GPU Programming for Video Games

Physically-Based Rendering

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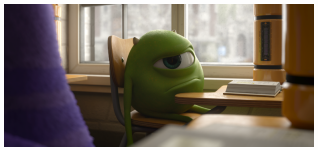
Georgia Institute of Technology

PBR does not imply "photorealistic"



B. Burley, "Physically Based Shading at Disney"

"Physically Based Lighting at Pixar," C. Hery and R. Villemin

From http://blog.selfshadow.com/publications/s2012-shading-course/ and http://blog.selfshadow.com/publications/s2013-shading-course/

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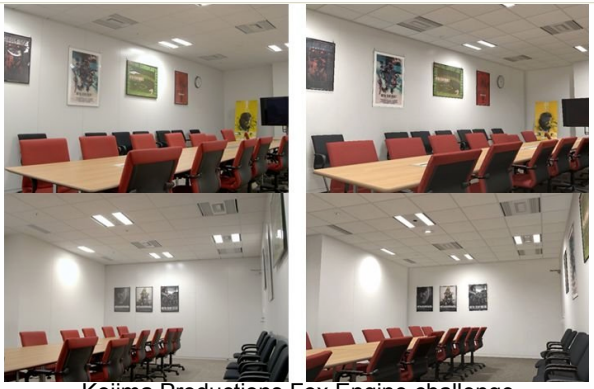
But photorealism implies PBR!



Kojima Productions Fox Engine challenge

From http://andriasang.com/con063/fox_engine_lighting

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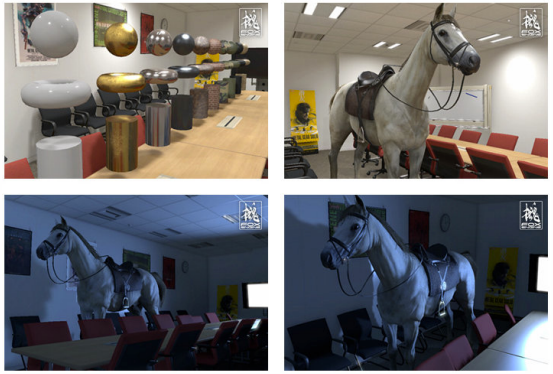
Which is real, which is rendered?



Kojima Productions Fox Engine challenge

From http://andriasang.com/con063/fox_engine_lighting

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Credit where it is due

Bio:
Little is known. Reliable sources have confirmed sightings at Georgia Tech, Electronic Arts in Vancouver and Los Angeles, and Naughty Dog. He is rumored to have worked on Uncharted 2 and Steven Spielberg's project, LMNO. Several eyewitnesses claim to have seen him compressing Tiger Woods's face, but said reports are dismissed as speculation.

filmicgames.com
filmicworlds.com

BS&MS in CS from GT

Elements of PBR

- Linear space lighting
- Energy conservation
- Reciprocity
- Metallic/dielectric distinction
- "Everything is shiny" (i.e., has specular)
- "Everything has Fresnel"
- Bonus: high definition render buffers and tonemapping to handle high dynamic range

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Important for Global Illumination

Hable on linear space lighting

"Linear-space lighting is the single most important thing for graphics programmers and technical artists to know.

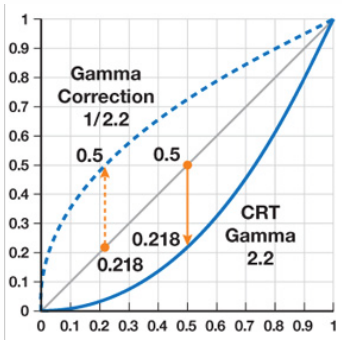
It's not that hard, but for whatever reason, no one really teaches it.

Personally, I got a BS and MS at Georgia Tech, took basically every graphics class they had, and didn't hear about it until I learned about it from George Borshukov."

