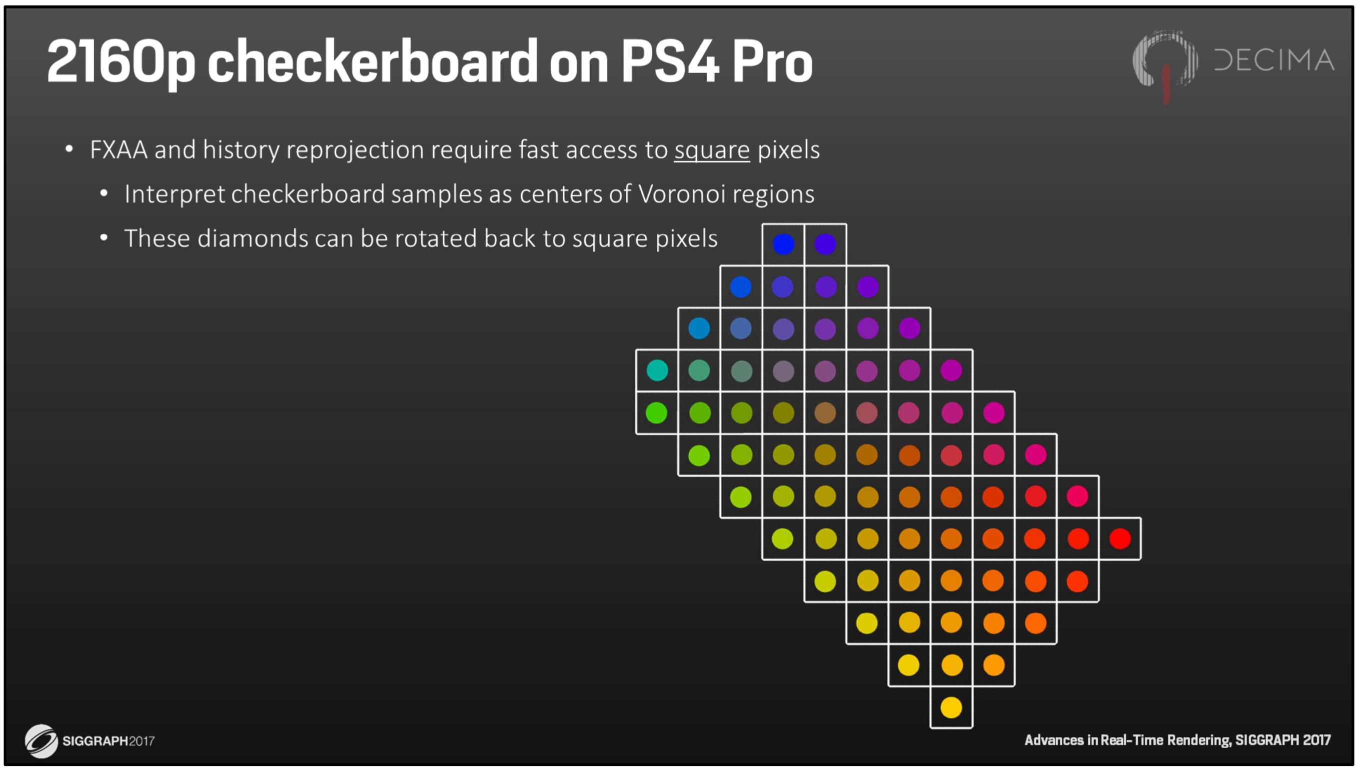
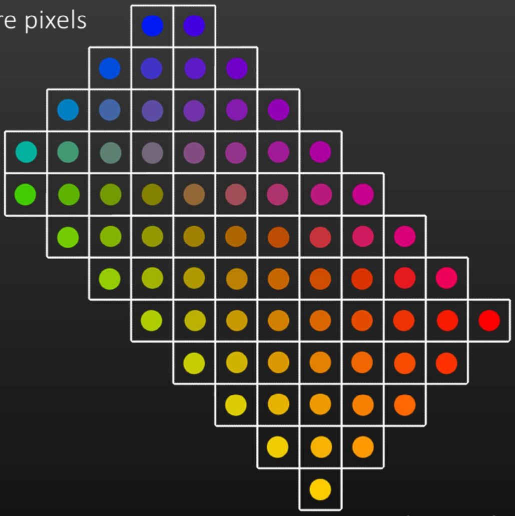
... we can interpret checkerboard samples as pixels, rotated by 45 degrees.



2160p checkerboard on PS4 Pro

- FXAA and history reprojection require fast access to square pixels
  - Interpret checkerboard samples as centers of Voronoi regions
  - These diamonds can be rotated back to square pixels



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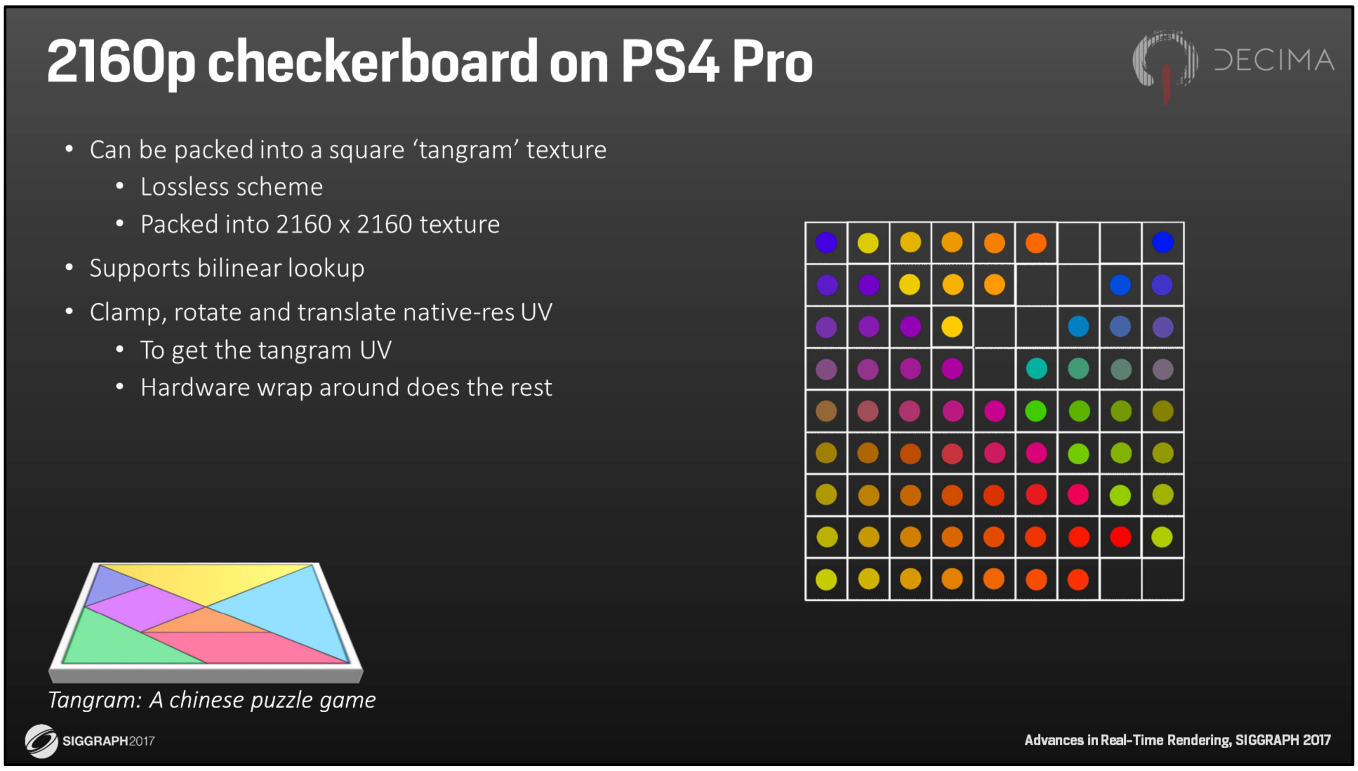
But when we rotate the framebuffer by 45 degrees as well, we end up with square pixels again.

