Real-Time High Quality Rendering

GAMES202, Lingqi Yan, UC Santa Barbara

Lecture 5:
Real-Time Environment Mapping

Announcement

- Assignment 1 has been released
  - Due in 1.5 weeks
- No class next week (traveling)
  - No streaming and no recording
  - Will resume when I'm back
- Will soon start recruiting GAMES101 graders

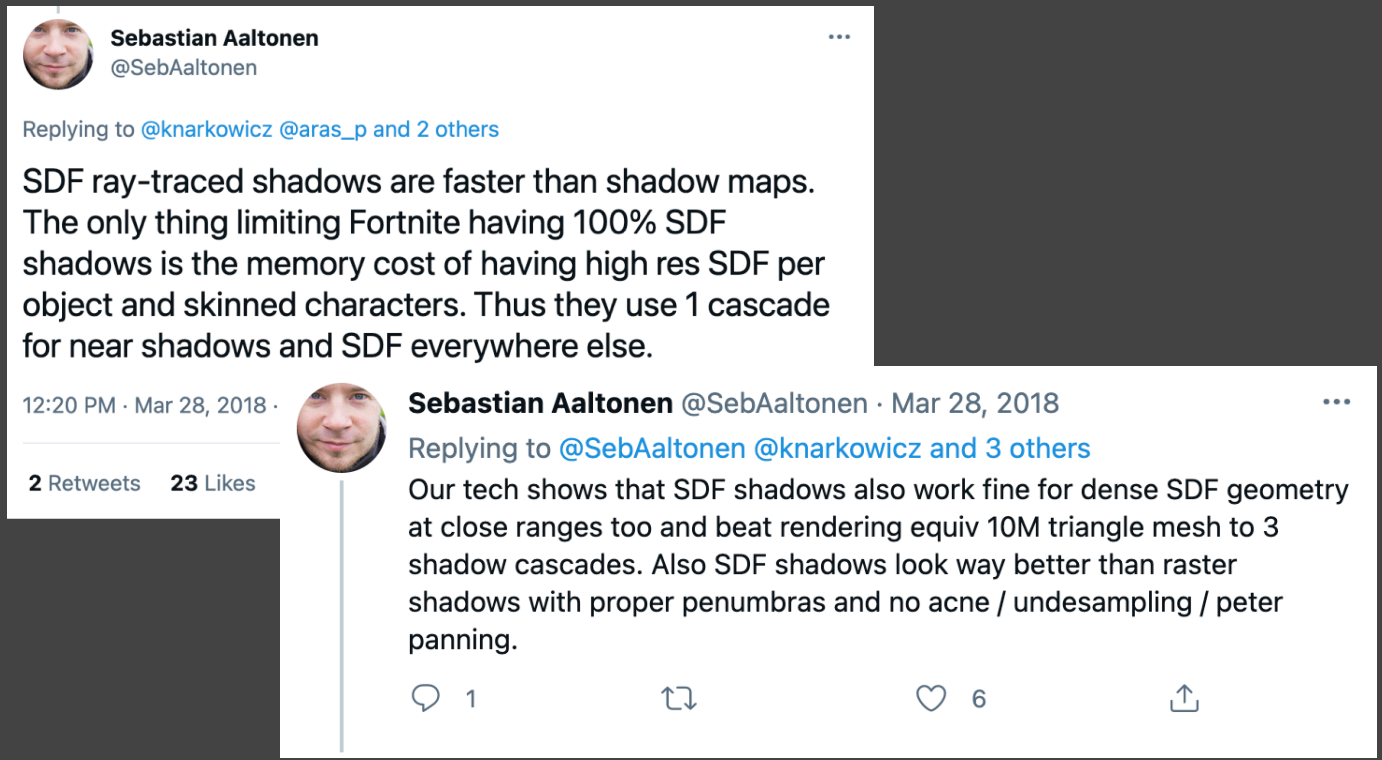
Last Lecture

- More on PCF and PCSS
- Variance soft shadow mapping
- MIPMAP and Summed-Area Variance Shadow Maps
- Moment shadow mapping

Today

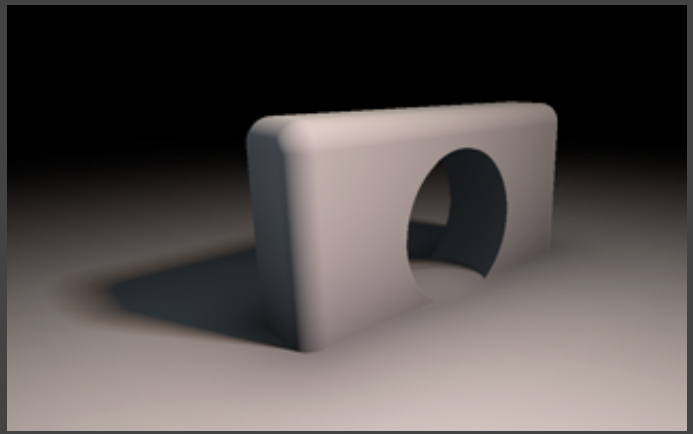
- Finishing up on shadows
  - Distance field soft shadows
- Shading from environment lighting
  - The split sum approximation
- Shadow from environment lighting

