Real-time Physically Based Rendering
- Implementation -

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Image Based Lighting (IBL)

- Lighting that uses a texture (an image) as light source
  - How is it different than Environment Mapping?
    - In a broad sense, environment mapping is one of techniques of Image Based Lighting

Physically Based IBL

- Ad-hoc IBL vs. Physically-based IBL
  - Has the same differences and similarities between ad-hoc rendering and physically based rendering
  - Ad-hoc rendering
    - Each process needed for rendering is implemented one by one, ad-hoc
  - Physically Based Rendering
    - The entire renderer is designed and built based on physical premises such as the Rendering Equation and etc.

Physically Based IBL advantages

- Guarantees a rendering result that is close to shading under punctual light sources
  - Materials in a scene dominated by direct lighting and indirect lighting seem the same
    - Consistency is preserved through different lighting
    - Artists spend less time tweaking parameters
    - Even in a scene dominated by indirect lighting, materials look realistic
    - No need to use an environment map for glossy objects
      - Just add an IBL light source

PBIBL implementation

- Implementing IBL as an approximation of the rendering equation
  - Physically Based Image Based Lighting is one of possible examples to reasonably implement physically based rendering

Equations

$$L_o(\mathbf{x},\omega) = \int_\Omega f_r(\mathbf{x},\omega',\omega) L_i(\mathbf{x},\omega')(\omega'\cdot\mathbf{n})d\omega'$$

$$f_r(\mathbf{x},\omega',\omega) = \frac{R_d}{\pi}(1-F_0) + (0.0397436\,shininess + 0.0856832)\frac{F_{spec}(F_0)(\mathbf{n}\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^{shininess}}{\max(\mathbf{n}\cdot\omega',\mathbf{n}\cdot\omega)}$$

substitute

$$F_{spec}(F_0) = F_0 + (1-F_0)(1-\omega\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^5$$

$$L_o(\mathbf{x},\omega) = \int_\Omega (\omega'\cdot\mathbf{n})\left(\frac{R_d}{\pi}(1-F_0) + (0.0397436\,shininess + 0.0856832)\frac{\left(F_0 + (1-F_0)(1-\omega\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^5(\mathbf{n}\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^{shininess}\right)}{\max(\mathbf{n}\cdot\omega',\mathbf{n}\cdot\omega)}\right)L_i(\mathbf{x},\omega')d\omega'$$

Decompose integral

$$L_o(\mathbf{x},\omega) = \int_\Omega \frac{R_d}{\pi}(\omega'\cdot\mathbf{n})(1-F_0)L_i(\mathbf{x},\omega') + (c_1\cdot shi + c_2)\frac{(\omega'\cdot\mathbf{n})\left(F_0 + (1-F_0)(1-\omega\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^5\right)(\mathbf{n}\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^{shi}}{\max(\mathbf{n}\cdot\omega',\mathbf{n}\cdot\omega)}L_i(\mathbf{x},\omega')d\omega'$$

$$\mathrm{IEM}(\omega) = \int_\Omega \frac{1}{\pi}(\omega'\cdot\mathbf{n})L_i(\mathbf{x},\omega')d\omega'$$

Irradiance Environment Map (IEM)

$$\mathrm{REM}(\omega, shi) = \int_\Omega (\mathbf{n}\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^{shi} L_i(\mathbf{x},\omega')d\omega'$$

Pre-filtered Radiance Environment Map (PFREM)

$$\mathrm{AmbientBRDF}(\omega, shi, F_0) = \int_\Omega (c_1\cdot shi + c_2)\frac{(\omega'\cdot\mathbf{n})\left(F_0 + (1-F_0)(1-\omega\cdot\frac{\omega'+\omega}{|\omega'+\omega|})^5\right)}{\max(\mathbf{n}\cdot\omega',\mathbf{n}\cdot\omega)}d\omega'$$

AmbientBRDF Volume Texture

Implement Ambient BRDF

$$\text{AmbientBRDF}(\omega, shi, F_0) = \int_\Omega (c_1 \cdot shi + c_2) \frac{(\omega' \cdot \mathbf{n}) \left(F_0 + (1 - F_0)(1 - \omega \cdot \frac{\omega' + \omega}{|\omega' + \omega|})^5 \right)}{\max(\mathbf{n} \cdot \omega', \mathbf{n} \cdot \omega)} d\omega'$$

- Precompute this equation off line and store result to a volume texture
  - U – Dot product of eye vector (ω) and normal ($\mathbf{n}$)
  - V – $shininess$
  - W – F_0

AmbientBRDF texture usage

- Fetch the texture
  - For specular component
    - Use the value for $\int_{\Omega}(c_1 \cdot shi + c_2)\frac{(\omega' \cdot \mathbf{n})\left(F_0 + (1-F_0)(1-\omega \cdot \frac{\omega'+\omega}{|\omega'+\omega|})^5\right)}{\max(\mathbf{n}\cdot\omega', \mathbf{n}\cdot\omega)}d\omega'$
  - For diffuse component
    - R_d*(1 – the value)
      - For optimization
    - Ideally values for diffuse component should be precomputed and stored to the texture for accurate shading

AmbientBRDF comparison

AmbientBRDF ON

AmbientBRDF OFF

Generate textures

- Use AMD CubeMapGen?
  - It can't be used for real-time processing on multi-platform, because it is released as a tool / library

Generate textures

- Use AMD CubeMapGen?
  - It can't be used for real-time processing on multi-platform, because it is released as a tool / library

But it has become open-source ☺

  - Even so, the quality is not perfect and there is room for improvement

Generate IEM

$$\mathrm{IEM}(\omega) = \int_{\Omega} \frac{1}{\pi} (\omega' \cdot \mathbf{n}) L_i(\mathbf{x}, \omega') d\omega'$$

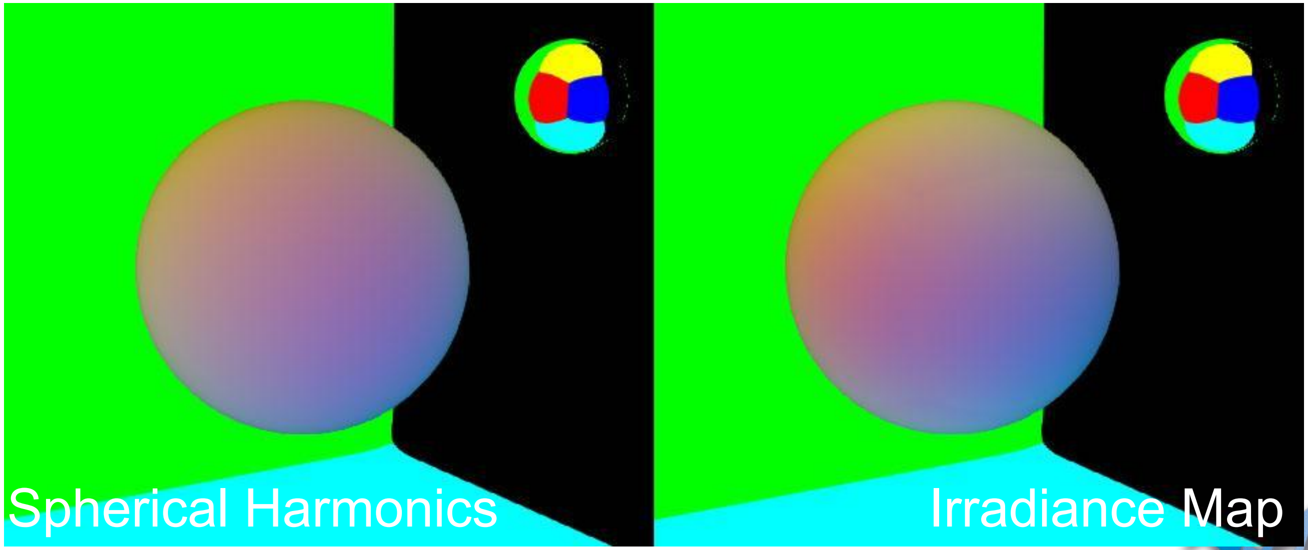
- Implement this equation straightforwardly on GPU
  - Diffuse BRDF is Lambert
    - In the case of IBL, the use of other models doesn't bring any significant differences
      - Strictly speaking, it depends of the intensity distribution in an IBL image
  - Texture resolution is 16x16x6

Generate IEM (2)

- Using a radiance map reduced to 8x8x6
  - Store accurately precomputed $\Delta\omega$ to the texture using spherical quadrilateral
    - AMD CubeMapGen uses approximated $\Delta\omega$
  - Normalizing coefficient is also stored in the texture
  - Fp16 format
  - 8x8x5 = 320tap filter on GPU
    - Xbox360 0.5ms
    - PS3 2.0ms
      - Would be better on SPU

Optimize diffuse term

- Using SH lighting instead of IEM for a high performance configuration
  - Our engine already implements SH lighting
    - No extra GPU cost
  - Compute the coefficients from 6 texels at the center in each face