– John Hable

From http://filmicgames.com/archives/299

Gamma curves



From http://http.developer.nvidia.com/GPUGems3/gpugems3_ch24.html

DIY linear space (helpers)

```
inline float3 DeGamma (in float3 c) {
  // return c*c;
  return pow(c,2.2);
}

inline float3 ReGamma (in float3 c) {
  // return sqrt(c);
  return pow(c,1/2.2);
}
```


DIY linear space in shader

```
#pragma surface surf BlinnPhong finalcolor:finalgamma
```

• • •

```
void finalgamma (Input IN,
      SurfaceOutput o, inout fixed4 c) {
      c = fixed4(ReGamma(c.xyz),c.a);
}
```

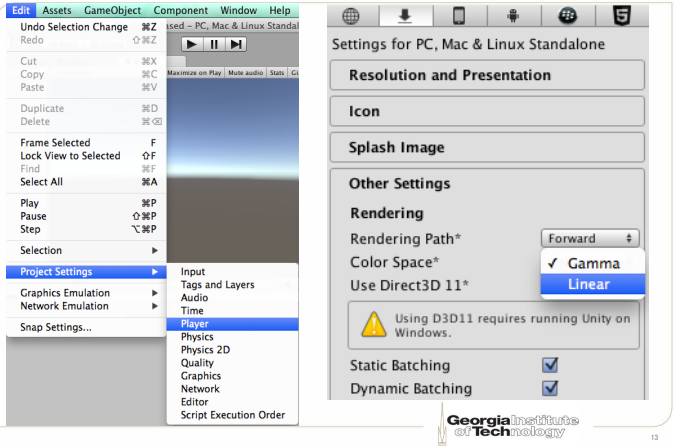
In your surface shader:

```
float4 tex = tex2D(_MainTex,IN.uv_MainTex);
tex.rgb = DeGamma(tex.rgb);
```

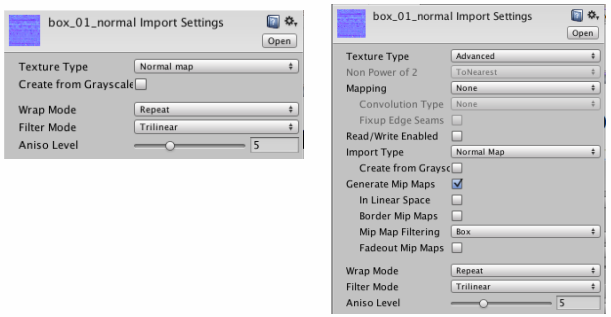

Let the GPU magically handle it

- Avoid wasting instructions in pixel shader
- Direct3D API:
  - Texture read: `D3DSAMP_SRGBTEXTURE`
  - Pixel write: `D3DRS_SRGBWRITEENABLE`
- OpenGL API:
  - Texture read: `GL_EXT_texture_sRGB`
  - Pixel write: `GL_EXT_framebuffer_sRGB`

Tell Unity to let GPU handle it

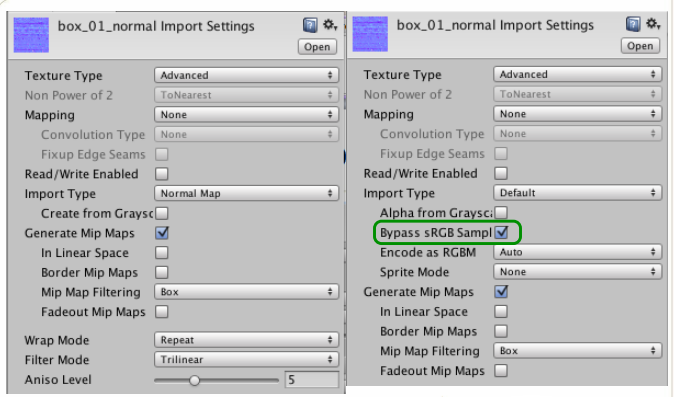


When to bypass sRGB sampling (1)



From http://http.developer.nvidia.com/GPUGems3/gpugems3_ch24.html

When to bypass sRGB sampling (2)



Bidirectional Reflectance Functions

- For "punctal" lights (typical point, directional, spotlight...)

$$C_{final} = C_{light} \otimes \pi BDRF(stuff)\max(0, n \bullet L)$$

- Classic diffuse lighting model: $BRDF = \frac{C_{diff}}{\pi}$
- Classic Blinn-Phong lighting model:

$$BRDF = \frac{C_{spec}}{\pi}\frac{(n \bullet H)^s}{n \bullet L} \text{ for } n \bullet L > 0$$