Why Distance Field Soft Shadows

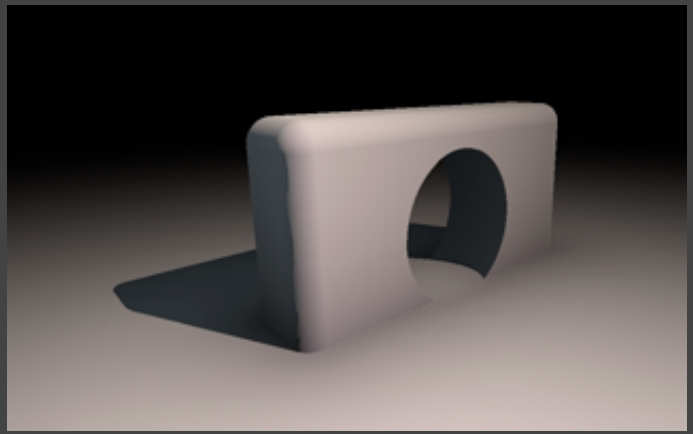


Some tweets by an indie game developer

Distance Field Soft Shadows



Soft shadow and penumbra computed using distance fields



Hard shadow

https://www.iquilezles.org/www/articles/rmshadows/rmshadows.htm

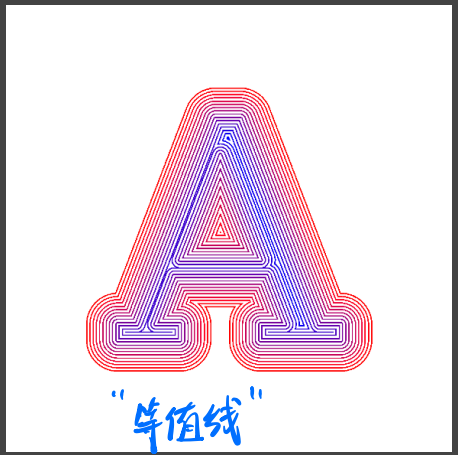
From GAMES101: Distance Functions

Distance functions:

在任意点，给出到对象上最近位置的最小距离（可为有符号距离）

At any point, giving the minimum distance (could be **signed** distance) to the closest location on an object