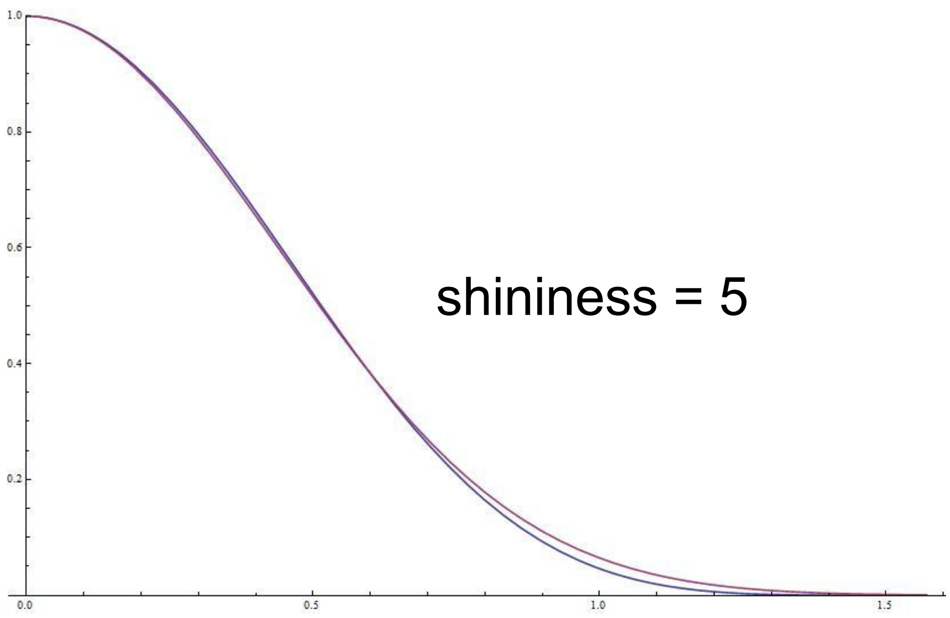
Generate REM

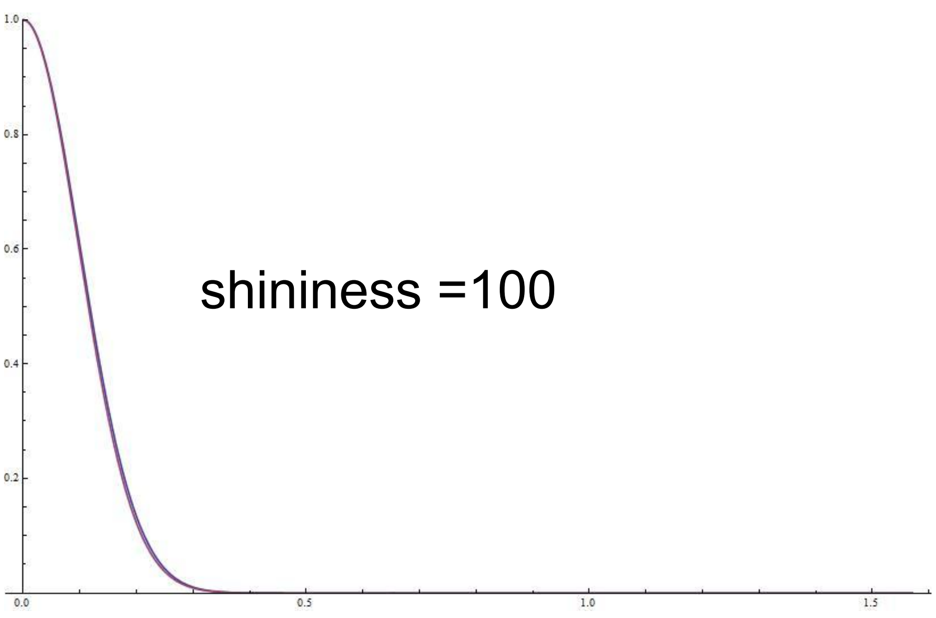
$$\mathrm{REM}(\omega, shi) = \int_{\Omega} (\mathbf{n} \cdot \frac{\omega' + \omega}{|\omega' + \omega|})^{shi} L_i(\mathbf{x}, \omega') d\omega'$$

- Pre-filtered Mipmapped Environment Map
  - Compute the equation with different shininess values and store results to each mipmapped texture
  - Blinn based NDF?
    - Approximated with Phong
      - This is a compromise solution because the specular highlight shape changes due to different microfacet models
    - Only fitting the size difference of NDFs using shininess

Fitting shininess

- $\cos^{n}\theta \approx \cos^{4.2n}\dfrac{\theta}{2}$

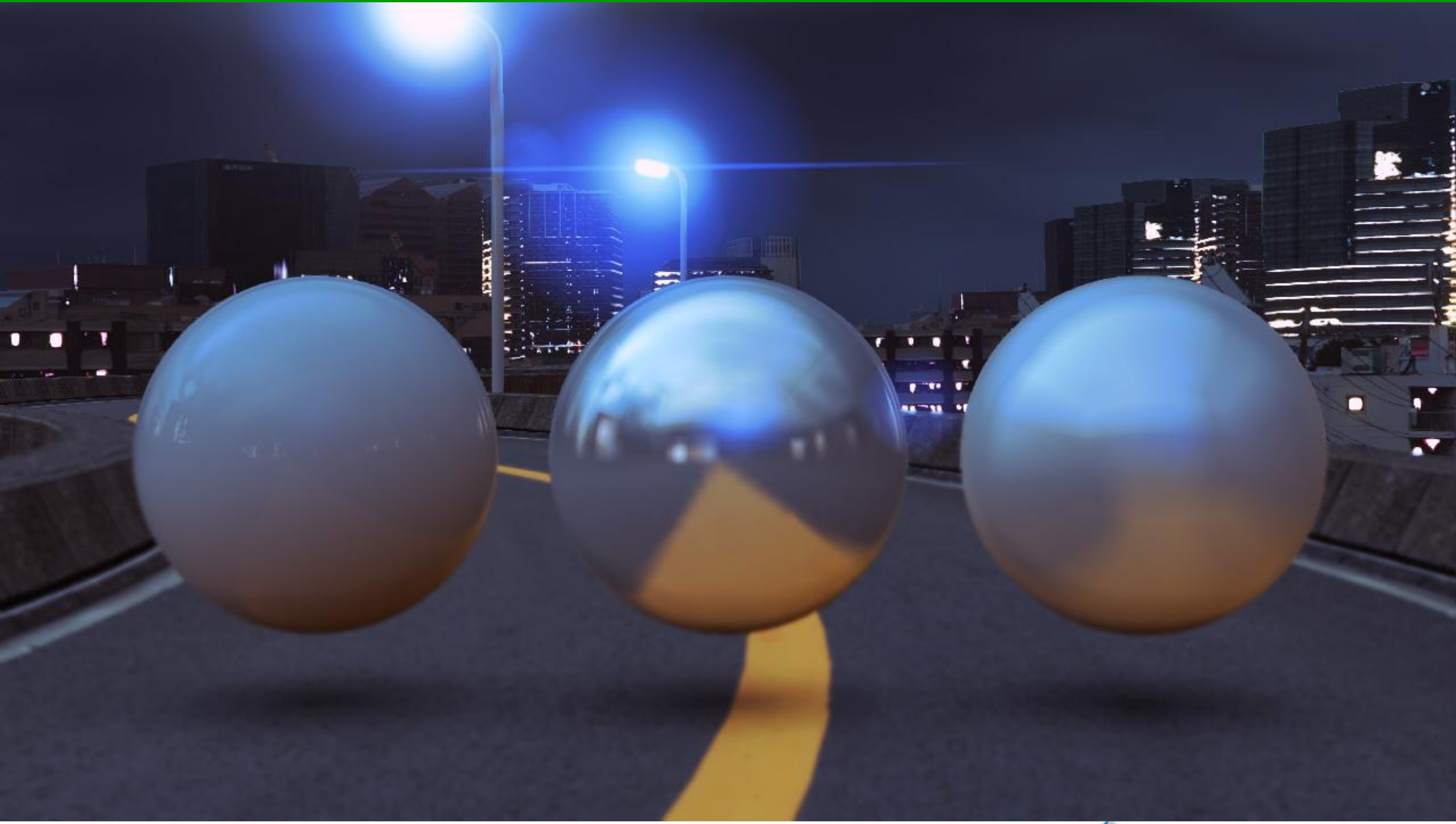




Generate PMREM (1)

- Box-filter kernel filtering
  - Simply use bilinear filtering to generate mipmaps
  - LOD values are set according to shininess
    - Quality is quite low
    - Not even an approximation
  - Use as a fastest profile for dynamic PMREM generation

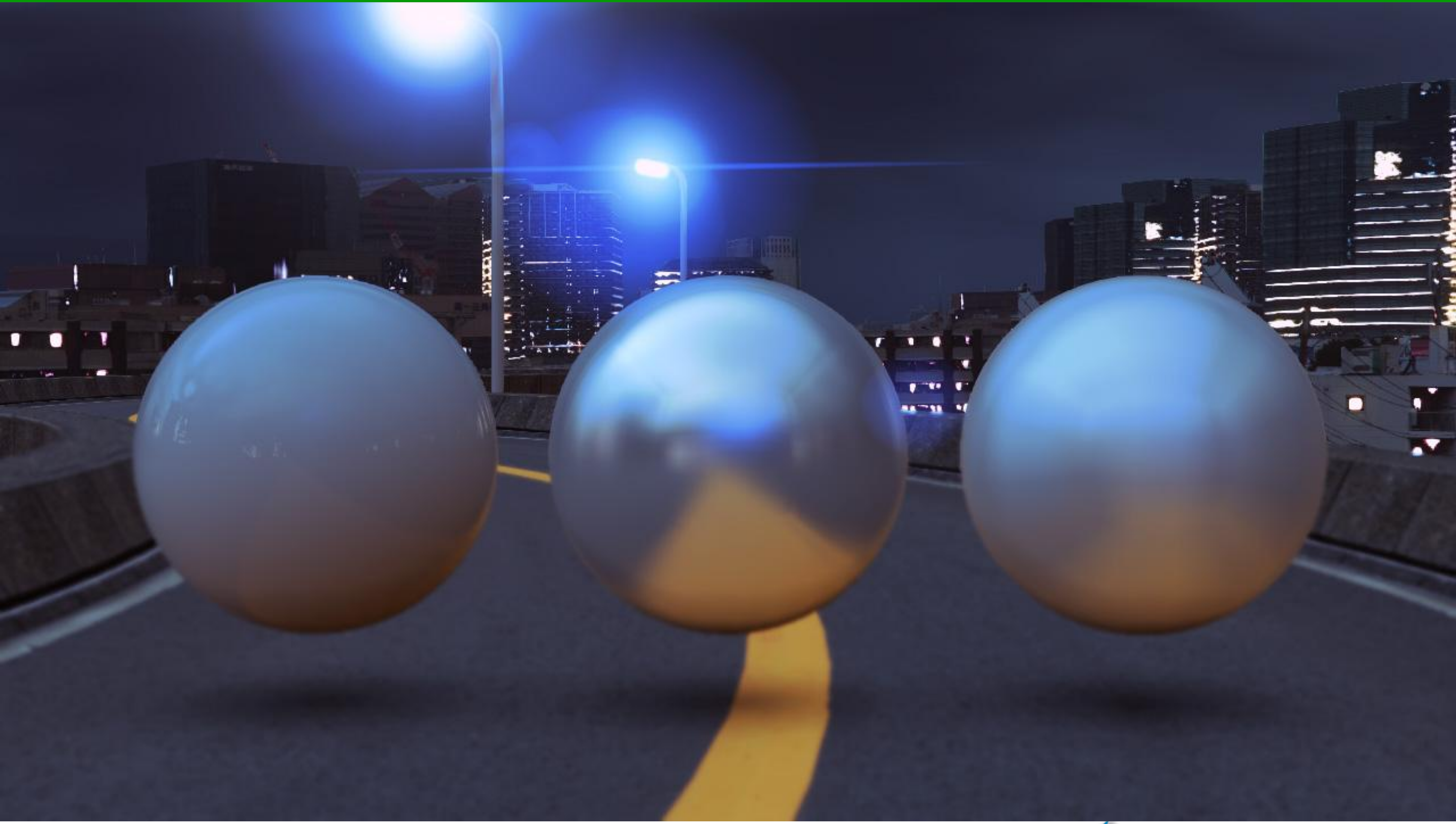
Box kernel filter



Generate PMREM (2)