Reciprocity

- Reciprocity means we can swap the incoming and outgoing light directions in the BRDF
- Obviously true for classic diffuse lighting:

$$BRDF = \frac{C_{diff}}{\pi}$$

Reciprocity

- Does not hold for classic Blinn-Phong:

$$BRDF = \frac{C_{spec}}{\pi} \frac{\left(n \bullet \frac{L+V}{|L+V|} \right)^s}{n \bullet L} \text{ for } n \bullet L > 0$$

$$\neq \frac{C_{spec}}{\pi} \frac{\left(n \bullet \frac{V+L}{|V+L|} \right)^s}{n \bullet V} \text{ for } n \bullet V > 0$$

Modified Blinn-Phong

- Modified Blinn-Phong:

$$BRDF = \frac{C_{spec}}{\pi} (n \bullet H)^s$$

$$C_{final} = C_{light} \otimes \pi BDRF(stuff) \max(0, n \bullet L)$$

$$= C_{light} \otimes C_{spec} (n \bullet H)^s \max(0, n \bullet L)$$

Energy conservation

"Total amount of reflected light cannot be more than the amount of incoming light" – Rory Driscoll

- For classic diffuse model $BRDF = \frac{C_{diff}}{\pi}$

  turns out you *technically* need $\pi C_{diff} < 1$

- Since π is just a constant, "we usually just ignore it and assume that our lights are just π times too bright." – Steve McAuley

From http://blog.stevemcauley.com/2011/12/03/energy-conserving-wrapped-diffuse and http://www.rorydriscoll.com/2009/01/25/energy-conservation-in-games

A common yet confusing convention

- For classic diffuse model $BRDF = \frac{C_{diff}}{\pi}$

  we'll pretend you *practically* need $C_{diff} < 1$
- Convenient for artists: hit a diffuse surface with a color of "1" with a directional light with an "intensity" of "1" parallel with its normal and you get "1"
- Will use same convention throughout
- If you are implementing global illumination, be careful!

Normalized modified Blinn-Phong

- To achieve energy conservation:

$$BRDF = \frac{s+8}{8\pi} C_{spec} \left(n \bullet H\right)^s$$

with *practical* need $C_{spec} < 1$

$$C_{final} = C_{light} \otimes \frac{s+8}{8} C_{spec} \left(n \bullet H\right)^s \max(0, n \bullet L)$$

From http://blog.stevemcauley.com/2011/12/03/energy-conserving-wrapped-diffuse
and http://www.rorydriscoll.com/2009/01/25/energy-conservation-in-games

Combining specular and diffuse

- Combined BRDF:

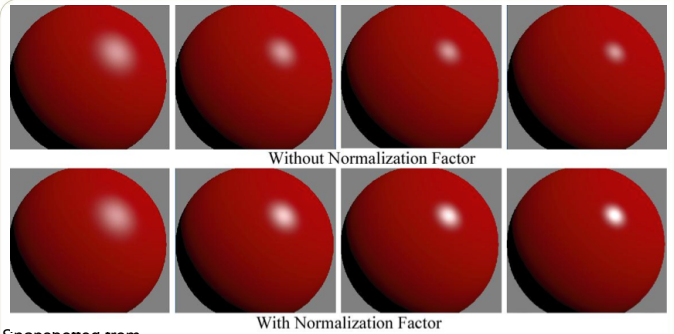
$$BRDF = \frac{C_{diff}}{\pi} + \frac{s+8}{8\pi} C_{spec} \left(n \bullet H\right)^s$$

with *practical* need $C_{diff} + C_{spec} < 1$

$$C_{final} = C_{light} \otimes \left[C_{diff} + \frac{s+8}{8} C_{spec} \left(n \bullet H\right)^s \right] \max(0, n \bullet L)$$

From http://blog.stevemcauley.com/2011/12/03/energy-conserving-wrapped-diffuse
and http://www.rorydriscoll.com/2009/01/25/energy-conservation-in-games