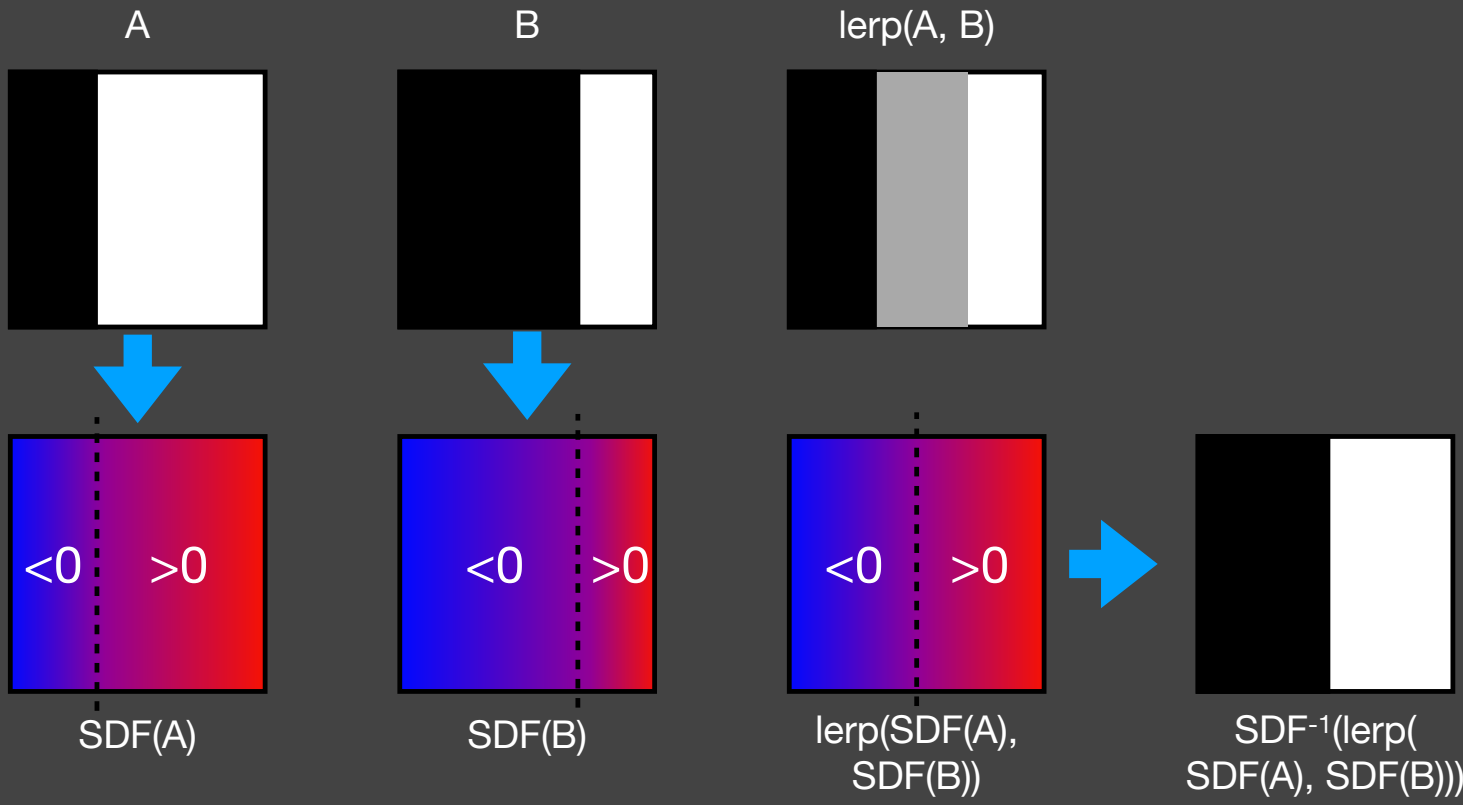
距离场 SDF



https://stackoverflow.com/questions/43613256/

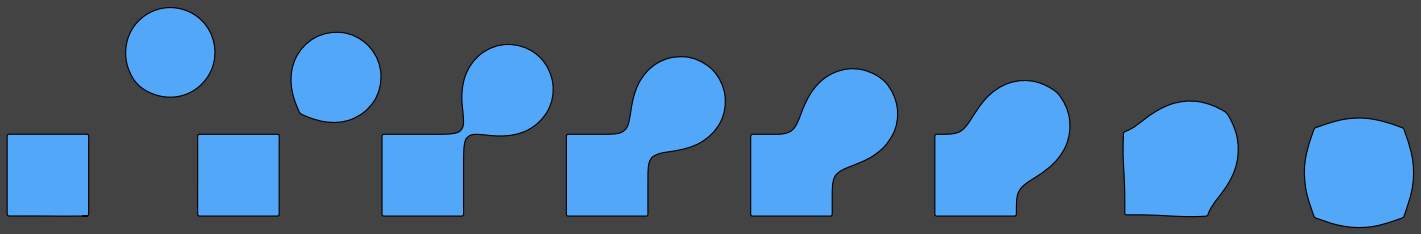
From GAMES101: Distance Functions

An Example: Blending (linear interp.) a moving boundary



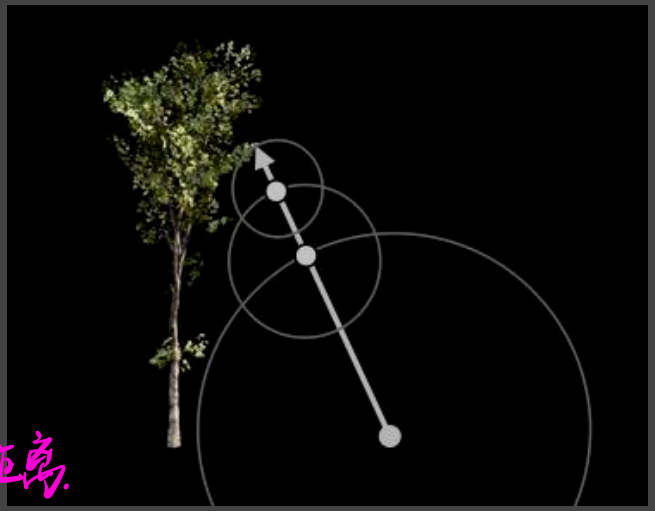
From GAMES101: Distance Functions

- Can blend any two distance functions d1, d2



The Usages of Distance Fields

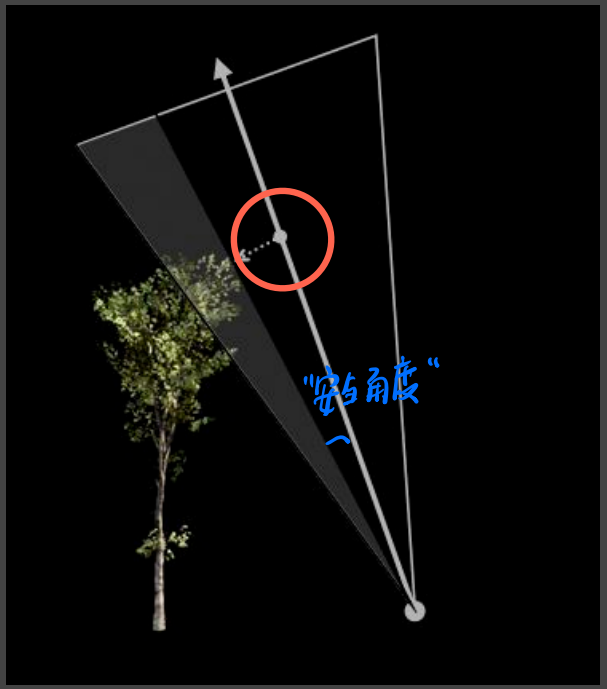
- Usage 1
  - Ray marching (sphere tracing) to perform ray-SDF intersection
  - Very smart idea behind this:
  - The value of SDF == a “safe” distance around
  - Therefore, each time at p, just travel SDF(p) distance



https://docs.unrealengine.com/en-US/BuildingWorlds/LightingAndShadows/MeshDistanceFields/index.html