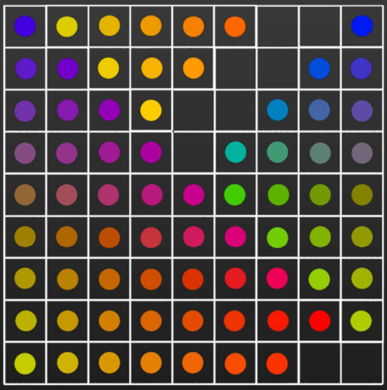
So if we could store a rotated framebuffer instead, we could simply use that to sample using bilinear filtering, apply FXAA, and do a plain reprojection again.

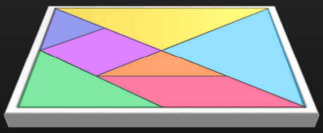
The downside, of course, is that this doesn't look like regular buffer or texture anymore. But we can fix that.



2160p checkerboard on PS4 Pro

- Can be packed into a square 'tangram' texture
  - Lossless scheme
  - Packed into 2160 x 2160 texture
- Supports bilinear lookup
- Clamp, rotate and translate native-res UV
  - To get the tangram UV
  - Hardware wrap around does the rest





Tangram: A chinese puzzle game

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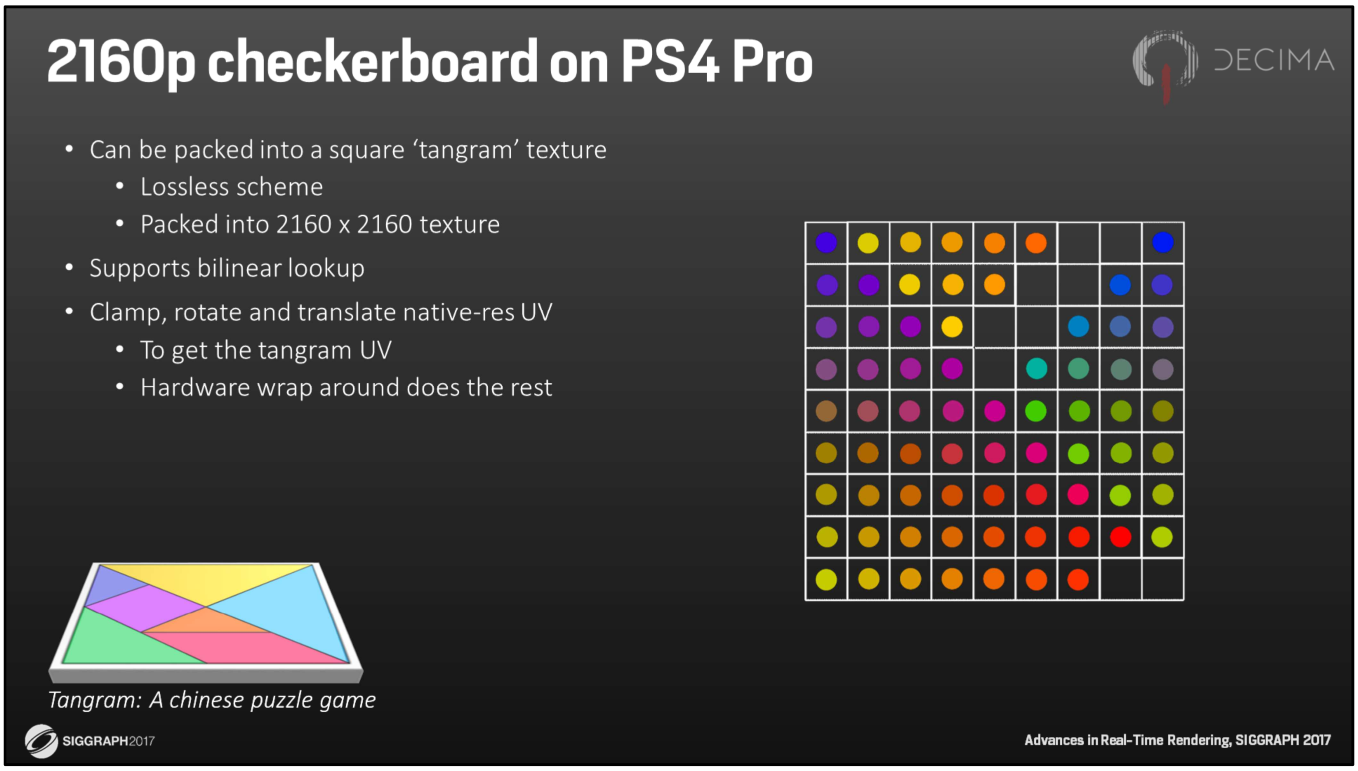
We can transform this rotated buffer into what we call a 'tangram'. We call it a tangram because it's sort of like that so-called puzzle game.