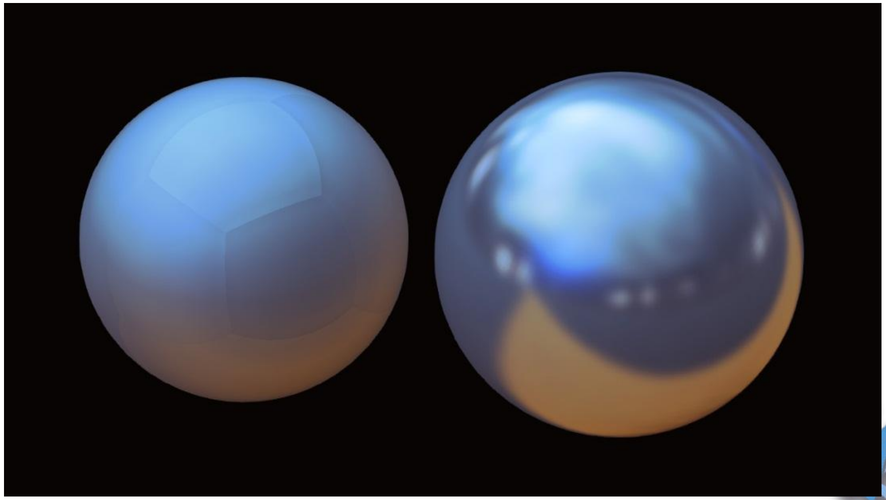
- Gaussian kernel filtering
  - Apply 2D Gaussian blur to each face
    - Not physically based
      - As the blur radius increases, visual artifacts from error in $\Delta\omega$ become noticeable
    - The cube map boundary problem is noticeable
      - Even using overlapping (described later) for slow gradation generated by the blur process, since filtering isn't performed over edges, banding is perceived on the edges when colors are changed rapidly
    - Use as the second fastest profile for dynamic PMREM generation

Gaussian kernel filter

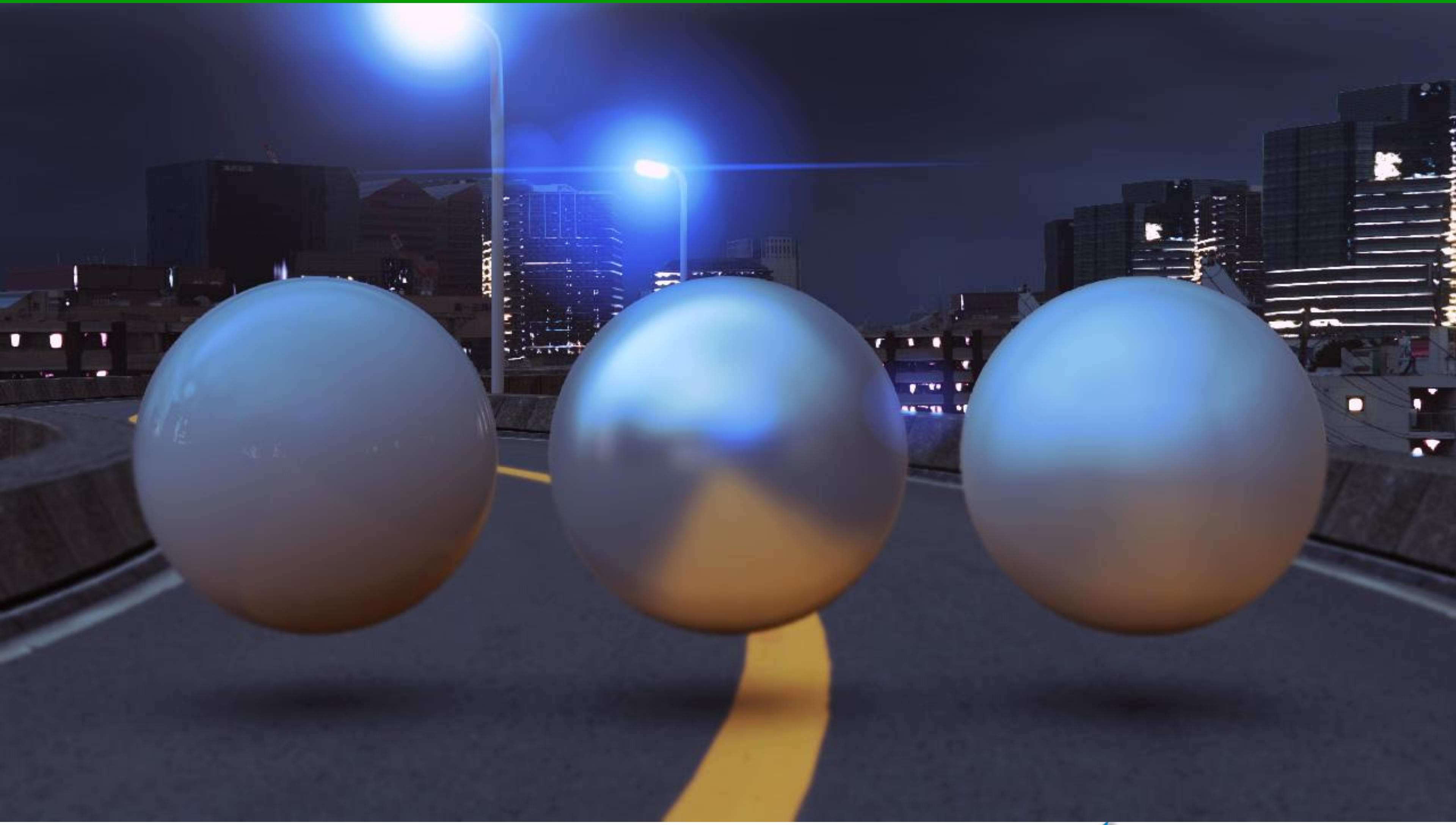


Generate PMREM(3)

- Spherical Phong kernel filtering
  - The shininess values are converted using the fitting function
  - The cube map boundary problem still exists
    - We expected to solve it before the implementation
    - The reason is that, since the centers of adjacent pixels across the edges are not matched, the filtered colors are also not matched



Spherical Phong kernel filter



Phong kernel implementation(GPU)

- Brute force implementation similar to irradiance map generation
  - In the final implementation, a face is subdivided into 9 rectangles for texture fetch reduction
    - Faster by 50%
    - 9x6=54 shaders are used for each mip level
  - Subdivision is not used below 16x16
    - It becomes ALU bound as texture cache efficiently works for smaller textures

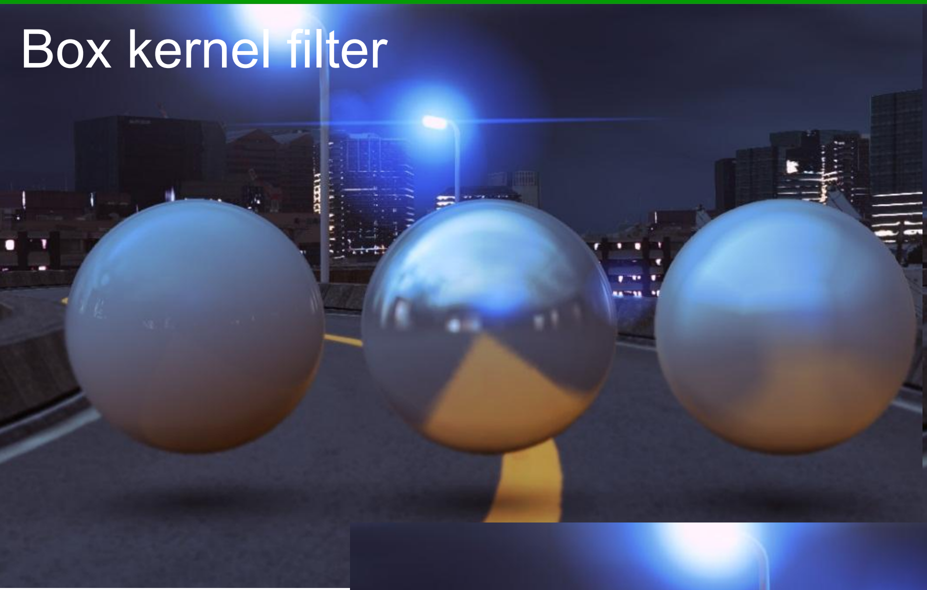
Phong kernel implementation(CPU)

- Offline generation by the tool for static IBL
  - SH coefficients and PMREM are automatically generated during scene export
    - For performance, 64x64x6 PMREM is only supported for static IBL
    - Brute force implementation
      - All level mipmaps are generated from the top level texture at the same time
    - Core2 8 hardware threads @ 2.8GHz
      - 64x64x6 : 5.6s
      - 32x32x6 : 0.5s
      - SSE & multithread

Generate PFREM (4)

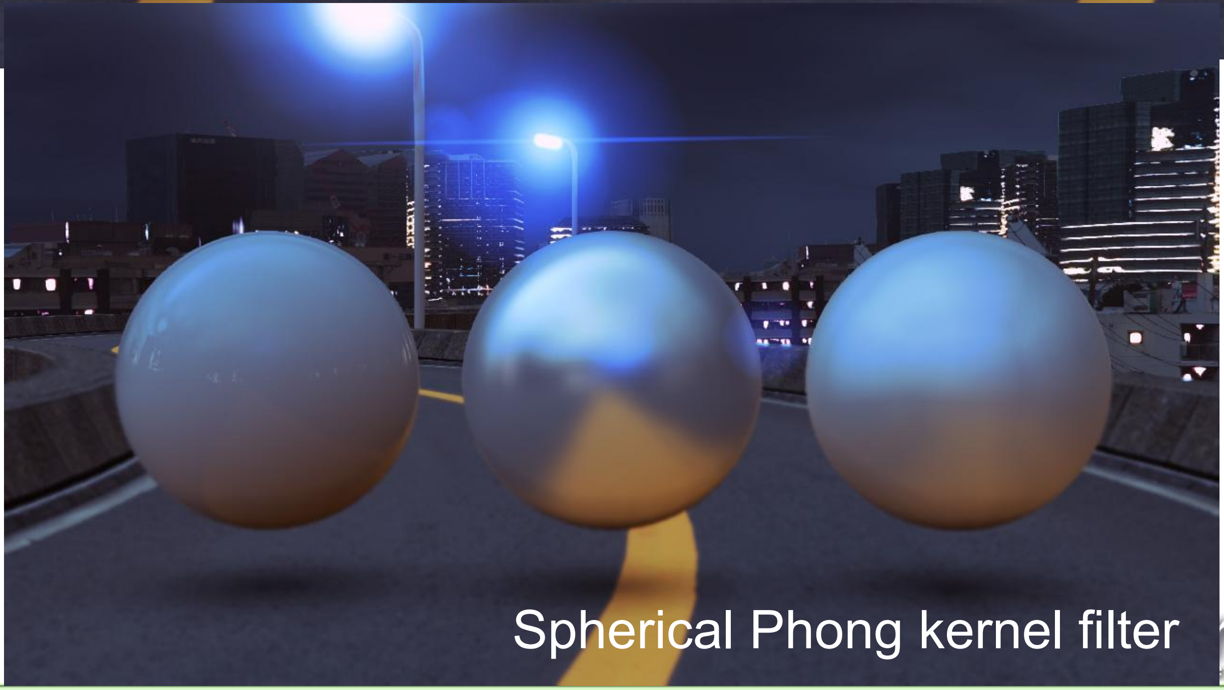
- Poisson kernel filtering
  - Implemented a faster version of Phong kernel filtering
    - Apply about 160tap filter with one lower level mipmap texture
      - Quality is compromised even with this process
    - Many taps are needed for desired quality
      - Didn’t work as optimization
      - Didn’t work well with Overlapping process
    - Not used because of bad quality and performance