Normalized specular helps your artists

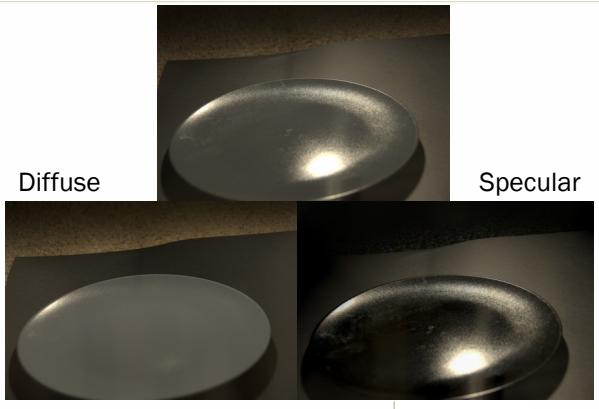


Snapshotted from
http://renderwonk.com/publications/s2010-shading-course/hoffman/s2010_physically_based_shading_hoffman_b.pdf
Image from "Real-Time Rendering," 3rd Edition, A K Peters 2008

Metals vs. dielectrics

- Dielectrics have diffuse and specular reflections
  - Specular reflection is white
- Metals have purely specular reflections
  - Specular reflection may be non-white

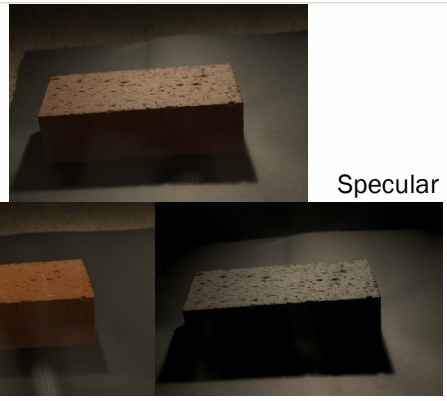
Of course, metal plates are shiny



Diffuse Specular

From http://filmicgames.com/archives/547

But bricks are shiny too

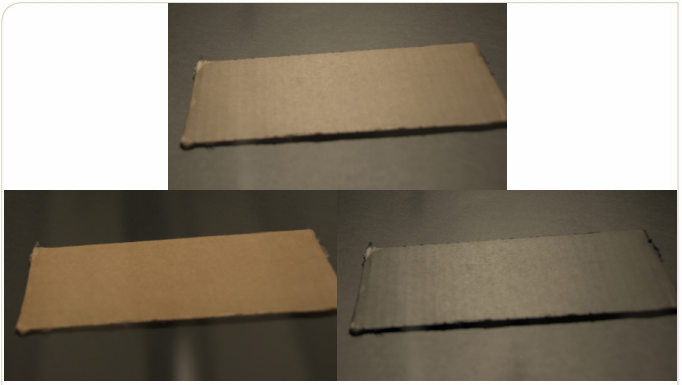


Diffuse Specular

From http://filmicgames.com/archives/547

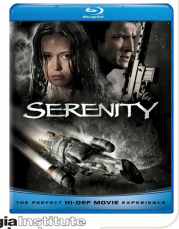
But cardboard can't be shiny, right?

Nope, cardboard is shiny!



From http://filmicgames.com/archives/547

BECAUSE EVERYTHING IS SHINY!



Pictures from amazon.com

John Hable on cardboard

"Poor cardboard.

So misunderstood.

It always gets referred to as a 'pure diffuse material', even though it actually deserves to hang out with its shiny friends."

– John Hable

From http://filmicgames.com/archives/557

Fresnel effect

- Specular reflections increase dramatically at high grazing angles
- Schlick approximation:

$$F(V,H) = F_0 + (1 - F_0)(1 - V \bullet H)^5$$

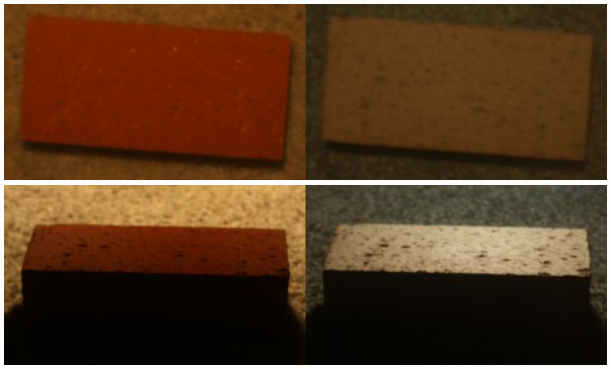
$$= F_0 + (1 - F_0)(1 - L \bullet H)^5$$