We can cut the rotated buffer into parts and shuffle them around like so.
The nice thing about that is that it's completely lossless, and allows the 2160p checkerboard data to be packed into a compact 2160x2160 texture again. And it also still supports bilinear sampling.
And because of the exact way we placed these parts, we can use the built-in texture-wrap hardware to do the unwrapping for us, without any additional logic or shader instructions during sampling.

The only thing required during sampling is rotating the native-res UV by 45 degrees, and offsetting this by an offset that's constant per frame.



2160p checkerboard on PS4 Pro

DECIMA

- Can be packed into a square 'tangram' texture
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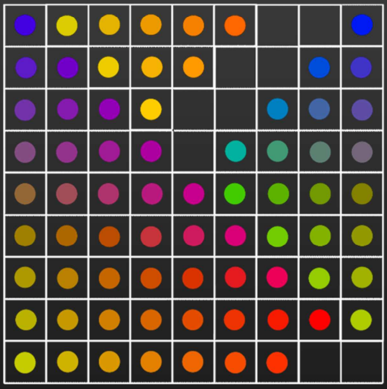

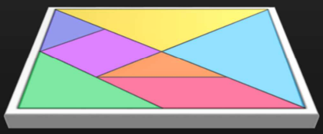

Tangram: A chinese puzzle game

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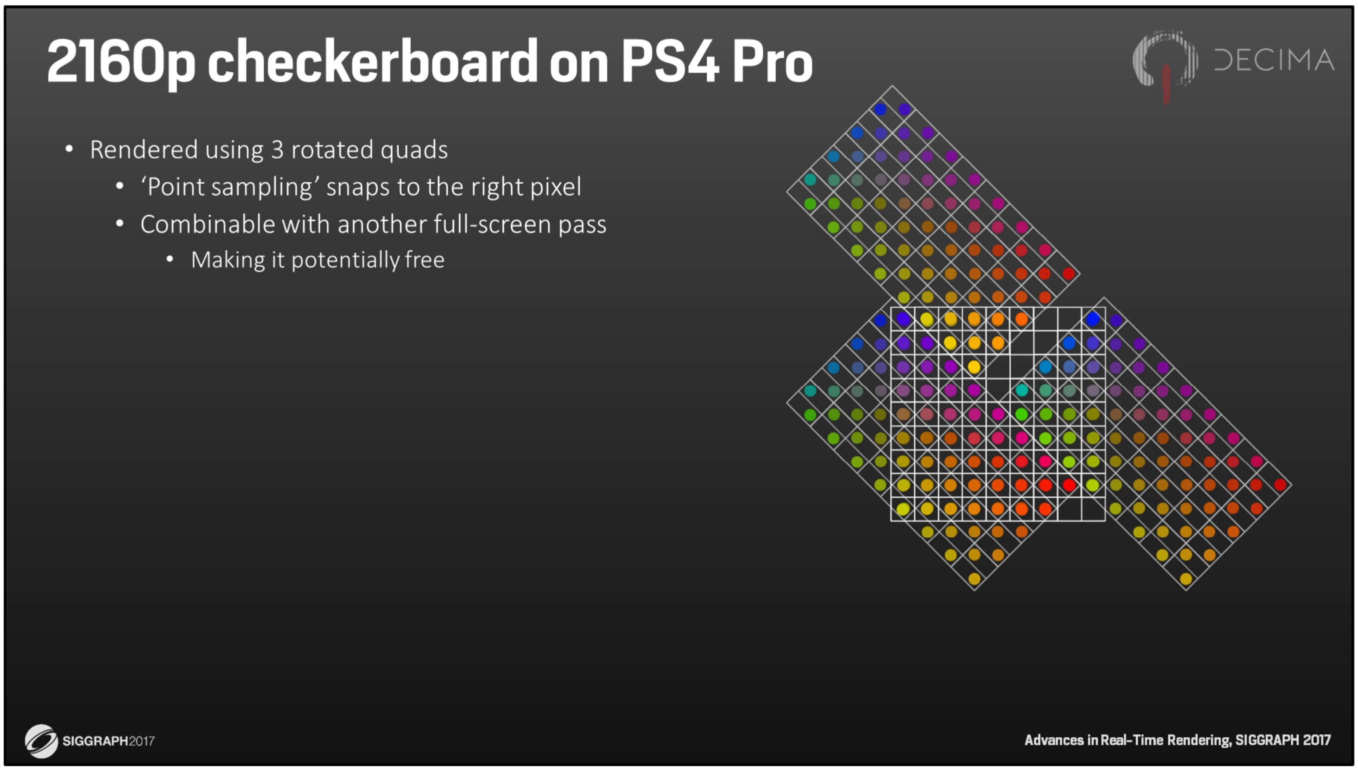
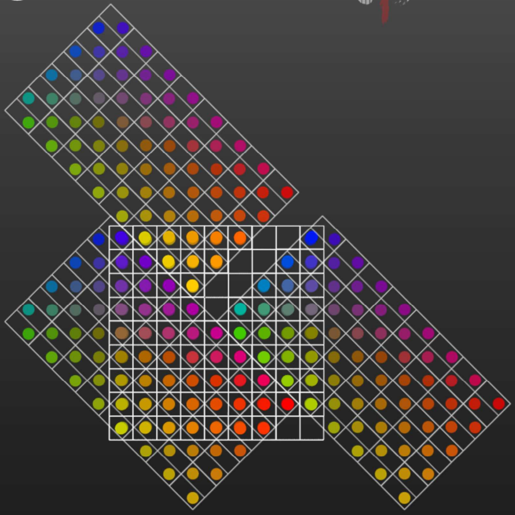
You may have noticed there's actually some padding in this tangram as well.
That's a side offect of this exact shuffling and is required to make the wrap around work correctly.
But as a result, a tangram takes up 12% more memory than a regular checkerboard buffer.

And yet it doesn't take up any more bandwidth, because there's simply no reason to sample the padding.