The Usages of Distance Fields

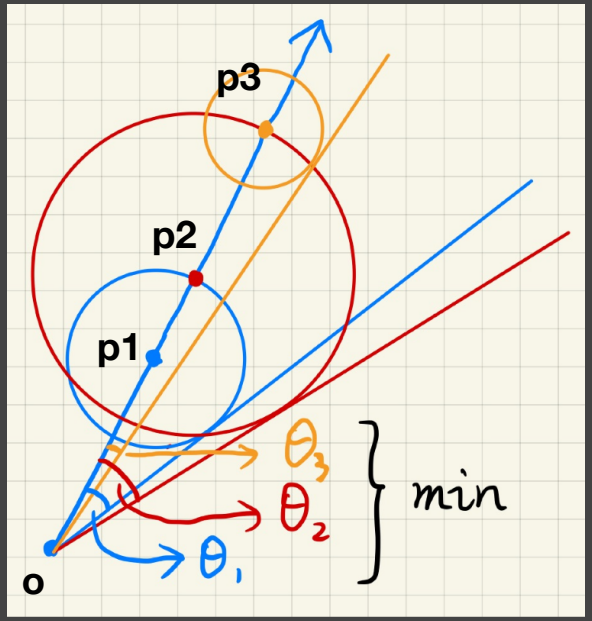
- Usage 2
  - Use SDF to determine the (approx.) percentage of occlusion
  - the value of SDF -> a “safe” angle seen from the eye
- Observation
  - Smaller “safe” angle <-> less visibility



https://docs.unrealengine.com/en-US/BuildingWorlds/LightingAndShadows/MeshDistanceFields/index.html

Distance Field Soft Shadows

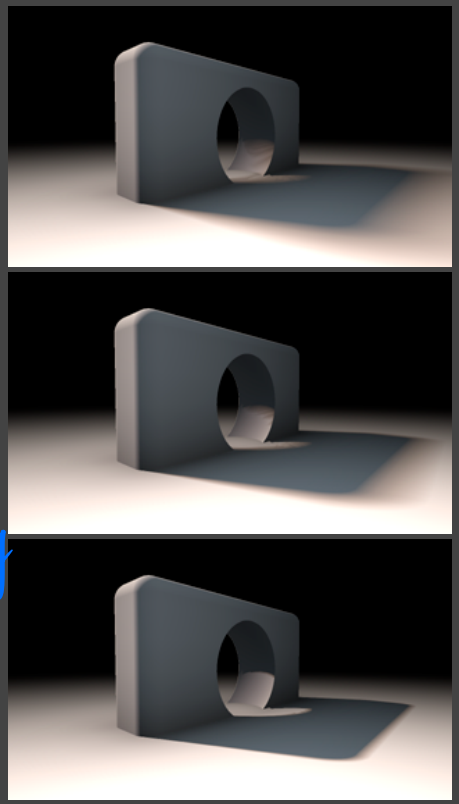
- During ray matching
  - Calculate the “safe” angle from the eye at every step
  - Keep the minimum
  - How to compute the angle?



Distance Field Soft Shadows

- How to compute the angle?

$$\arcsin \frac{\mathrm{SDF}(p)}{p-o} \qquad \min\left\{\frac{k\cdot \mathrm{SDF}(p)}{p-o}, 1.0\right\}$$

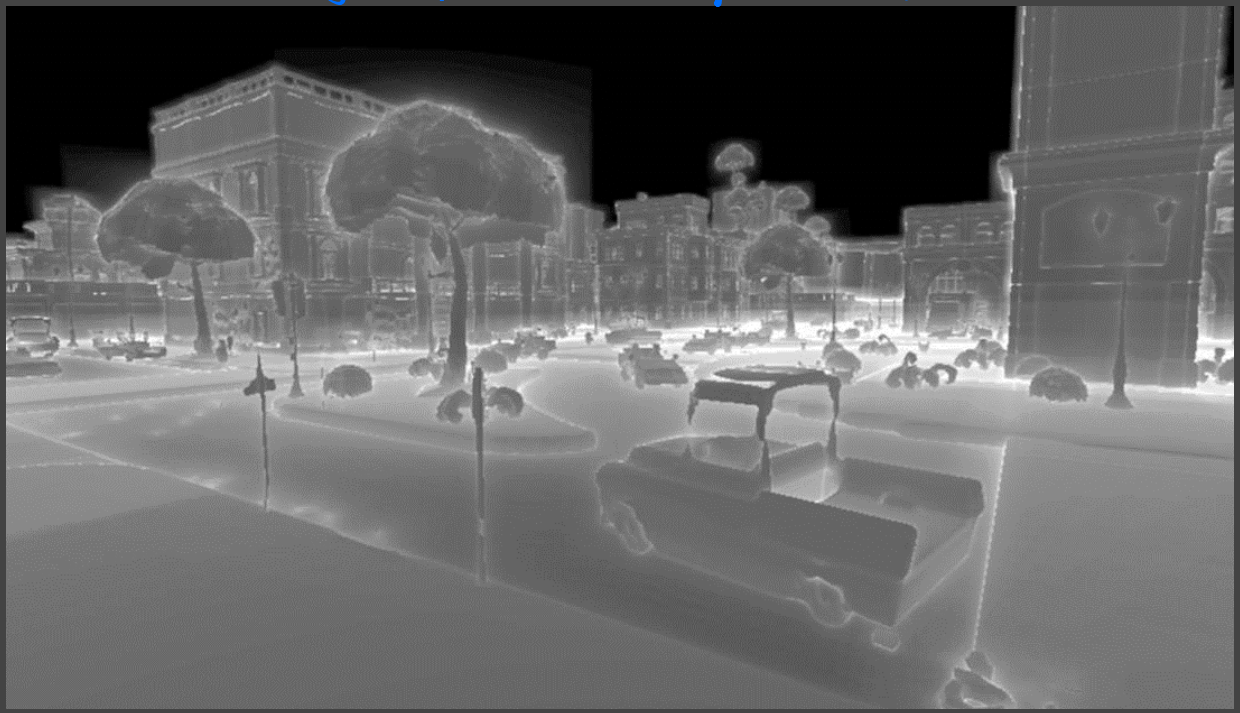


- Larger k <-> earlier cutoff of penumbra <-> harder

[https://www.iquilezles.org/www/articles/rmshadows/rmshadows.htm]