Comparisons



Box kernel filter

Gaussian kernel filter



Spherical Phong kernel filter

Mipmap LOD

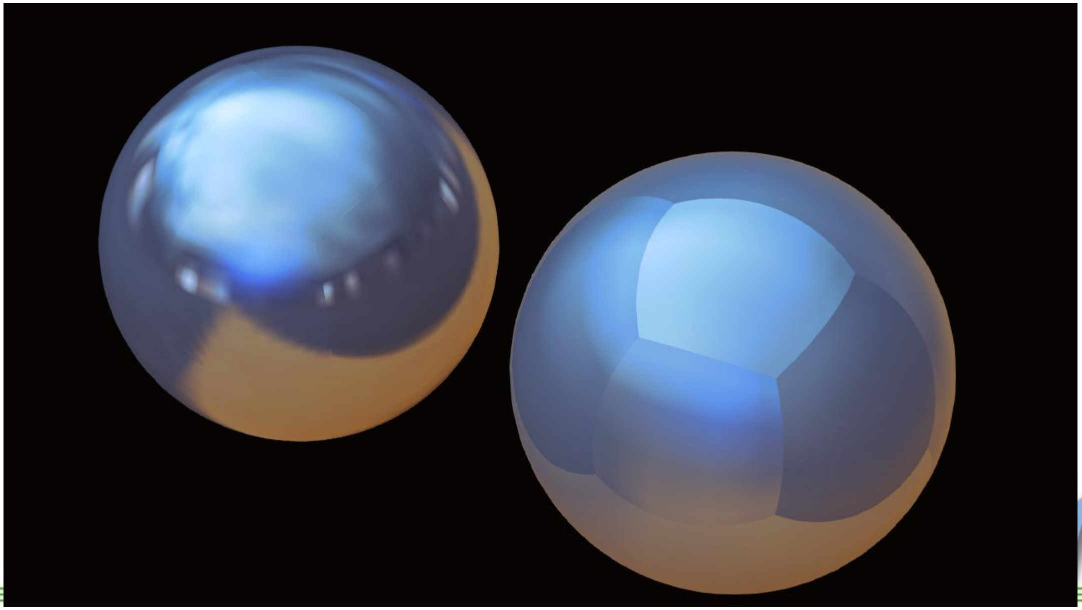
- Mipmap LOD parameter is calculated for generated PMREM
  - Select the mip level according to shininess
    - Using texCUBElod() for each pixel

$$lod = a - 0.5 \log_2 shininess$$

      - a is calculated according to the texture size and shininess
    - With trilinear filtering
  - Each shininess value corresponding to each mip level is calculated by fitting
    - Fitted for both Box Filter Kernel and Phong Filter Kernel

Edge overlapping

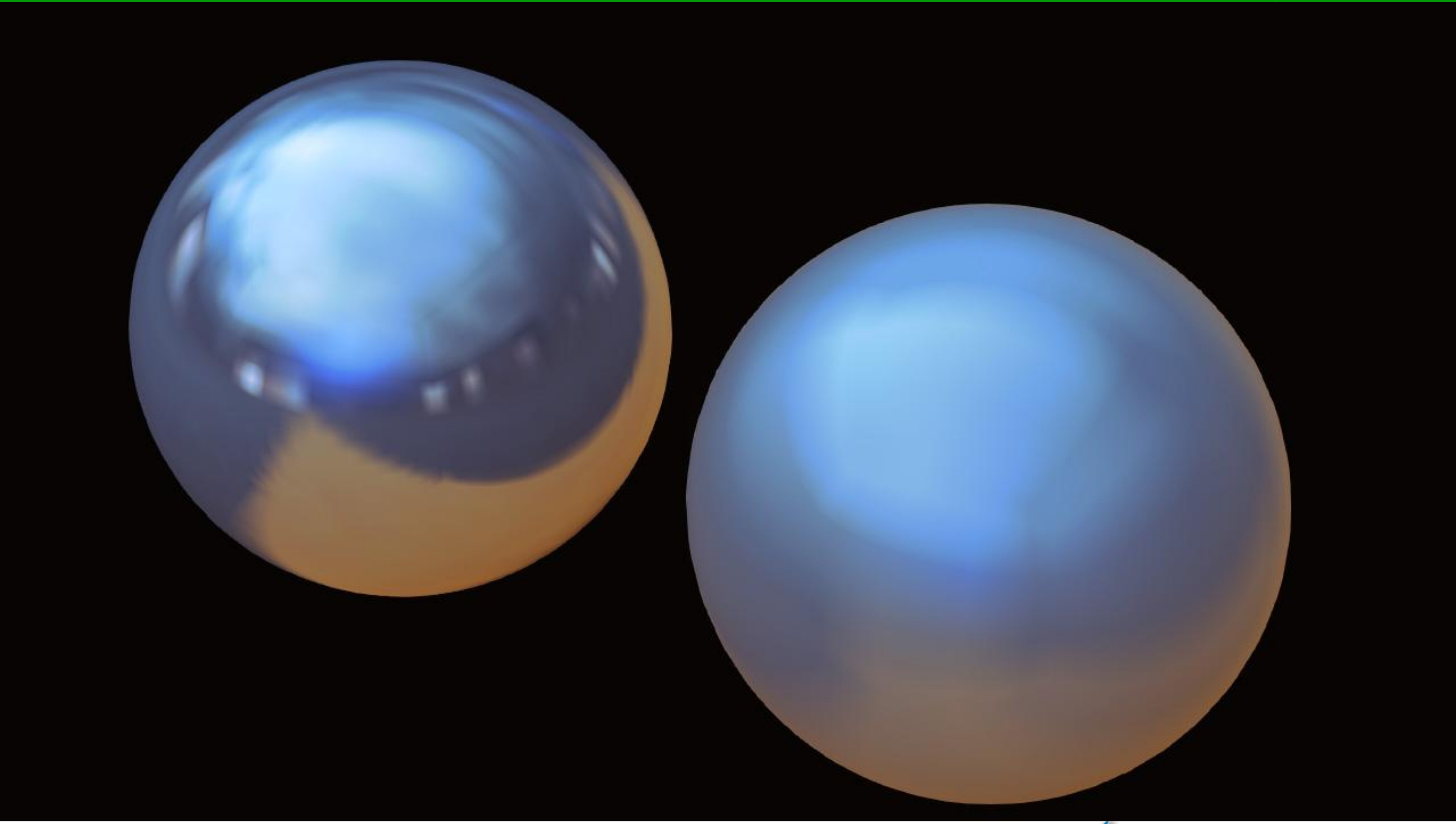
- Need to solve the cubemap boundary problem
  - No bilinear filtering is applied on the cubemap boundaries of each face with DX9 hardware
  - Problematic especially for low resolution mipmaps (1x1 or 2x2)
  - Edge fixup in AMD CubeMapGen



Edge overlapping (1)

- Blend adjacent boundaries by 50%
  - Simplified version of AMD CubeMapGen's Edge Fixup
    - Adjacent texels across the boundaries become the same colors
      - If corners, the colors become the average of adjacent three texel colors
      - If 1x1, the color becomes the average of all faces
        - » All texels become the same color
    - Banding is still noticeable because color gradation velocity varies

Edge overlapping (1)



Edge overlapping (2)

- Blend multiple texels
  - For the next step, blend 2 texels
    - In order to reduce gradation velocity variation, blend 2 texels by 1/4 and 3/4 ratio
      - Same approach as CubeMapGen
      - However, banding is still noticeable in the case where gradation acceleration drastically varies
      - As the area where banding is noticeable increases, the impression gets worse
      - Because the blurred area increases, the accuracy of the integration decreases
        - » Worse rendering quality

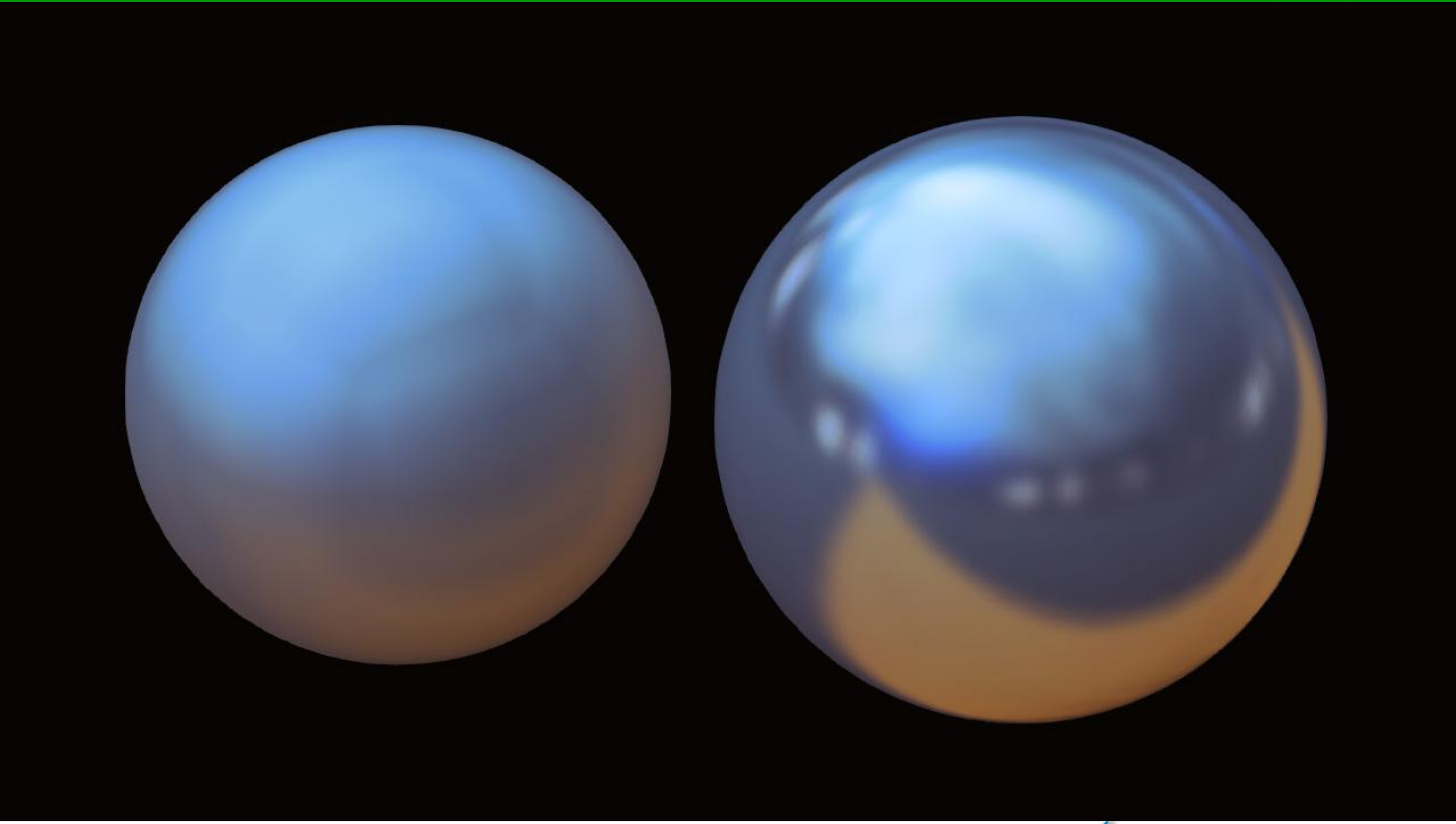
Edge overlapping (3)