2160p checkerboard on PS4 Pro

- Rendered using 3 rotated quads
  - ‘Point sampling’ snaps to the right pixel
  - Combinable with another full-screen pass
    - Making it potentially free



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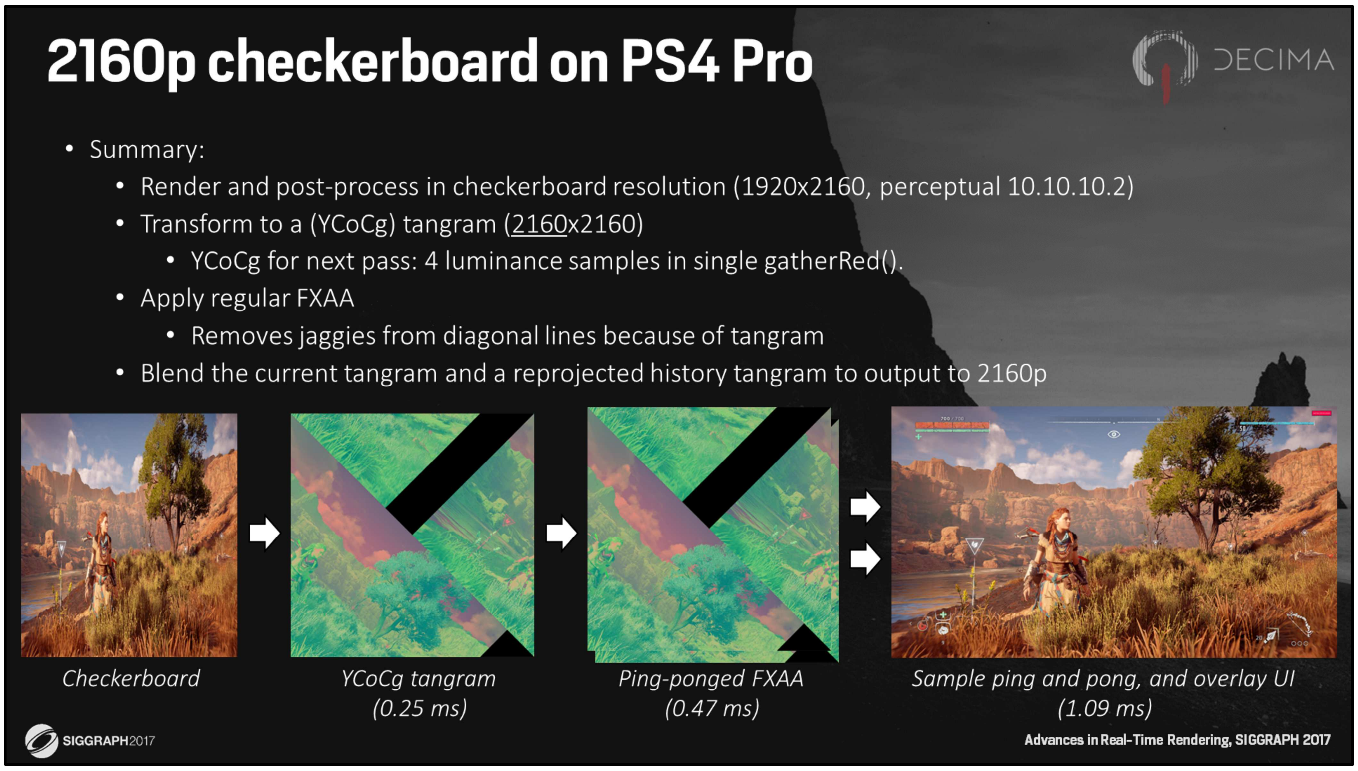
There’s also no need to write to the padding areas.
In fact, a tangram can be rendered using only 3 precisily positioned quads.
That way, every checkerboard pixel is rendered exactly to one position in the tangram.

Depending on the pipeline, it may even be possible to apply this process from within an already existing full-screen pass, making this tangram transform virtually free.



2160p checkerboard on PS4 Pro

- Summary:
  - Render and post-process in checkerboard resolution (1920x2160, perceptual 10.10.10.2)
  - Transform to a (YCoCg) tangram (2160x2160)
    - YCoCg for next pass: 4 luminance samples in single gatherRed().
  - Apply regular FXAA
    - Removes jaggies from diagonal lines because of tangram
  - Blend the current tangram and a reprojected history tangram to output to 2160p

Checkerboard → *YCoCg tangram (0.25 ms)* → *Ping-ponged FXAA (0.47 ms)* → *Sample ping and pong, and overlay UI (1.09 ms)*

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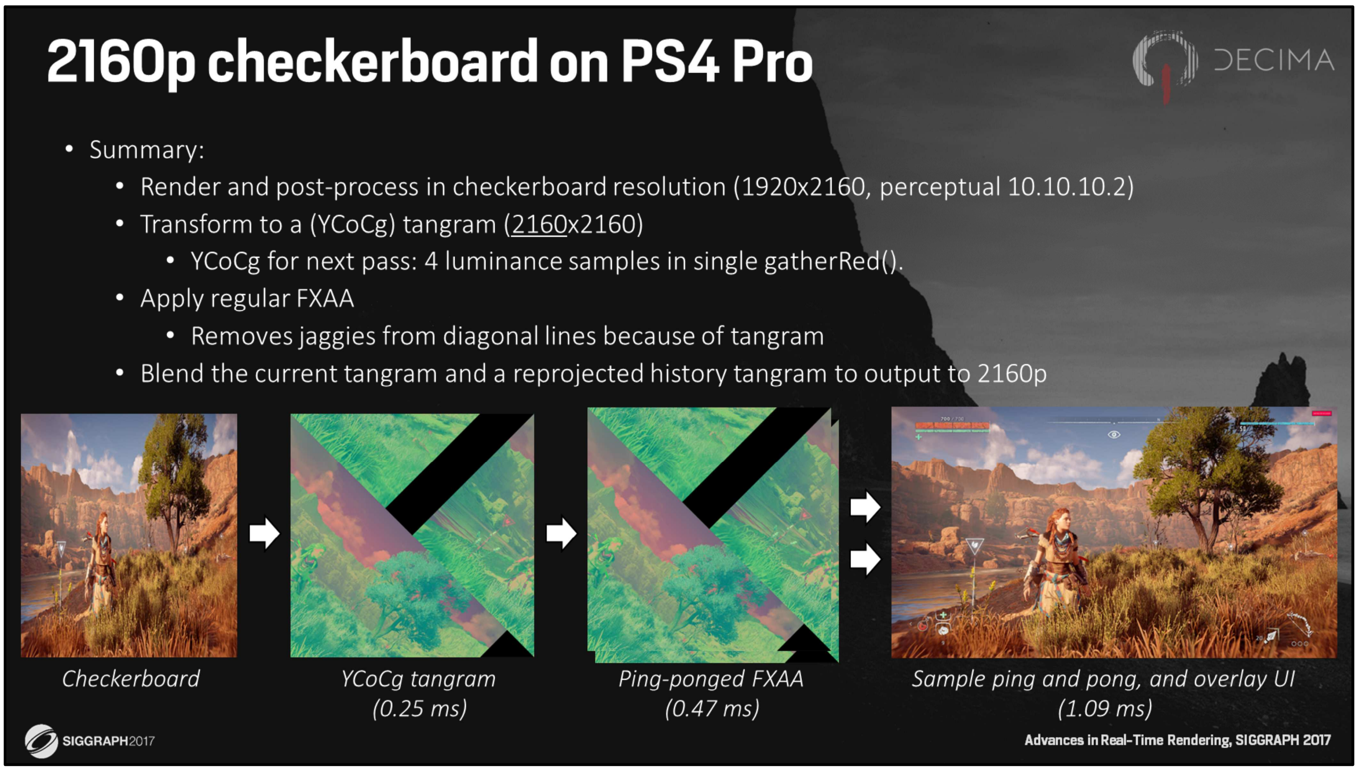
So to finish this topic, let me summarize our checkerboarded rendering approach:

- We first render in checkerboard resolution without any native-res hints. We also apply all post effects at that point, do the tonemapping, encode the output in either sRGB or PQ, and store the result in a 10-bit format.

- We then transform that into a tangram, and we store that in YCoCg color space.

- The YCoCg tangram is then sampled by the FXAA pass, which outputs a new tangram. The reason we use YCoCg is because FXAA does most of its work on luminance data, and this allows us to sample 4 luminance values per texture gather.

- The output of the FXAA pass is stored in a ping-ponged buffer, giving us the current and previous frame to resolve from.



2160p checkerboard on PS4 Pro

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As a final pass, we take the current and previous tangram, convert back to RGB, and reject or reproject based on standard criteria.
If history is to be rejected, we only sample the current tangram, giving us effectively 2 samples per pixel.
And if history is accepted, we blend the previous and current value 50/50, and we end up with effectively 4 samples per pixel.
And conceptually, this last part is quite similar to our TAA solution in 1080p, but without the sharpening.

And that’s how we resolve in checkerboard mode in less than 2 milliseconds.

Topics

- GGX spherical area light
- Height fog
- AA in 1080p
- 2160p checkerboard on PS4 Pro

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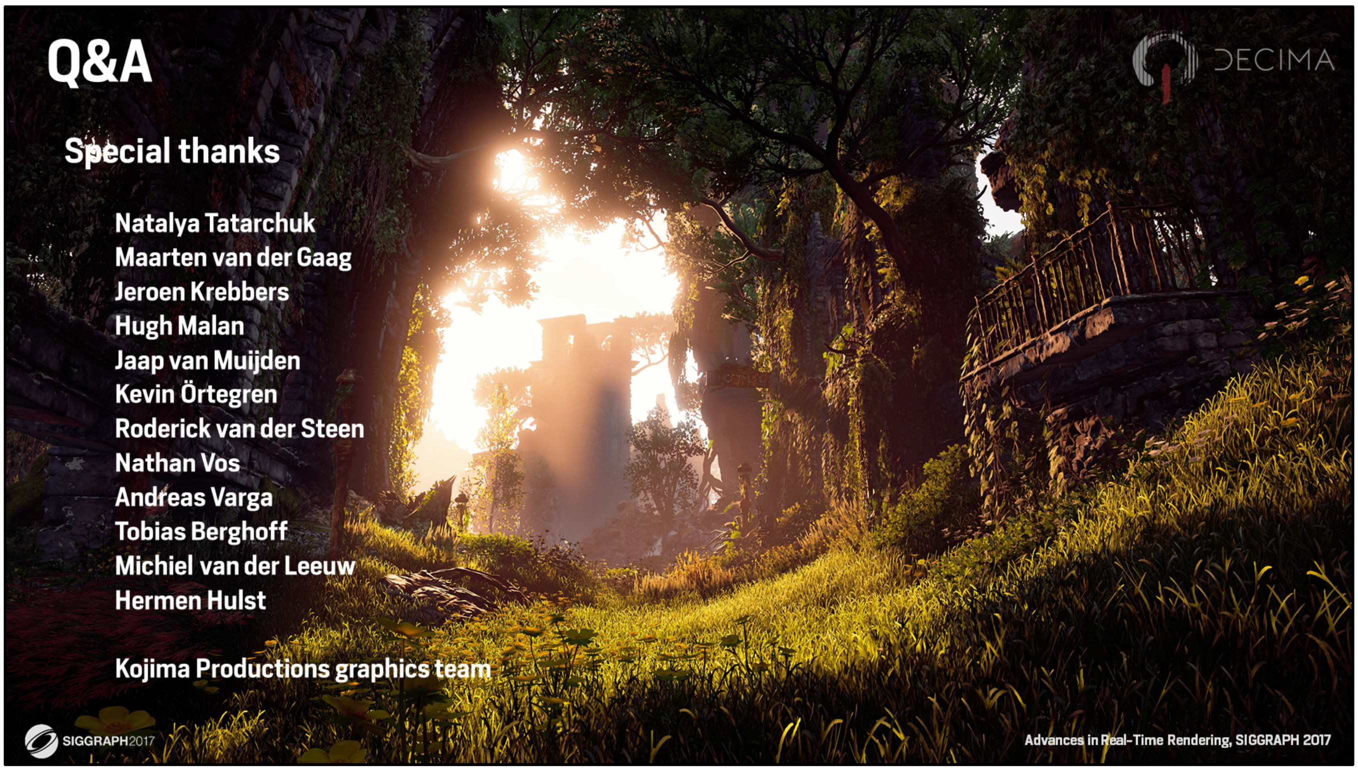
And that was also the end of the material we wanted to present today.

Obviously, some details had to be were left out for brevity.
But for those who are interested, be sure to download this presentation and check out the references and detailed code snippets at the end of this slide deck.