Distance Field: Visualization

每个像素存储对应mSDF（标量场）



https://docs.unrealengine.com/en-US/BuildingWorlds/LightingAndShadows/MeshDistanceFields/index.html

Pros and Cons of Distance Field

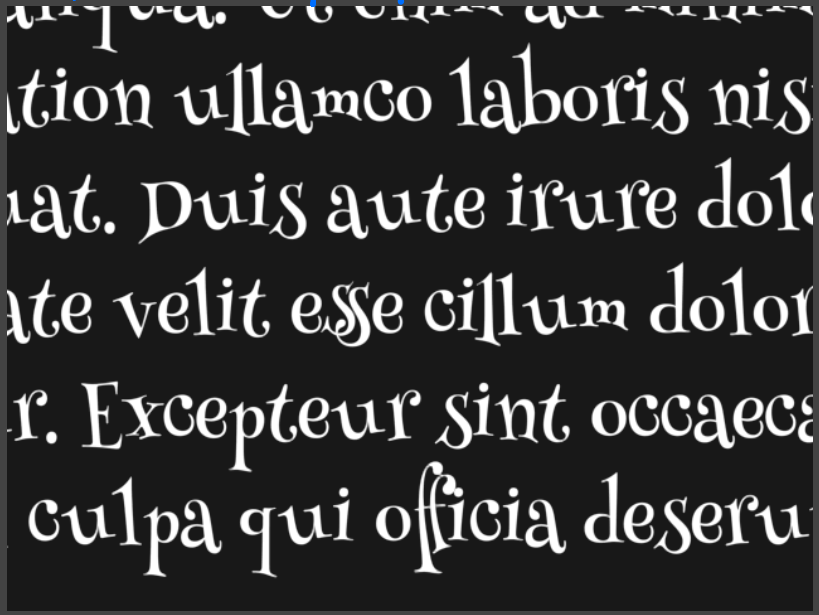
- Pros
  - Fast* Ray matching
  - High quality
- Cons
  - Need precomputation 需要预计算
  - Need heavy storage* 需要大量存储
  - Artifact?

静态物体，刚体变形 ✓
动态物体 重新计算 ×

Another Interesting Application

- Antialiased / infinite resolution characters in RTR

抗锯齿，无限分辨率字符 in RTR.



https://github.com/protectwise/troika/tree/master/packages/troika-three-text

Questions?

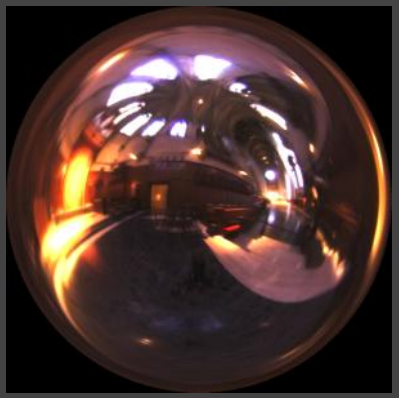
Today

- Finishing up on shadows
  - Distance field soft shadows
- Shading from environment lighting
  - The split sum approximation
- Shadow from environment lighting

Recap: Environment Lighting

表示来自所有方向的远处照明的图像

- An image representing distant lighting from all directions



- Spherical map vs. cube map

球面贴图　　立方体贴图

Shading from Environment Lighting

- Informally named Image-Based Lighting (IBL)
- How to use it to shade a point (without shadows)?
  - Solving the rendering equation

$$L_o(\mathrm{p}, \omega_o) = \int_{\Omega^+} L_i(\mathrm{p}, \omega_i) f_r(\mathrm{p}, \omega_i, \omega_o) \cos\theta_i V(\mathrm{p}, \omega_i) \mathrm{d}\omega_i$$

For all directions from the upper hemisphere

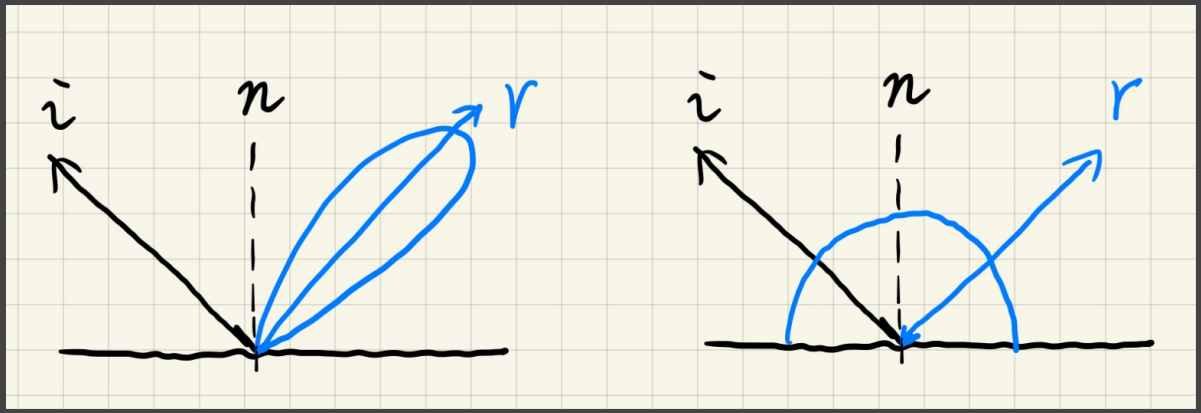
上半球所所有方向.