- 4 texel blend?
  - More blends don't make sense according to our research
    - 4 texel blending in CubeMapGen is not so high quality
    - Moreover, the precision as a signal decreses

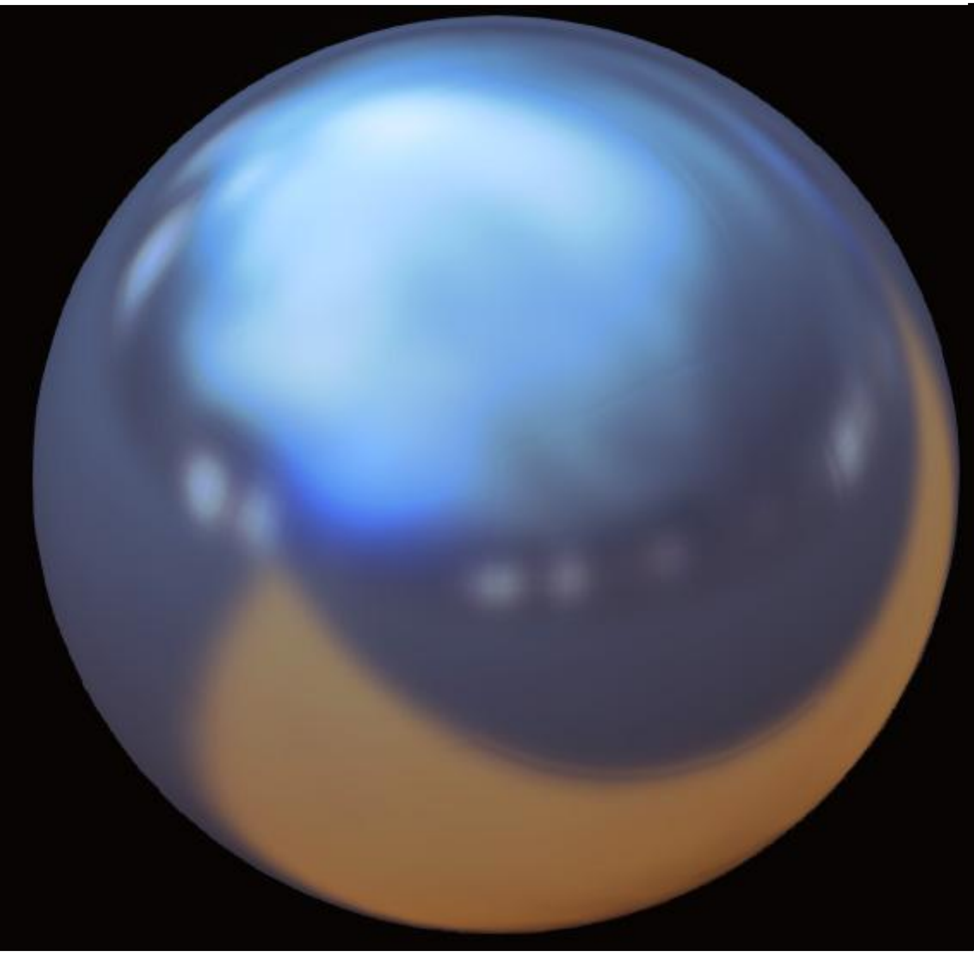
Bent Phong filter kernel

- This algorithm blends normals instead of colors
  - Similar to the difference between Gouraud Shading and Phong Shading
- The normal from the center of the cube map through the center of the texel is bent by an offset angle
  - The offset angle is interpolated from zero at the center of the face to a target angle at the edge
  - The target angle is the angle between the two normals of adjacent faces' edge texels
    - The result from just the above steps was improved, but still not perfect
    - Then, using only 50% of target angle gave a much better result
- In the final implementation, the target angle is additionally modified based on the blur radius
  - Large radius : 100% of target angle used
  - Small radius : 50% used
  - Since optimal values for the target angle are image dependant, adjust the values by visual adjustment instead of mathematical fitting

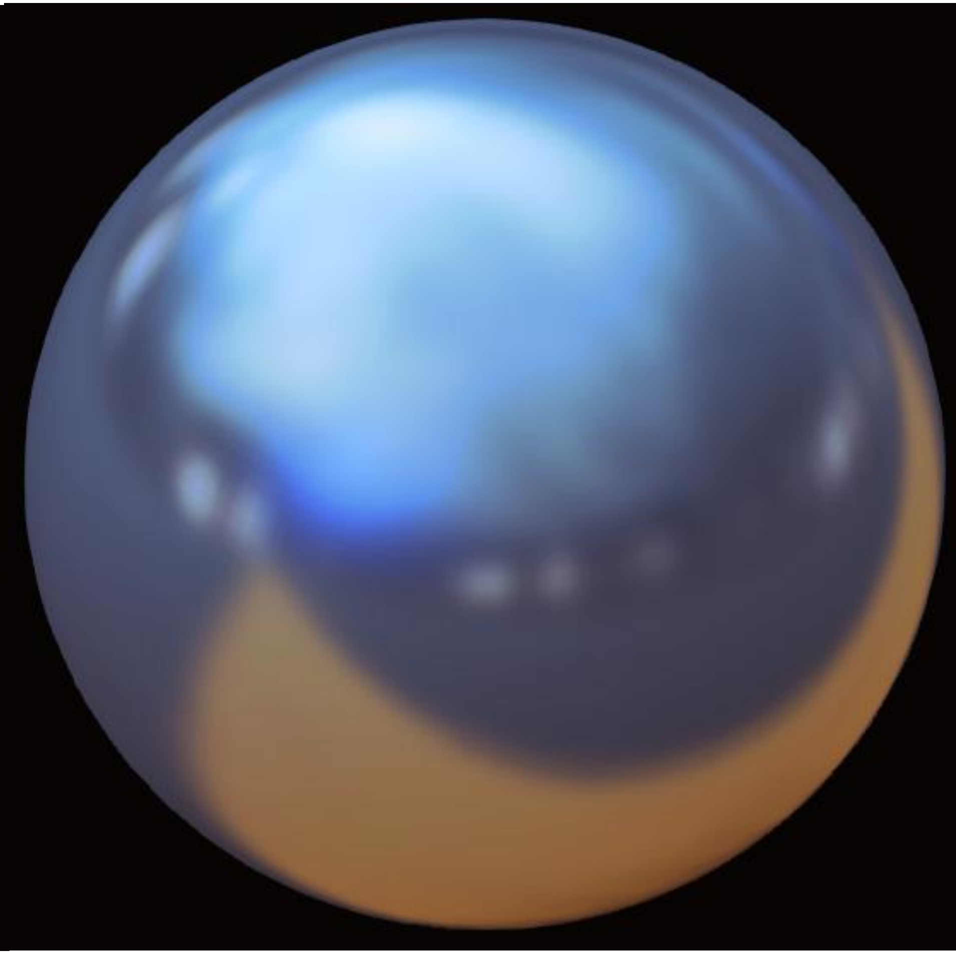
Bent Phong filter kernel



Bent Phong filter kernel



Edge overlapping w/ Phong filter kernel



Bent Phong filter kernel

Implemented configurations

- Dynamic IBL

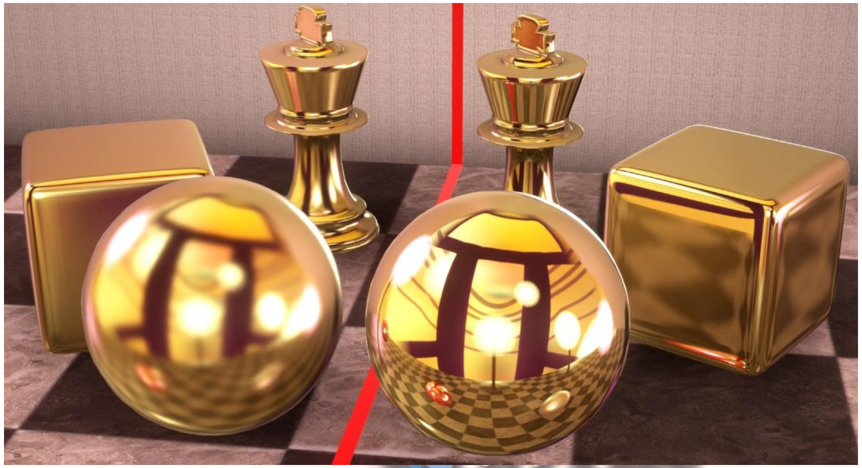
Resolution	Shininess	Filtering	Edge fixup
16x16x6	1-500	None	Edge overlapping
32x32x6	1-1000	2D Gaussian	Edge overlapping
16x16x6	1-250	Spherical Phong	Bent Phong
32x32x6	1-1000	Spherical Phong	Bent Phong

- Static IBL

Resolution	Shininess	Filtering	Edge fixup
32x32x6	1-1000	Spherical Phong	Bent Phong
64x64x6	1-2000	Spherical Phong	Bent Phong