Reflection when view and light vector align

white

(grey for dielectrics, but metals can have color)

Bricks have Fresnel

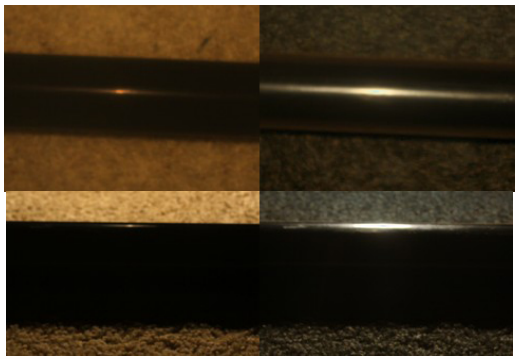


From http://filmicgames.com/archives/557

Cardboard has Fresnel

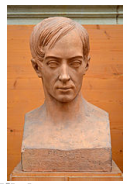
From http://filmicgames.com/archives/557

PVC pipes have Fresnel



From http://filmicgames.com/archives/557

EVERYTHING HAS FRESNEL



Pictures from wikipedia

F_0 for dialectrics (linear)

Quartz	0.045593921
Ice	0.017908907
Water	0.020373188
Alcohol	0.01995505
Glass	0.04
Milk	0.022181983
Ruby	0.077271957
Crystal	0.111111111
Diamond	0.171968833
Skin	0.028

Remember *specular* reflection of dielectrics is white!

From https://seblagarde.wordpress.com/2011/08/17/feeding-a-physical-based-lighting-mode/

F_0 for metals (linear)

	R	G	B
Silver	0.971519	0.959915	0.915324
Aluminium	0.913183	0.921494	0.924524
Gold	1	0.765557	0.336057
Copper	0.955008	0.637427	0.538163
Chromium	0.549585	0.556114	0.554256
Nickel	0.659777	0.608679	0.525649
Titanium	0.541931	0.496791	0.449419
Cobalt	0.662124	0.654864	0.633732
Platinum	0.672411	0.637331	0.585456

From https://seblagarde.wordpress.com/2011/08/17/feeding-a-physical-based-lighting-mode/

Incorporating Fresnel term

- Combined BRDF:

$$BRDF = \frac{C_{diff}}{\pi} + \frac{s+8}{8\pi} F(v,h)\left(n \bullet H\right)^s$$

with *practical* need $C_{diff} + F(v,h) < 1$

$$C_{final} = C_{light} \otimes \left[C_{diff} + \frac{s+8}{8} F(v,h)\left(n \bullet H\right)^s \right] \max(0, n \bullet L)$$

Top equation corresponds to equation 7.49 on p. 257 of "Real-Time Rendering," 3rd Edition, A K Peters 2008

A reflective paradox?

From http://www.thetenthplanet.de/archives/255

General Cook-Torrance specular

- Combined BRDF:

$$BRDF = \frac{C_{diff}}{\pi} + \frac{D(n \bullet H)F(V \bullet H)G(n,L,V)}{4(n \bullet L)(n \bullet V)}$$

Blinn-Phong microfacet distribution

- Microfacet Blinn-Phong:

$$D_{BP}(n \bullet H) = \frac{s+2}{2\pi}(n \bullet H)^s$$

- Throughout rest of slides, imagine the artist makes "smoothness maps" containing "gloss" g in the range [0,1]
- Call of Duty: Black Ops

$$s = 8192^g = 2^{(13g)}$$

GGX microfacet distribution

- GGX:

$$D_{GGX}(n \bullet H) = \frac{\alpha^2}{\pi[(n \bullet H)^2(\alpha^2 - 1) + 1]^2}$$

- Crytek: $\alpha = (1 - 0.7g)^2$
- Unreal: $\alpha = (\text{disney roughness})^2 = (1-g)^2$