Shading from Environment Lighting

- General solution — Monte Carlo integration
  - Numerical
  - Large amount of samples required
- Problem — can be slow
  - In general, sampling is not preferred in shaders*
  - **Can we avoid sampling?**

Shading from Environment Lighting

- Observation
  - If the BRDF is glossy — small support!
  - If the BRDF is diffuse — smooth!
  - Does the observation remind you of something?



The Classic Approximation

- Recall: the approximation
  - Note the slight edit on Ω_G here

$$\int_{\Omega} f(x)g(x)\,\mathrm{d}x \approx \frac{\int_{\Omega_G} f(x)\,\mathrm{d}x}{\int_{\Omega_G}\,\mathrm{d}x} \cdot \int_{\Omega} g(x)\,\mathrm{d}x$$

- Conditions for acceptable accuracy?

The Split Sum: 1st Stage

- BRDF satisfies the accuracy condition in any case
  - We can safely take the lighting term out!

$$L_o(p,\omega_o) \approx \frac{\int_{\Omega_{f_r}} L_i(p,\omega_i)\,\mathrm{d}\omega_i}{\int_{\Omega_{f_r}} \mathrm{d}\omega_i} \cdot \int_{\Omega^+} f_r(p,\omega_i,\omega_o)\cos\theta_i\,\mathrm{d}\omega_i$$

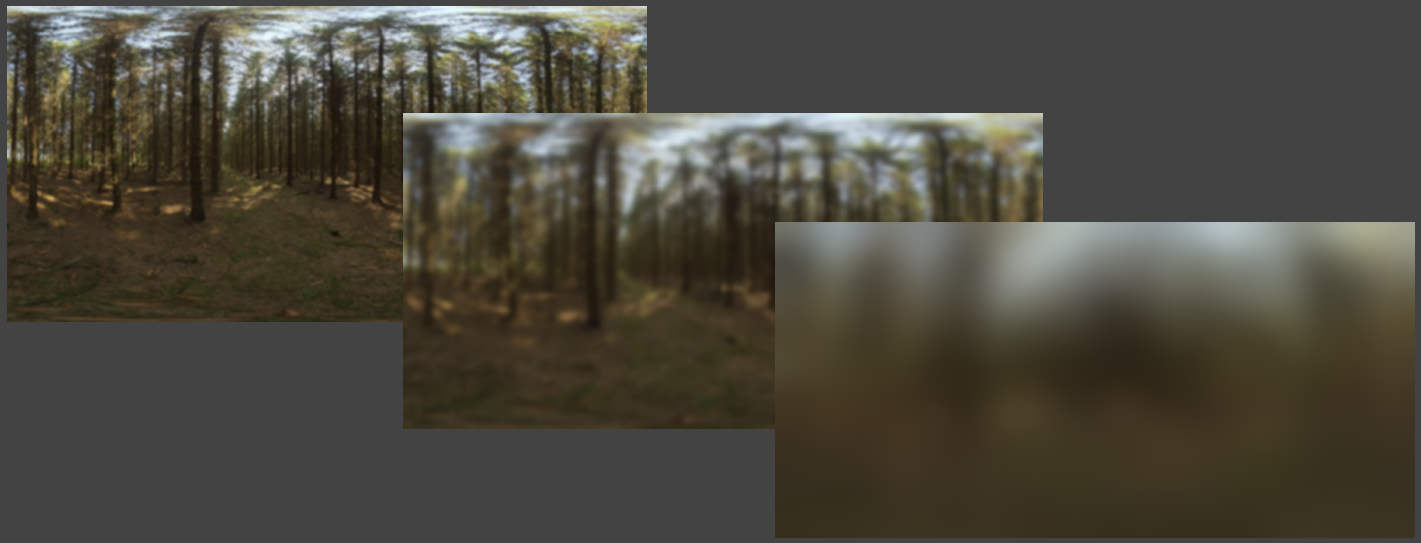
- Note: different usage in shadows (taking vis. out)

$$L_o(\mathrm{p},\omega_o) \approx \frac{\int_{\Omega^+} V(\mathrm{p},\omega_i)\,\mathrm{d}\omega_i}{\int_{\Omega^+} \mathrm{d}\omega_i} \cdot \int_{\Omega^+} L_i(\mathrm{p},\omega_i) f_r(\mathrm{p},\omega_i,\omega_o)\cos\theta_i\,\mathrm{d}\omega_i$$