Q&A

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Hermen Hulst

Kojima Productions graphics team

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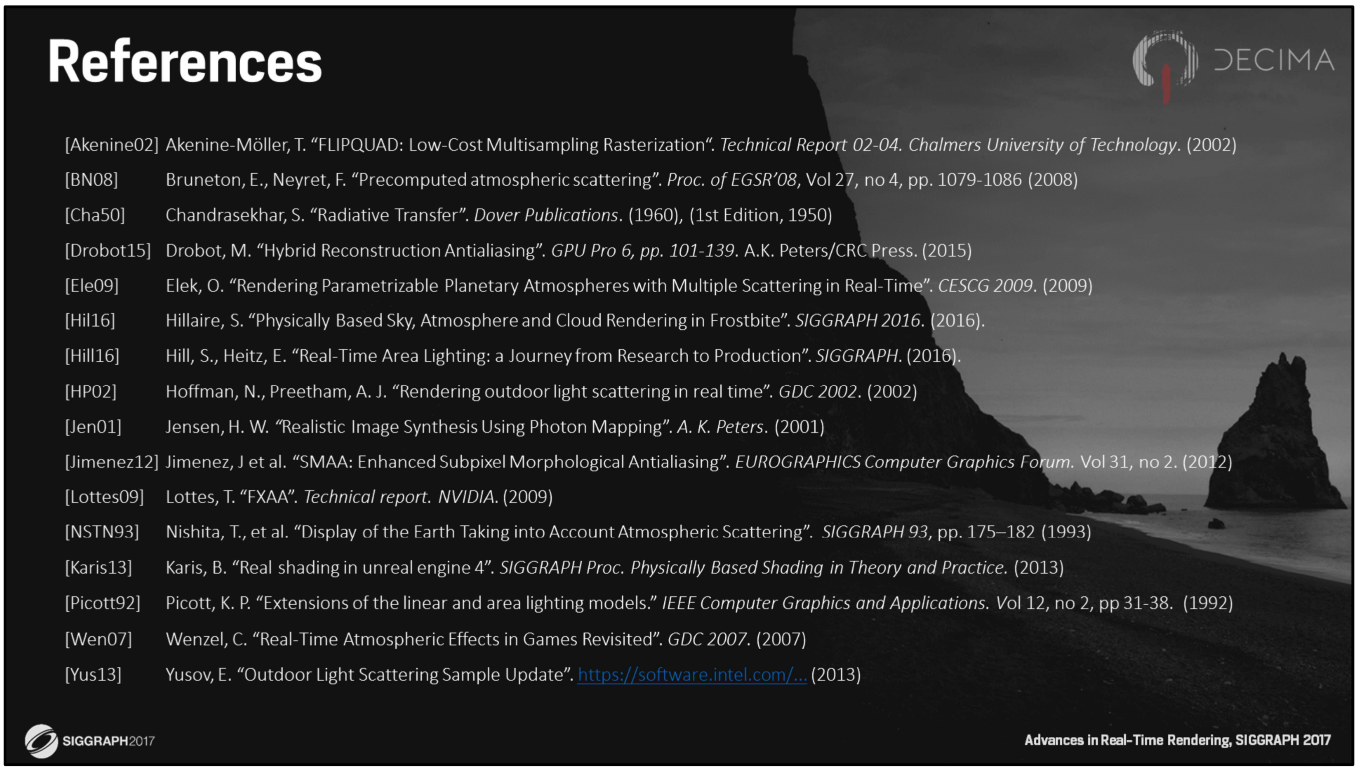

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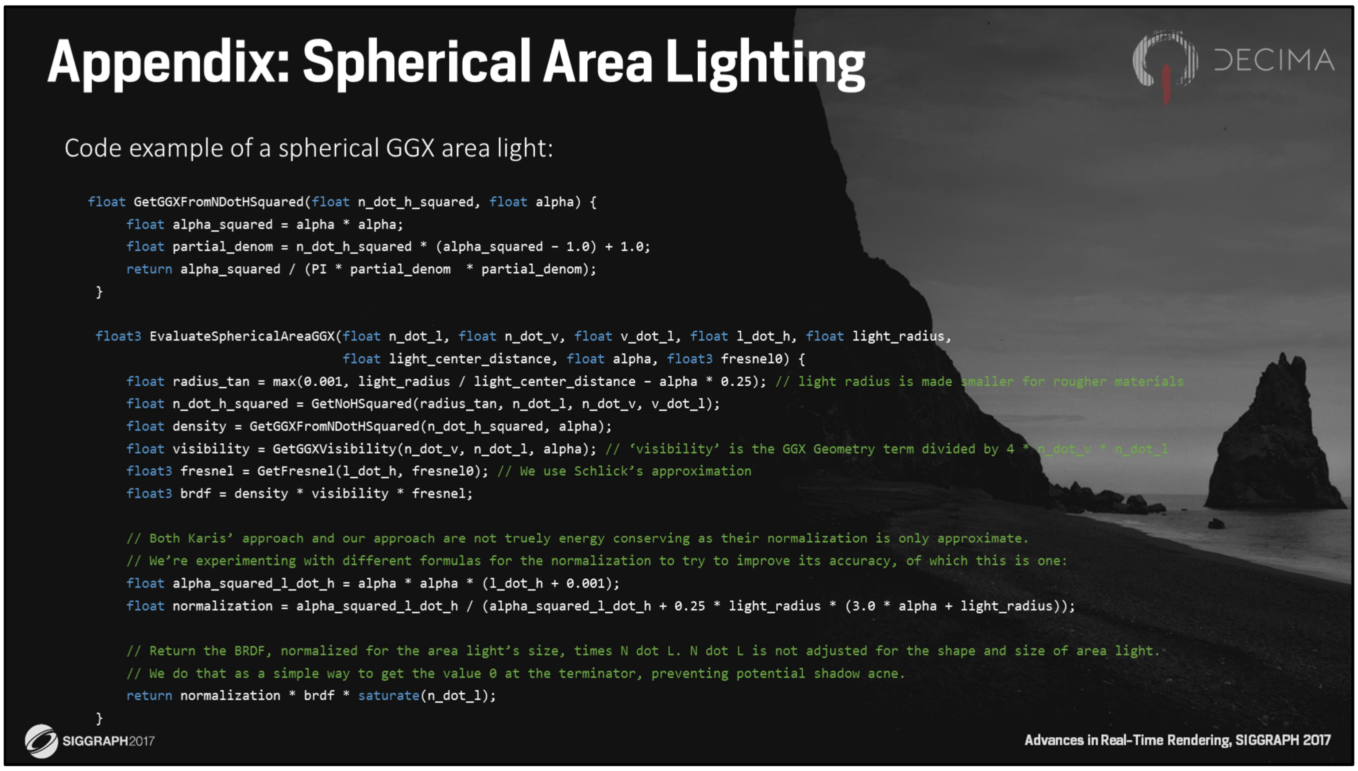