Problems with large shininess

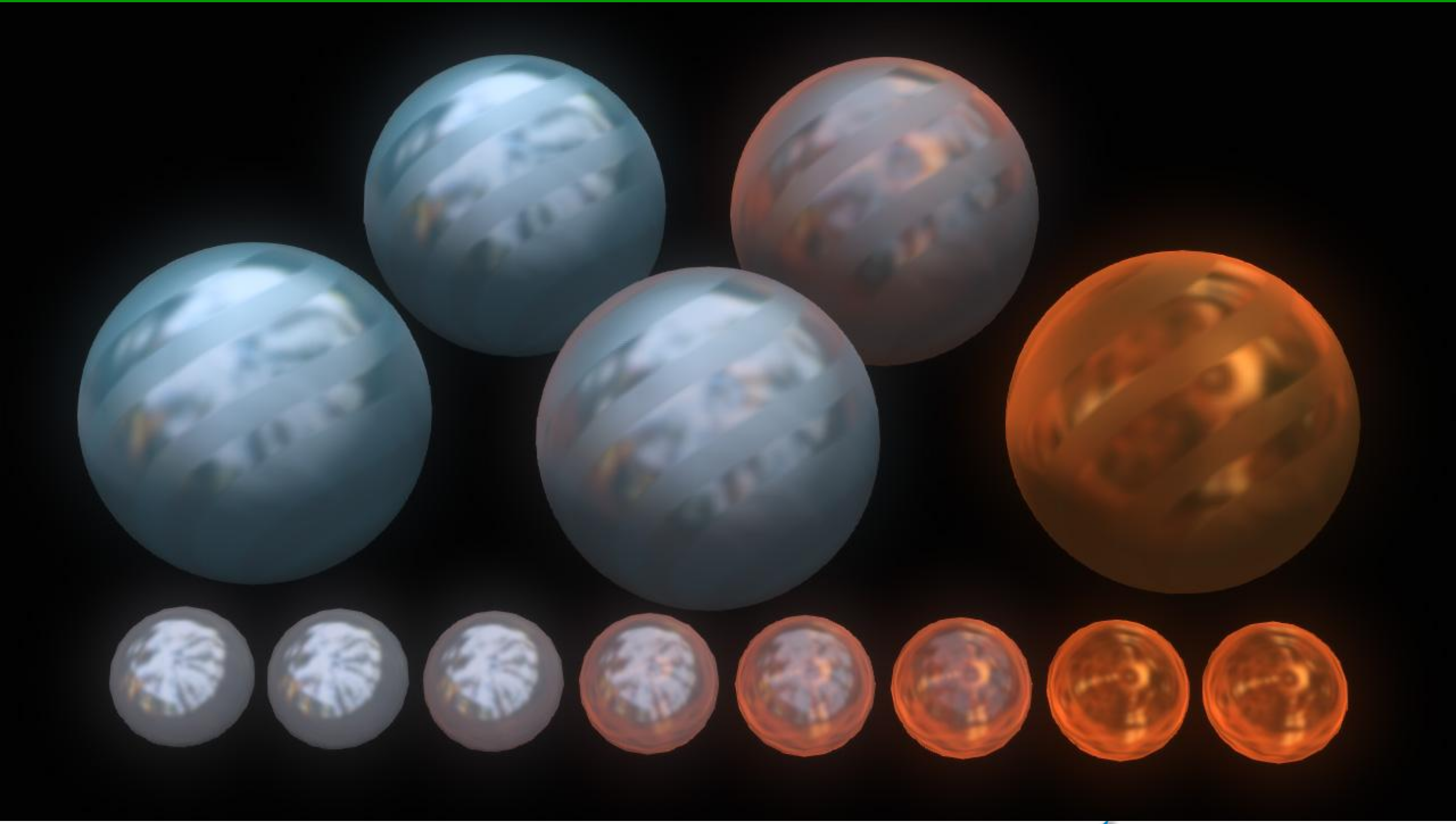
- In practice with IBL, materials still look glossy even with shininess of 1,000 or 2,000
  - For mirror like materials, shininess of ten thousands is preferred
  - Difficult to have high enough resolution mipmap textures, because of memory and performance issues
- Adding the mirror reflection option
  - When this functionality is turned on, the original high resolution texture is automatically chosen



IBL Blending

- Blending is necessary when using multiple Image Based Lights
  - Implemented blending between an SH light and an IBL
    - Popping was annoying when the blend factor cross 50%
    - Not practical
  - Blending by fetching Radiance Map twice
    - Diffuse term is blended with SH
    - For optimization, this process is performed only for the specified attenuation zone
      - Switching shader

IBL Blending



IBL Offset

- A little tweak for a local reflection problem with IBL
  - The usual method
    - Reflection vector is modified according to the virtual IBL position

$$\mathbf{R}' = \mathrm{normalize}\left(c(\mathbf{P}_{obj} - \mathbf{P}_{IBL}) + \mathbf{R}\right)$$

    - c is computed from the IBL size, the object size and another coefficient which is adjusted by hand

Matching IBL with point light

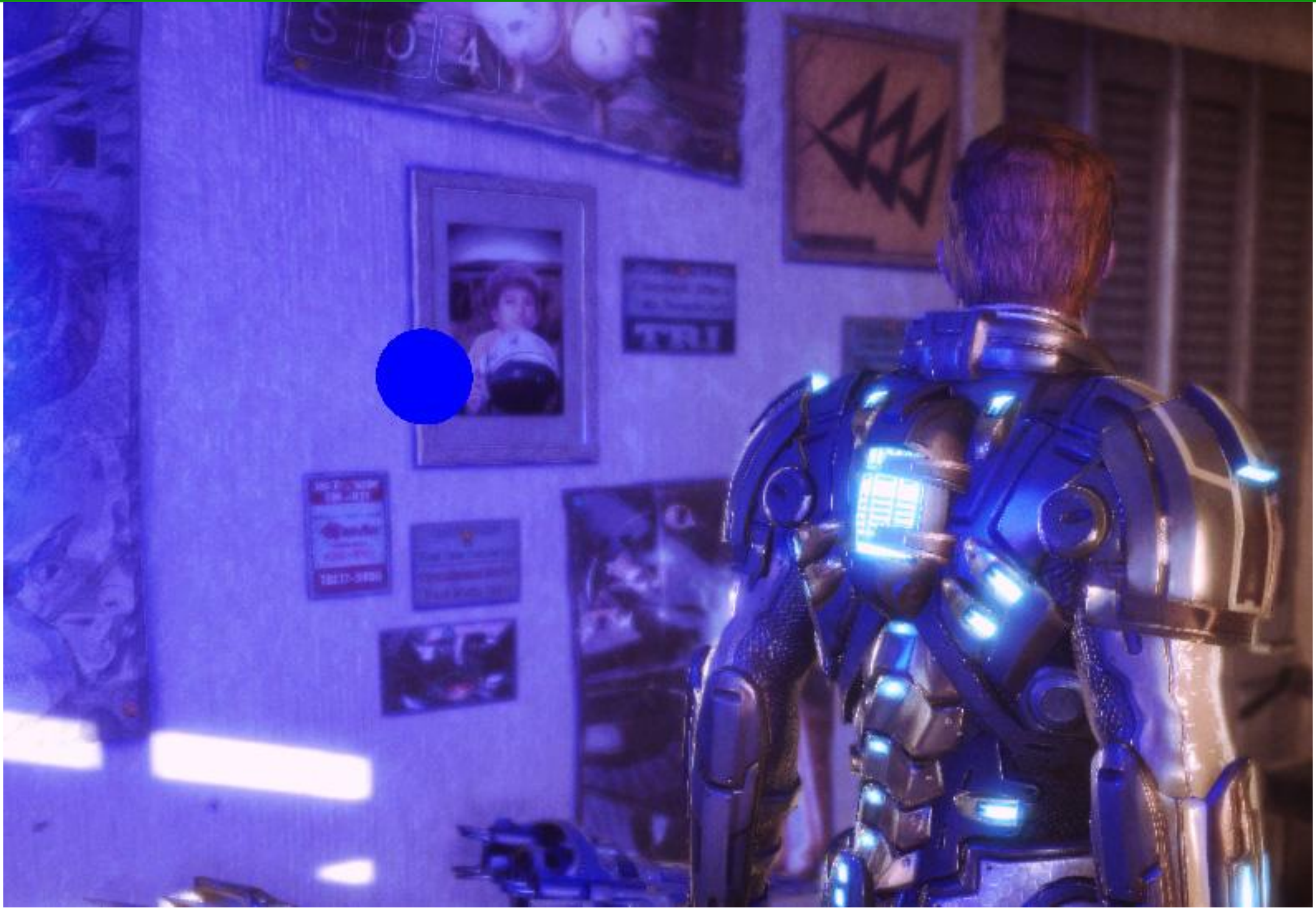
- In the case where area lighting becomes practical with IBL, punctual lights becomes problematic
  - When adjusting specular for punctual lights, artists tend to set smaller (blurrier) shininess values than physically based values
    - But it is too blurry for IBL
    - When adjusted for IBLs, it is too sharp for punctual lights
  - No way for artists to adjust specular without matching

Shininess hack

- Not mathematical matching, but matching the result from punctual lights to the result from IBL
  - Anyhow, this is a hack
    - The coefficient can't be precisely adjusted
      - Depends on the shape of the object lit
      - Depends on the size of the light source
  - Shininess value is compensated by the lighting attenuation factor
    - In the case of distant light source, shininess value tends to be the original shininess value
    - In the case of close light source, shininess values tends to be smaller than the original value

$$shininess' = shininess(\mathrm{saturate}(\frac{60}{light\_size}(1 - attenuation\_factor))^2$$