The Split Sum: 1st Stage

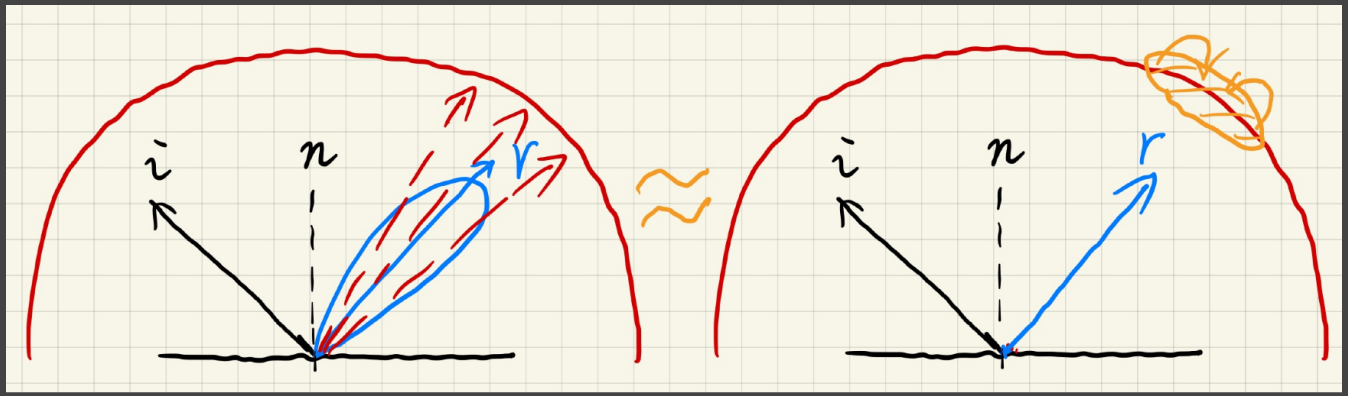
对立射 lighting

- Prefiltering of the environment lighting
  预先生成一组不同 filtered 和环境照明.
  - Pre-generating a set of differently filtered environment lighting
  - Filter size in-between can be approximated via trilinear interp.
    处于两张图之间的 Filter size 可通过三线性插值近似.



The Split Sum: 1st Stage

- Then query the pre-filtered environment lighting at the r (mirror reflected) direction!



The Split Sum: 2nd Stage

- The second term is still an integral
  - How to avoid sampling this term?

$$L_o(p,\omega_o) \approx \frac{\int_{\Omega_{fr}} L_i(p,\omega_i)\,\mathrm{d}\omega_i}{\int_{\Omega_{fr}} \mathrm{d}\omega_i} \cdot \boxed{\int_{\Omega^+} f_r(p,\omega_i,\omega_o)\cos\theta_i\,\mathrm{d}\omega_i}$$

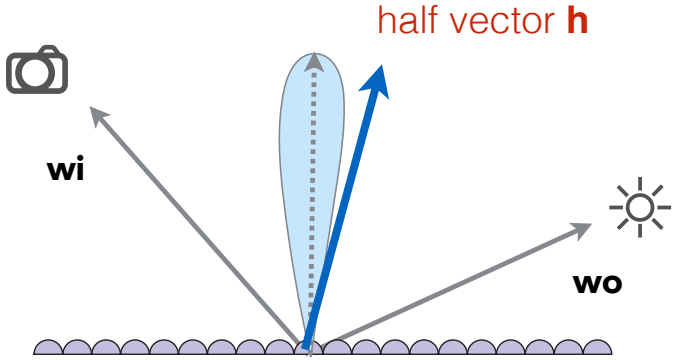
- Idea
  - Precompute its value for all possible combinations of variables roughness, color (Fresnel term), etc.
  - But we'll need a huge table with extremely high dimemsions

如何有可能的变量组合（粗糙度、颜色（菲涅耳项）等）预计算其值.

表格巨大（>5 dimensions）

Recall: Microfacet BRDF

- What kind of microfacets reflect wi to wo? (hint: microfacets are mirrors)



Fresnel term

shadowing-masking term

distribution of normals

$$f(\mathbf{i},\mathbf{o}) = \frac{\mathbf{F}(\mathbf{i},\mathbf{h})\mathbf{G}(\mathbf{i},\mathbf{o},\mathbf{h})\mathbf{D}(\mathbf{h})}{4(\mathbf{n},\mathbf{i})(\mathbf{n},\mathbf{o})}$$

The Fresnel Term and the NDF

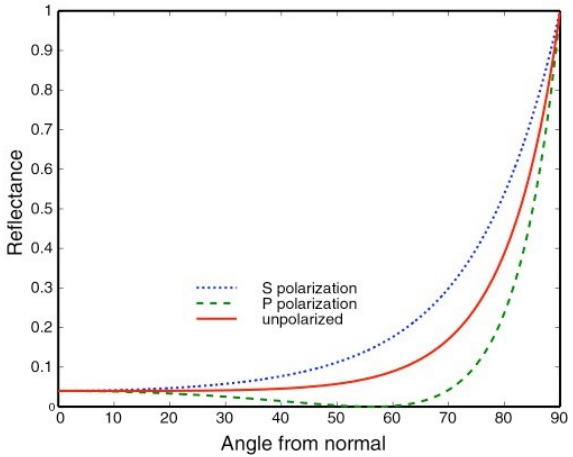
近似 Fresnel term

Fresnel term: the Schlick's approximation

基础反射率（颜色）

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos\theta)^5$$

$$R_0 = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$



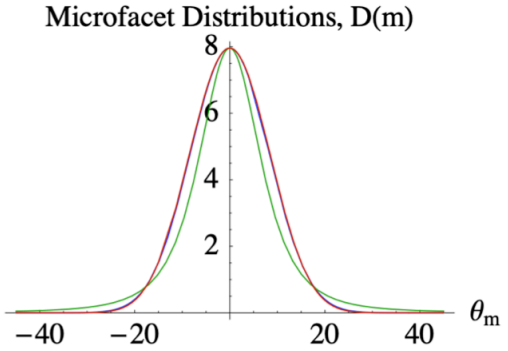
微面元分布（normals 法线）

The NDF term: e.g. Beckmann distribution

$$D(h) = \frac{e^{-\frac{\tan^2\theta_h}{\alpha^2}}}{\pi\alpha^2\cos^4\theta_h}$$

roughness

{ diffuse
glossy



三维预计算 $R_0 \alpha \theta$

The Split Sum: 2nd Stage

- Idea & Observation
  - Try to split the variables again!
  - The Schlick approximated Fresnel term is much simpler: Just the "base color" R_0 and the half angle θ

- Taking the Schlick's approximation into the 2nd term
  - The "base color" is extracted!