Appendix: Spherical Area Lighting

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Code example of a spherical GGX area light:

```
float GetGGXFromNDotHSquared(float n_dot_h_squared, float alpha) {
     float alpha_squared = alpha * alpha;
     float partial_denom = n_dot_h_squared * (alpha_squared - 1.0) + 1.0;
     return alpha_squared / (PI * partial_denom  * partial_denom);
 }

 float3 EvaluateSphericalAreaGGX(float n_dot_l, float n_dot_v, float v_dot_l, float l_dot_h, float light_radius,
                                  float light_center_distance, float alpha, float3 fresnel0) {
     float radius_tan = max(0.001, light_radius / light_center_distance - alpha * 0.25); // light radius is made smaller for rougher materials
     float n_dot_h_squared = GetNoHSquared(radius_tan, n_dot_l, n_dot_v, v_dot_l);
     float density = GetGGXFromNDotHSquared(n_dot_h_squared, alpha);
     float visibility = GetGGXVisibility(n_dot_v, n_dot_l, alpha); // 'visibility' is the GGX Geometry term divided by 4 * n_dot_v * n_dot_l
     float3 fresnel = GetFresnel(l_dot_h, fresnel0); // We use Schlick's approximation
     float3 brdf = density * visibility * fresnel;

     // Both Karis' approach and our approach are not truely energy conserving as their normalization is only approximate.
     // We're experimenting with different formulas for the normalization to try to improve its accuracy, of which this is one:
     float alpha_squared_l_dot_h = alpha * alpha * (l_dot_h + 0.001);
     float normalization = alpha_squared_l_dot_h / (alpha_squared_l_dot_h + 0.25 * light_radius * (3.0 * alpha + light_radius));

     // Return the BRDF, normalized for the area light's size, times N dot L. N dot L is not adjusted for the shape and size of area light.
     // We do that as a simple way to get the value 0 at the terminator, preventing potential shadow acne.
     return normalization * brdf * saturate(n_dot_l);
 }
```

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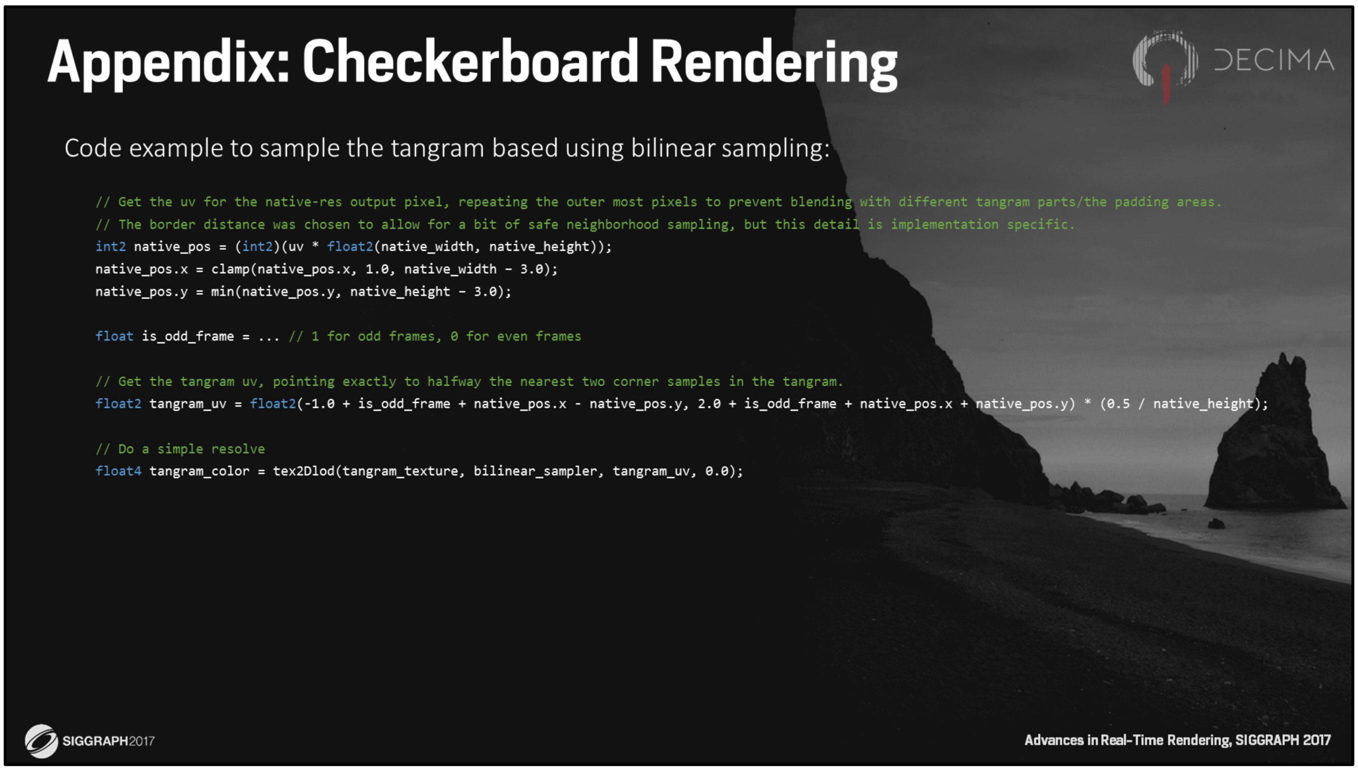
This sample code is provided as an example on how to use GetNoHSquared().
It also includes some further adjustments to better match our reference:
With the presented light bending techniques, the intensity falls off outside the light's area reflected on the surface, but is constant inside it, which isn't realistic for rough materials. That's why we also reduce the radius based on alpha.
As the light bending techniques mess aren't energy conserving, we need to compensate for this somehow. We're currently experimenting with alternative formulas for normalization to better match our reference. This, however, is still in flux.
Lastly, we only use GetNoHSquared() to modify the input to the GGX microfacet distribution. The Geometry, Fresnel, normalization and final N-dot-L are left unadjusted. This leads to zero intensity when the CENTER of the area light is on the horizon, which strictly speaking isn't correct, but it does prevent shadow acne at the terminator, which is more important to us.

NOTE: The code has been adjusted for this presentation and hasn't been tested in this form, and (thus) comes without any guarantees.