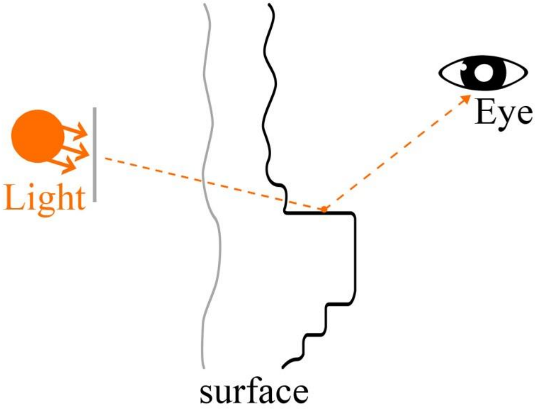
Shininess hack



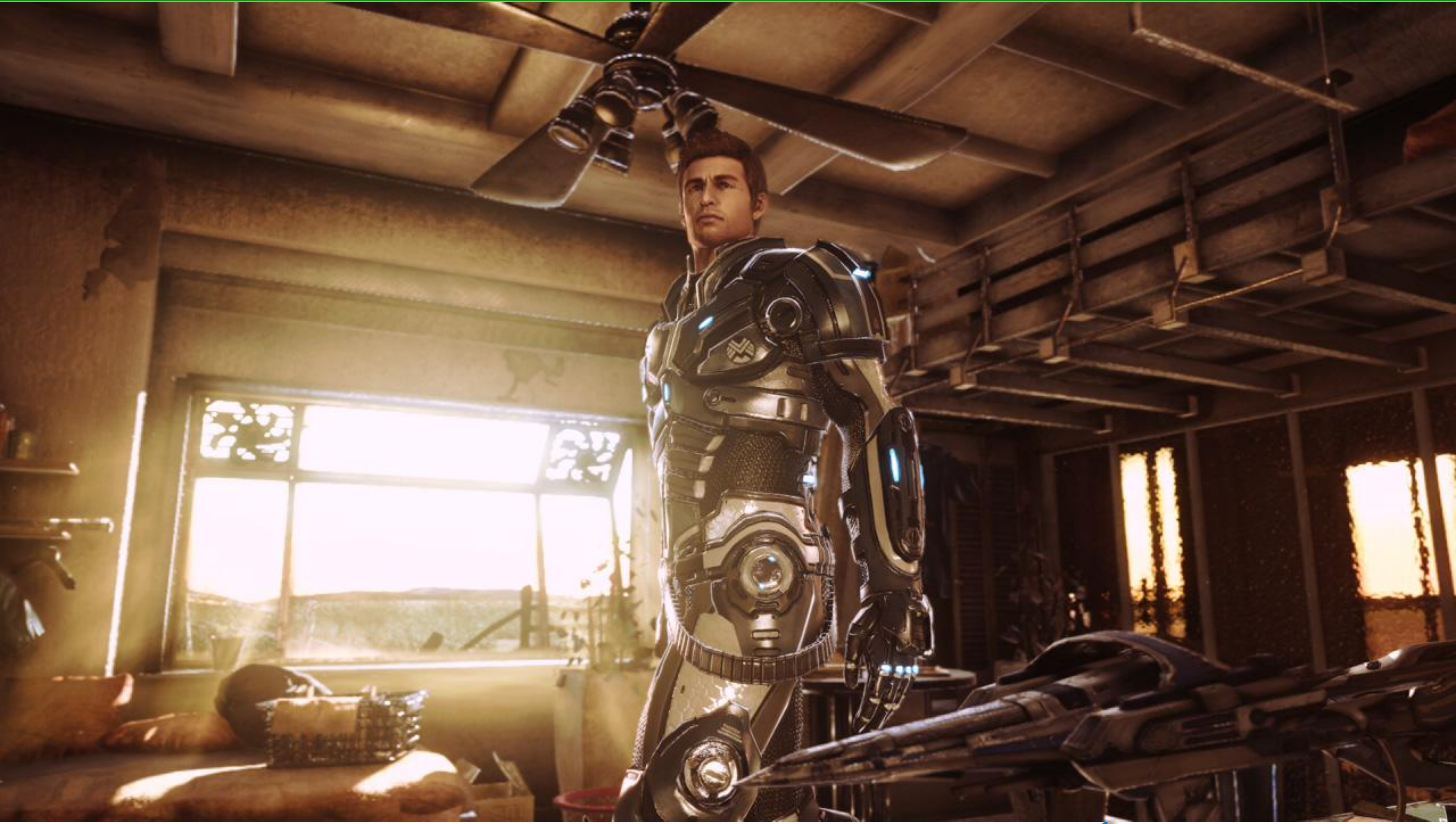
Shininess hack

HDR IBL Artifact

- The rendering result looks unnatural when the high intensity light that should be occluded is coming from grazing angles
  - Generally multiply by the ambient occlusion factor
    - Enough for LDR IBL
  - The artifact is noticeable when HDR IBL has a big difference of intensities, just like the real world
    - Multiplying by the ambient occlusion factor isn't enough



HDR IBL Artifact



Why does the artifact occur?

- Because it is physically based
  - It is sometimes very noticeable
    - It unnaturally looks too bright on some pixels (edge of objects)
  - This artifact occurs when all of the following are present: Fresnel effect, high intensity value from HDR IBL, physically based BRDF models, and high shininess values

Example of a material with a refractive index of 1.5

	Light intensity	E.H	Schlick	shininess	Result
Worst case	10.0	0.1	0.61	500	12.644
Best case	1.0	1.0	0.04	10	0.00502

A difference of about 2,500times!

Multiplying by AO factor

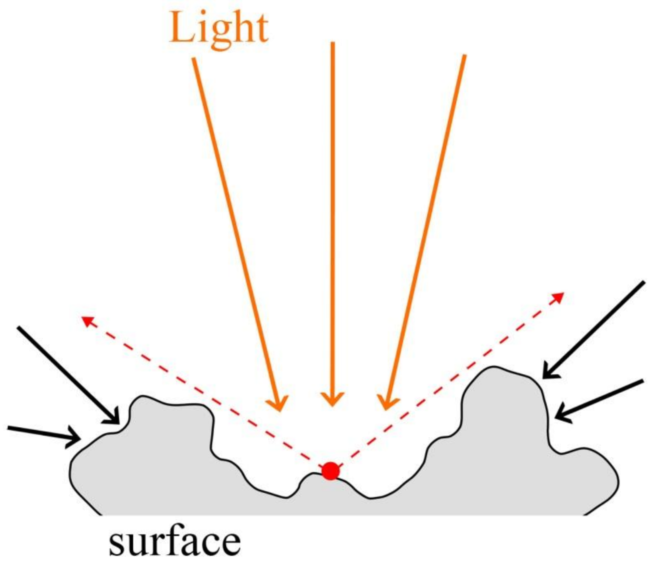
- Is not enough
  - Enough for LDR IBL and non physically based
    - Unnoticeable
  - Not enough for HDR IBL and physically based at all
    - If an AO factor is 0.1,
      - 12.64*0.1=1.264 with the example
      - Still higher than 1.0
  - Need a more aggressive occlusion factor

Novel Occlusion Factor

- Need almost zero for occluded cases
  - Not enough with 0.3 or 0.1 for HDR
    - Need 0.01 or less
  - Very small values for not occluded area are problematic
  - Need to compute an occlusion term designed for the specular component
    - High-order SH?
    - No more extra parameters!

Specular Occlusion

- SO is acquired from AO
  - Use AO factor as HBAO or SSAO
    - But precomputed AO factor is not HBAO factor
      - Using AO factor as HBAO factor that assumes that the pixel is occluded by the same angle for all horizontal directions
      - In other words, you can consider that the same occlusion happens for all directions in the case of SSAO

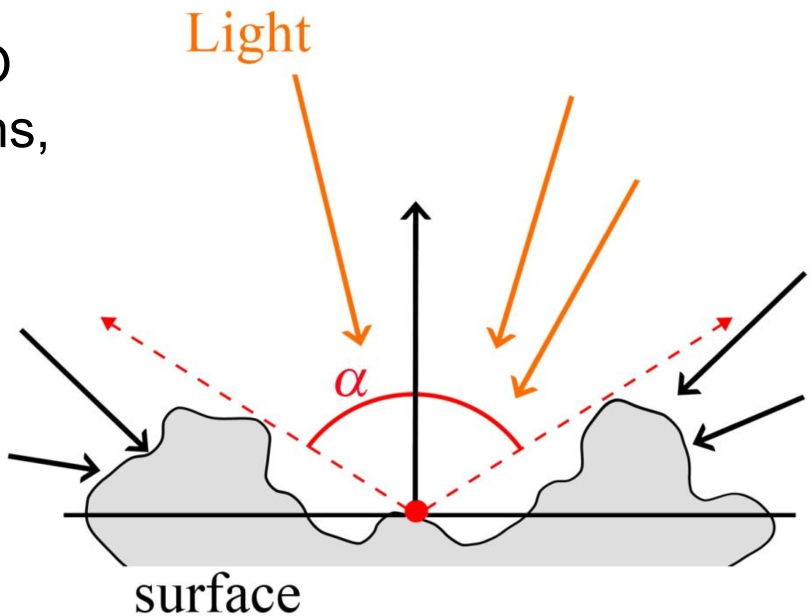


Aqcuire Specular Occlusion

- In the case where a pixel is isotropically occluded from the horizon without gaps
  - AO factor becomes

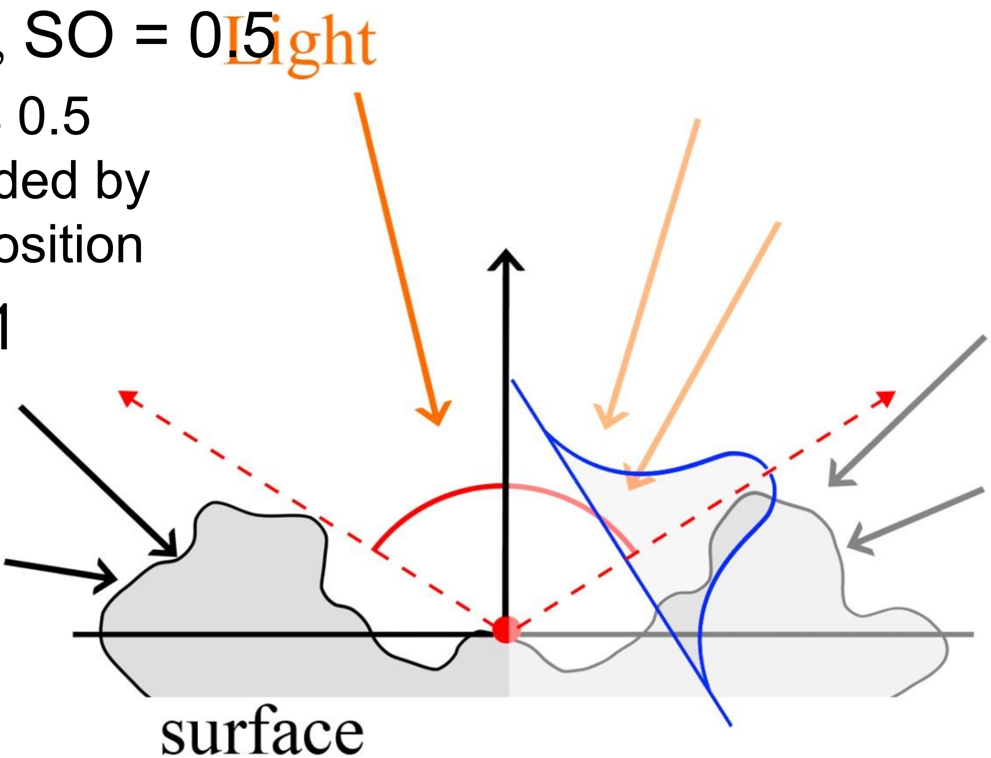
$$\frac{1}{\pi}\int_0^{\alpha}\int_0^{2\pi}\cos\theta\sin\theta d\phi d\theta = \cos^2\alpha$$

  - Neither conventional AO nor HBAO are isotropic for horizontal directions, but Specular Occlusion forcibly assumes that it is



Specular Occlusion implementation

- Required SO (Specular Occlusion) factor should satisfy the following as much as possible
  - Where θ = 0, SO = 0
  - Where $\theta = \cos^{-1}(AO^{0.5})$, SO = 0.5
    - Specular term becomes 0.5 where the pixel is occluded by a half at the occluded position
  - Where $\theta = \pi/2$, SO = 1