只剩2个变量 roughness、θi (入射角)

$$\int_{\Omega^+} f_r(p,\omega_i,\omega_o)\cos\theta_i \,\mathrm{d}\omega_i \approx R_0 \int_{\Omega^+} \frac{f_r}{F}\left(1-(1-\cos\theta_i)^5\right)\cos\theta_i \,\mathrm{d}\omega_i + \int_{\Omega^+} \frac{f_r}{F}(1-\cos\theta_i)^5\cos\theta_i \,\mathrm{d}\omega_i$$

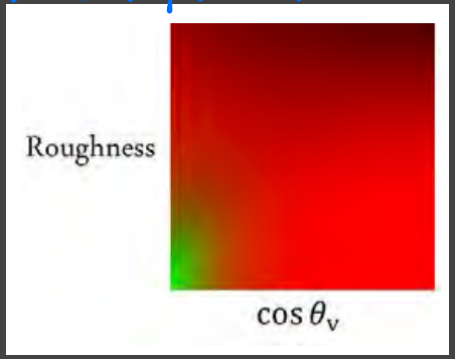
菲涅耳项 R(θi) (也就是 F(i,h))

The Split Sum: 2nd Stage

- Both integrals can be precomputed

$$\int_{\Omega^+} f_r(p,\omega_i,\omega_o)\cos\theta_i\,\mathrm{d}\omega_i \approx R_0 \int_{\Omega^+} \frac{f_r}{F}\left(1-(1-\cos\theta_i)^5\right)\cos\theta_i\,\mathrm{d}\omega_i + \int_{\Omega^+} \frac{f_r}{F}(1-\cos\theta_i)^5\cos\theta_i\,\mathrm{d}\omega_i$$

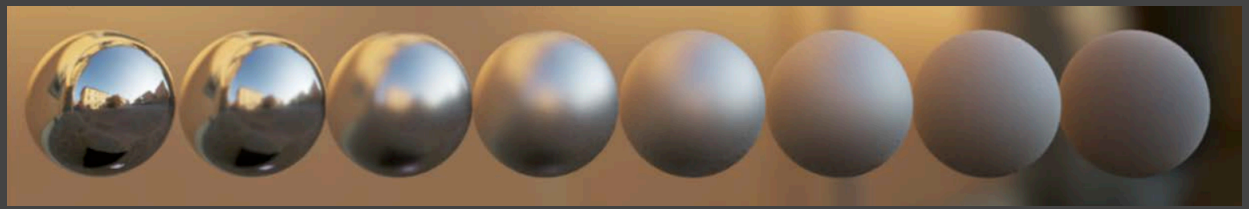
- Each integral produces one value for each (roughness, incident angle) pair
  - Therefore, each integral results in a 2D table (texture)



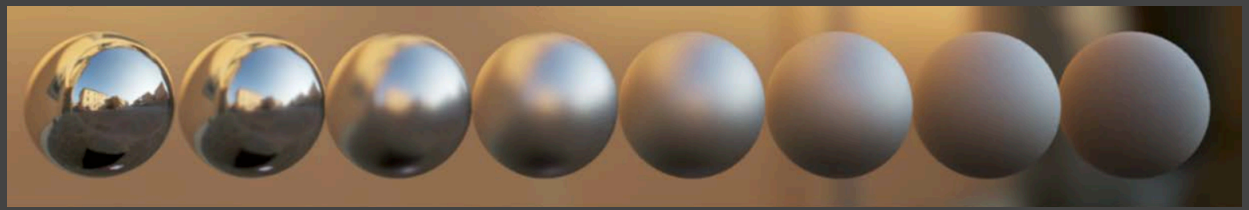
The Split Sum Approximation

- Finally, completely avoided sampling
- Very fast and almost identical results

Reference



Split sum



The Split Sum Approximation

- In the industry
  - Integral -> Sum 积分 => 求和

$$\frac{1}{N}\sum_{k=1}^{N}\frac{L_i(\mathbf{l}_k)f(\mathbf{l}_k,\mathbf{v})\cos\theta_{\mathbf{l}_k}}{p(\mathbf{l}_k,\mathbf{v})} \approx \left(\frac{1}{N}\sum_{k=1}^{N}L_i(\mathbf{l}_k)\right)\left(\frac{1}{N}\sum_{k=1}^{N}\frac{f(\mathbf{l}_k,\mathbf{v})\cos\theta_{\mathbf{l}_k}}{p(\mathbf{l}_k,\mathbf{v})}\right)$$

- That's why it's called split sum rather than "split integral"

Questions?

Next Lecture

- Stepping into real-time global illumination!
  - In 3D
  - In the image space
  - By precomputation
- We'll start with 3D methods
  - LPV, VXGI, RTXGI, etc.

[VXGI by NVIDIA]

Thank you!