Original Cook-Torrance geometric term

- From Cook-Torrance's original paper:

$$G_{CK}(n,L,V) = \min\left(1, \frac{2(n \bullet H)(n \bullet V)}{V \bullet H}, \frac{2(n \bullet H)(n \bullet L)}{L \bullet H}\right)$$

GGX-based geometric term (1)

- GGX-based geometric:

$$G_{GGX-R}(n,L,V) = G_{GGX-R}(n \bullet L) G_{GGX-R}(n \bullet V)$$

$$G_{GGX-R}(n \bullet V) = \frac{2(n \bullet V)}{n \bullet V + \sqrt{\alpha^2 + (1-\alpha^2)(n \bullet V)^2}}$$

- Used in The Order: 1886

GGX-based geometric term (2)

- Ideal of a "vizualization" term:

$$Viz(n,L,V) = \frac{G(n,L,V)}{4(n \bullet L)(n \bullet V)}$$

$$Viz_{GGX-R}(n,L,V) = \frac{1}{n \bullet V + \sqrt{\alpha^2 + (1-\alpha^2)(n \bullet V)^2}} \times \frac{1}{n \bullet L + \sqrt{\alpha^2 + (1-\alpha^2)(n \bullet L)^2}}$$

GGX-matched to GGX geometric term

- GGX-form matched to GGX distribution:

$$G_{GGX-M}(n \bullet V) = \frac{n \bullet V}{(n \bullet V)(1-k) + k}$$

- Disney standard: $k = \alpha / 2 = (g-1)^2 / 2$
- Disney "hotness remapping":

$$k = [0.5 + (1-g)/2]^2 / 2$$

Implicit geometric term

- Implicit geometric:

$$G_I(n,L,V) = 4(n \bullet L)(n \bullet V)$$

$$Viz_I(n,L,V) = \frac{G(n,L,V)}{4(n \bullet L)(n \bullet V)} = 1$$

Keleman geometric term

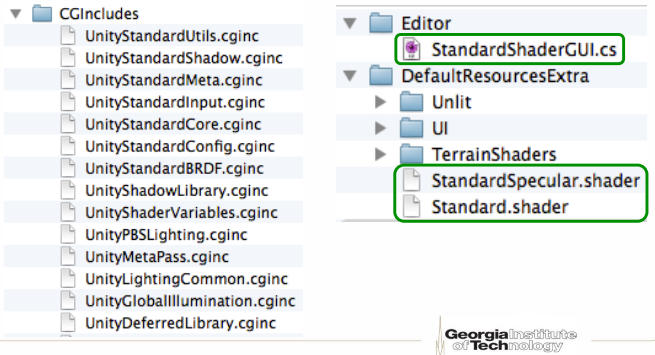
- Facilitates fast implementation:

$$G_K(n,L,V) = \frac{(n \bullet L)(n \bullet V)}{4(V \bullet H)^2}$$

$$Viz_K(n,L,V) = \frac{1}{4(V \bullet H)^2}$$

Unity 5's "Standard Shader"

- Source available separately:
  http://unity3d.com/unity/download/archive



SurfaceOutputStandard structure

- Your job is to fill this in, as necessary:

```
struct SurfaceOutputStandard {
  fixed3 Albedo;     // base (diffuse or specular) color
  fixed3 Normal;     // tangent space normal, if written
  half3 Emission;
  half Metallic;     // 0=non-metal, 1=metal
  half Smoothness;   // 0=rough, 1=smooth
  half Occlusion;    // occlusion (default 1)
  fixed Alpha;       // alpha for transparencies
};
```

From http://docs.unity3d.com/Manual/SL-SurfaceShaders.html

SurfaceOutputStandardSpecular structure

- Your job is to fill this in, as necessary:

```
struct SurfaceOutputStandardSpecular {
  fixed3 Albedo;     // diffuse color
  fixed3 Specular;   // specular color
  fixed3 Normal;     // tangent space normal, if written
  half3 Emission;
  half Smoothness;   // 0=rough, 1=smooth
  half Occlusion;    // occlusion (default 1)
  fixed Alpha;       // alpha for transparencies
};
```

From http://docs.unity3d.com/Manual/SL-SurfaceShaders.html