Specular Occlusion

Ambient Occlusion

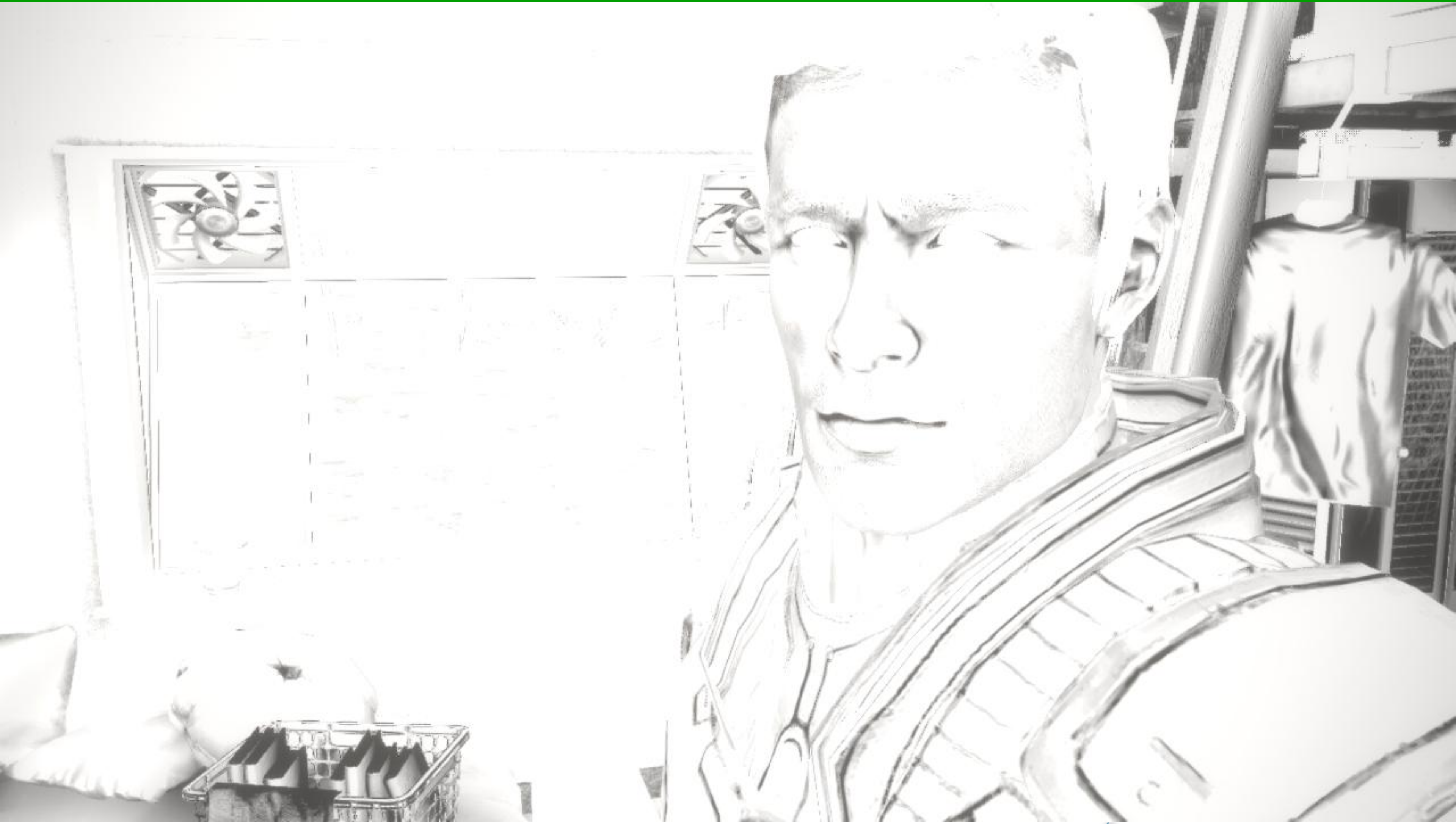
Specular Occlusion

SO implementation (1)

$$SO = \mathrm{saturate}\left((\mathbf{n}\cdot\mathbf{E})^2 + 2AO - 1\right)$$

- The first equation that satisfies the condition
  - Though this satisfies the conditions as Specular Occlusion, it is not physically based
  - Since Specular Occlusion literally represents the occlusion factor for the specular term, it should be affected by the shininess value

SO implementation (1)

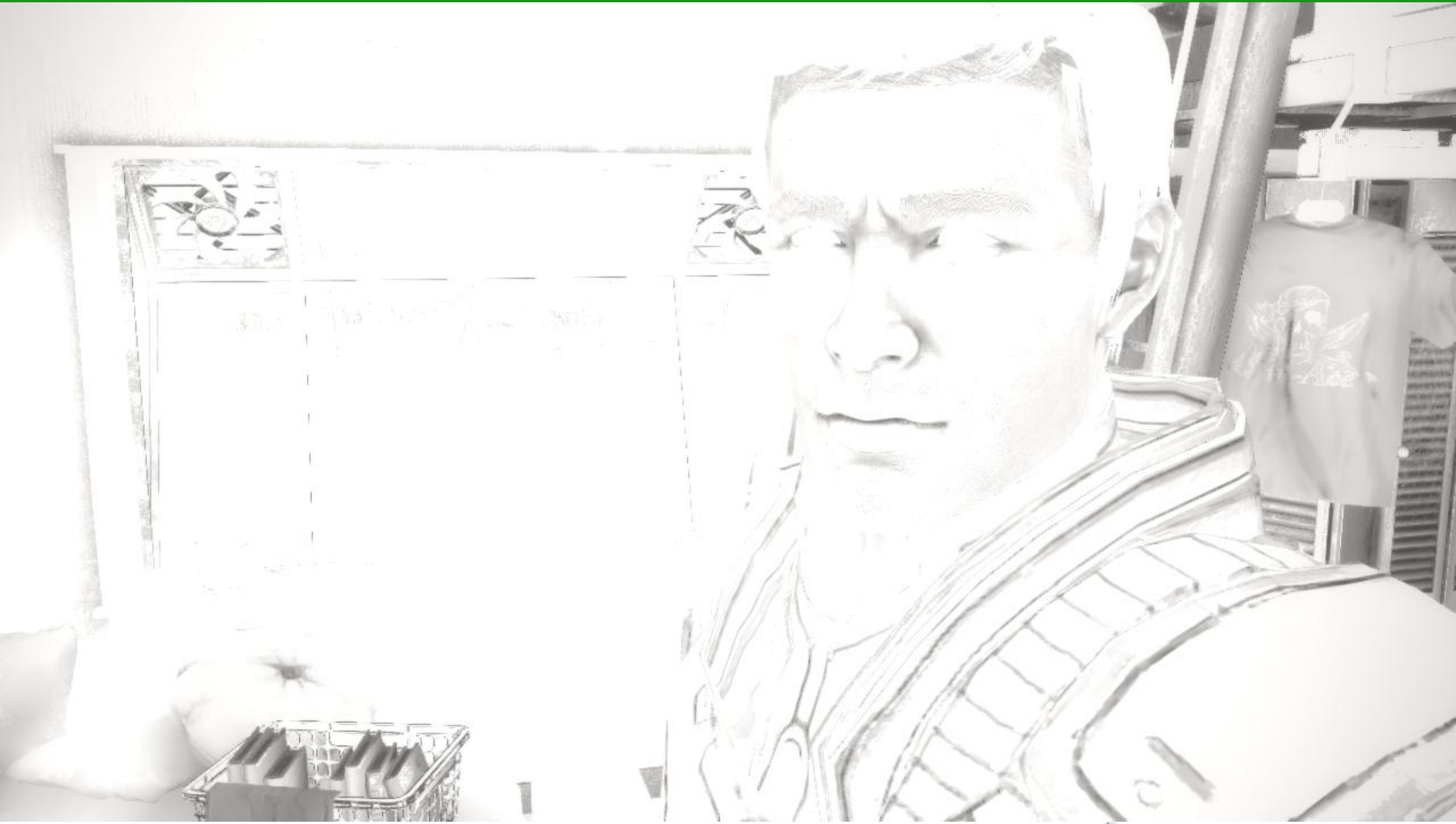


SO implementation (2)

$$SO = \mathrm{saturate}\left(\left((\mathbf{n}\cdot\mathbf{E}) + AO\right)^{0.01 shininess} - 1 + AO\right)$$

- Equation taking into account the shininess value
  - More physically based than the first one
  - SO suddenly changes with larger shininess values
  - High computational cost with Pow
    - A little visual contribution to the result
    - Smaller occlusion effect than expected

SO implementation (2)



SO implementation (3)

$$SO = \text{saturate}\left(\left((\mathbf{n}\cdot\mathbf{E}) + AO\right)^2 - 1 + AO\right)$$

- Optimizing the second equation
  - The physically based correctness with respect to shininess decreases
  - Stable as SO doesn't take into account shininess
    - Average occlusion effect becomes stronger
  - Optimized
    - The balance between quality and cost is good

SO implementation (3)

Ambient specular term computation

$$final = specular\_direct + specular\_ambient * SO$$

- Computing the final ambient term
  - With this equation, the pixel gets black, because the occluded pixel isn't lit by the ambient lights
    - In reality, the pixel would be illuminated by the some light reflected by some of the objects (interreflection)
    - The diffuse term has the same issue
      - AO itself is not such an aggressive occlusion term
      - Diffuse factor does not have such a high dynamic range
      - Not problematic
    - Problematic for the specular term
      - Unnaturally too dark

Ambient specular term computation

CROSS BORDER

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AS term computation (1)

$$final = s\_d + \mathrm{lerp}(diffuse\_ambient \cdot albedo, specular\_ambient, SO)$$

- Computing pseudo interreflection
  - Fundamentally, it should take into account light and albedo at the reflected point
    - Because this implementation is “pseudo”, it takes into account light and albedo at the shading point
- The results
  - Visually, we desired a little more aggressive occlusion effect
    - Not based on physics
  - Depending on the position, the rendering result becomes strange
    - This implementation does not take into account the actual interreflection

AS term computation (1)

AS term computation (2)

$$final = s\_d + \mathrm{lerp}(diffuse\_ambient * AO, specular\_ambient, SO)$$

- Multiplying by the AO factor instead of albedo
  - Interreflection like effect becomes smaller, but the occlusion effect becomes stronger
    - Visually preferable
    - Eventually, it depends on your preference
    - It is a good choice to make this an option for artists

AS term computation (2)

AS term computation (3)

$$final = s\_d + AO \cdot \mathrm{lerp}(diffuse\_ambient \cdot AO, specular\_ambient, SO)$$

- Again, the AO factor is multiplied by the specular term
  - Makes the specular effect for ambient lighting robust
    - Not based on physics
    - The SO factor itself approximates the approximation
    - Relatively adjusted to conservative result
      - It also depends on your preference

AS term computation (3)

AS term computation (4)

$$final = s\_d + \mathrm{lerp}(diffuse\_ambient \cdot AO^2, specular\_ambient, SO)$$

- The secondary AO factor is only multiplied by the diffuse term
  - Still your preference
    - This term is optional according to your preference
    - Not physical reason, but artistic direction

AS term computation (4)

$\mathrm{lerp}(diffuse\_ambient \cdot AO^2, specular\_ambient, SO)$

$AO \cdot \mathrm{lerp}(diffuse\_ambient \cdot AO, specular\_ambient, SO)$

Applying to the entire specular term

$$final = s\_d \cdot SO + AO \cdot \mathrm{lerp}(diffuse\_ambient \cdot AO, specular\_ambient, SO)$$

- SO factor is also available for the specular term with punctual lights
  - In our case, this is used for punctual lights
    - Big advantage with HDR, physically based materials and textures

With Specular Occlusion

W/o Specular Occlusion (Only AO)

With Specular Occlusion

IBL performance

ms @ 1280x720

	IBL	IBL+ 1direct light	SH	SH (no AmbientBRDF)
X360	5.8	7.0	5.0	4.5
PS3	5.9	7.9	5.1	4.3

Physically based IBL

CROSS BORDER

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Physically based IBL

Physically based IBL

Without the specular term for IBL

With the specular term for IBL

Conclusion

- When using physically based IBL
  - Area lighting which is difficult with punctual lights becomes feasible
    - Soft lighting by a large light source
    - Sharp lighting by a small light source
  - Consistent material representation with scenes by either direct and indirect lighting
    - Reduce hand adjustment by artists
    - Easy to set physically correct parameters to materials
  - True HDR representation becomes possible

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Questions?