Appendix: Checkerboard Rendering

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Code example to sample the tangram based using bilinear sampling:

```
// Get the uv for the native-res output pixel, repeating the outer most pixels to prevent blending with different tangram parts/the padding areas.
// The border distance was chosen to allow for a bit of safe neighborhood sampling, but this detail is implementation specific.
int2 native_pos = (int2)(uv * float2(native_width, native_height));
native_pos.x = clamp(native_pos.x, 1.0, native_width - 3.0);
native_pos.y = min(native_pos.y, native_height - 3.0);

float is_odd_frame = ... // 1 for odd frames, 0 for even frames

// Get the tangram uv, pointing exactly to halfway the nearest two corner samples in the tangram.
float2 tangram_uv = float2(-1.0 + is_odd_frame + native_pos.x - native_pos.y, 2.0 + is_odd_frame + native_pos.x + native_pos.y) * (0.5 / native_height);

// Do a simple resolve
float4 tangram_color = tex2Dlod(tangram_texture, bilinear_sampler, tangram_uv, 0.0);
```

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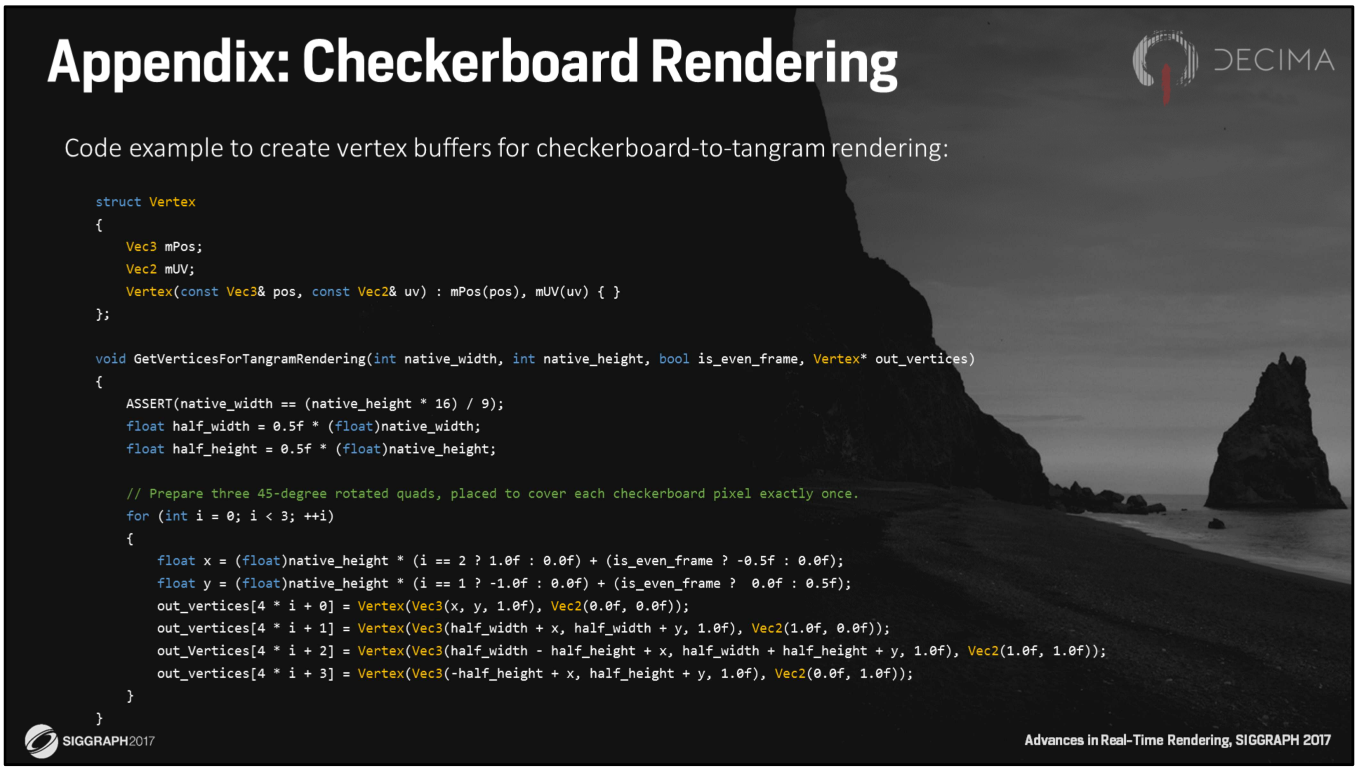
This is some sample code to sample a tangram based on a native-res UV and, in this case, do a corner-to-center-resolve using a single bilinear sample.

NOTE: The code has been adjusted for this presentation and hasn't been tested in this form, and (thus) comes without any guarantees.



Appendix: Checkerboard Rendering

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Code example to create vertex buffers for checkerboard-to-tangram rendering:

```
struct Vertex
{
    Vec3 mPos;
    Vec2 mUV;
    Vertex(const Vec3& pos, const Vec2& uv) : mPos(pos), mUV(uv) { }
};

void GetVerticesForTangramRendering(int native_width, int native_height, bool is_even_frame, Vertex* out_vertices)
{
    ASSERT(native_width == (native_height * 16) / 9);
    float half_width = 0.5f * (float)native_width;
    float half_height = 0.5f * (float)native_height;

    // Prepare three 45-degree rotated quads, placed to cover each checkerboard pixel exactly once.
    for (int i = 0; i < 3; ++i)
    {
        float x = (float)native_height * (i == 2 ? 1.0f : 0.0f) + (is_even_frame ? -0.5f : 0.0f);
        float y = (float)native_height * (i == 1 ? -1.0f : 0.0f) + (is_even_frame ?  0.0f : 0.5f);
        out_vertices[4 * i + 0] = Vertex(Vec3(x, y, 1.0f), Vec2(0.0f, 0.0f));
        out_vertices[4 * i + 1] = Vertex(Vec3(half_width + x, half_width + y, 1.0f), Vec2(1.0f, 0.0f));
        out_Vertices[4 * i + 2] = Vertex(Vec3(half_width - half_height + x, half_width + half_height + y, 1.0f), Vec2(1.0f, 1.0f));
        out_vertices[4 * i + 3] = Vertex(Vec3(-half_height + x, half_height + y, 1.0f), Vec2(0.0f, 1.0f));
    }
}
```

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This is example code to populate a vertex buffer with exactly enough pos&uv vertices to render a list of 3 quad. This can be used to render a tangram of size native_height x native_height using a simple point-sampling blit function. Note that the UV coordinates simply point to the four corners of the raw checkerboarded input buffer.

When the blit function is replaced with a full-screen effect shader that can run on the checkerboard data directly, you can even execute that effect AND do the checkerboard-to-tangram transform in the same pass.

NOTE: The code has been adjusted for this presentation and hasn’t been tested in this form, and (thus) comes without any guarantees.