Computer Graphics

Lecture 06 – Light

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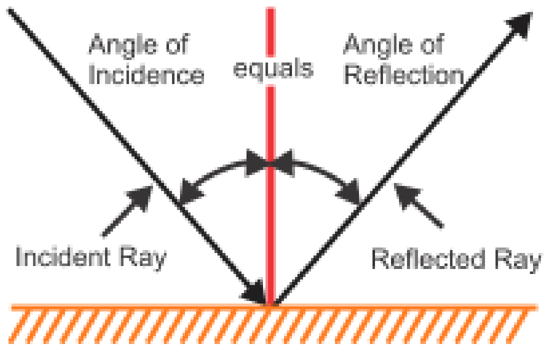
The Physics of Light

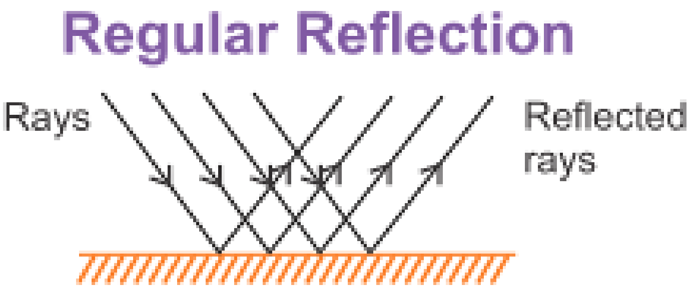
- Light is a electromagnetic radiation of a frequency that can be detected by the human eye (visible light).

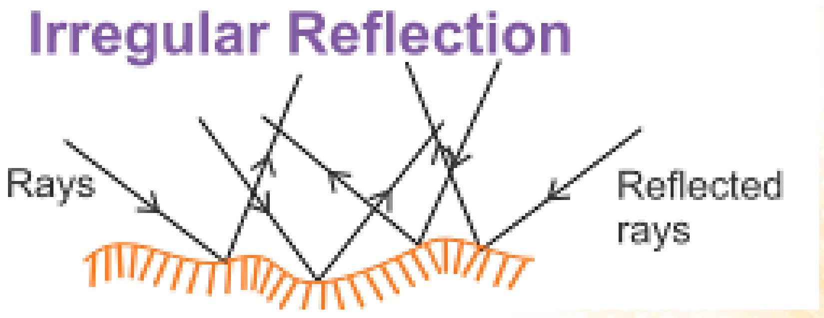
- From the optics view, light can be see as electromagnetic rays that travel in a straight line from its source.
  - The light source emits rays of light.
  - When the light hits an object, some of the light bounces off the object.
  - If the reflected light hits our eyes (or the camera lens) – then we see the object.



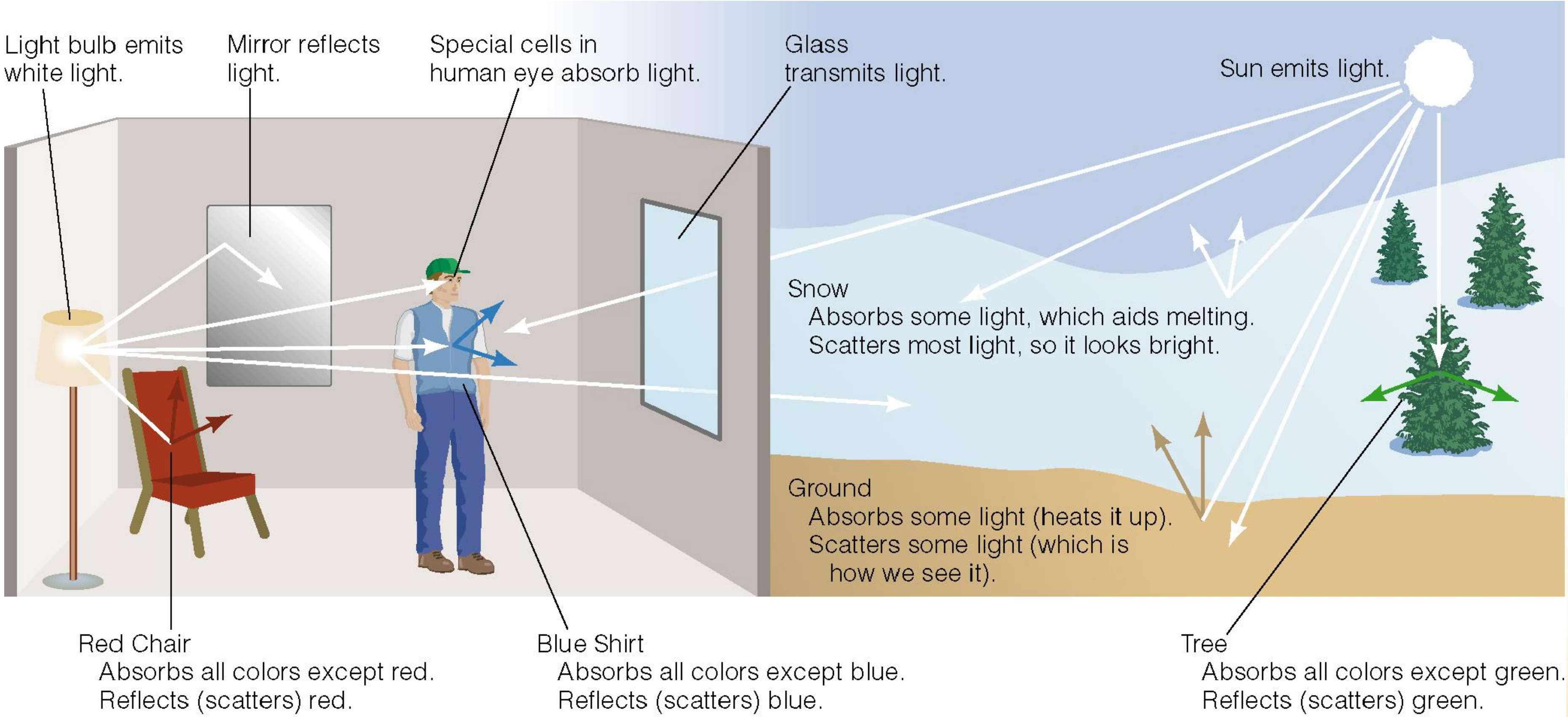
The Physics of Light

- Regular Reflection occurs when the angle at which light initially hits a surface is equal to the angle at which light bounces off the same surface.
  - It occurs only when the rays fall on a highly smooth surface, such as a mirror.
- Irregular Reflection occurs when the rays fall on an irregular surface and are scattered in different directions.

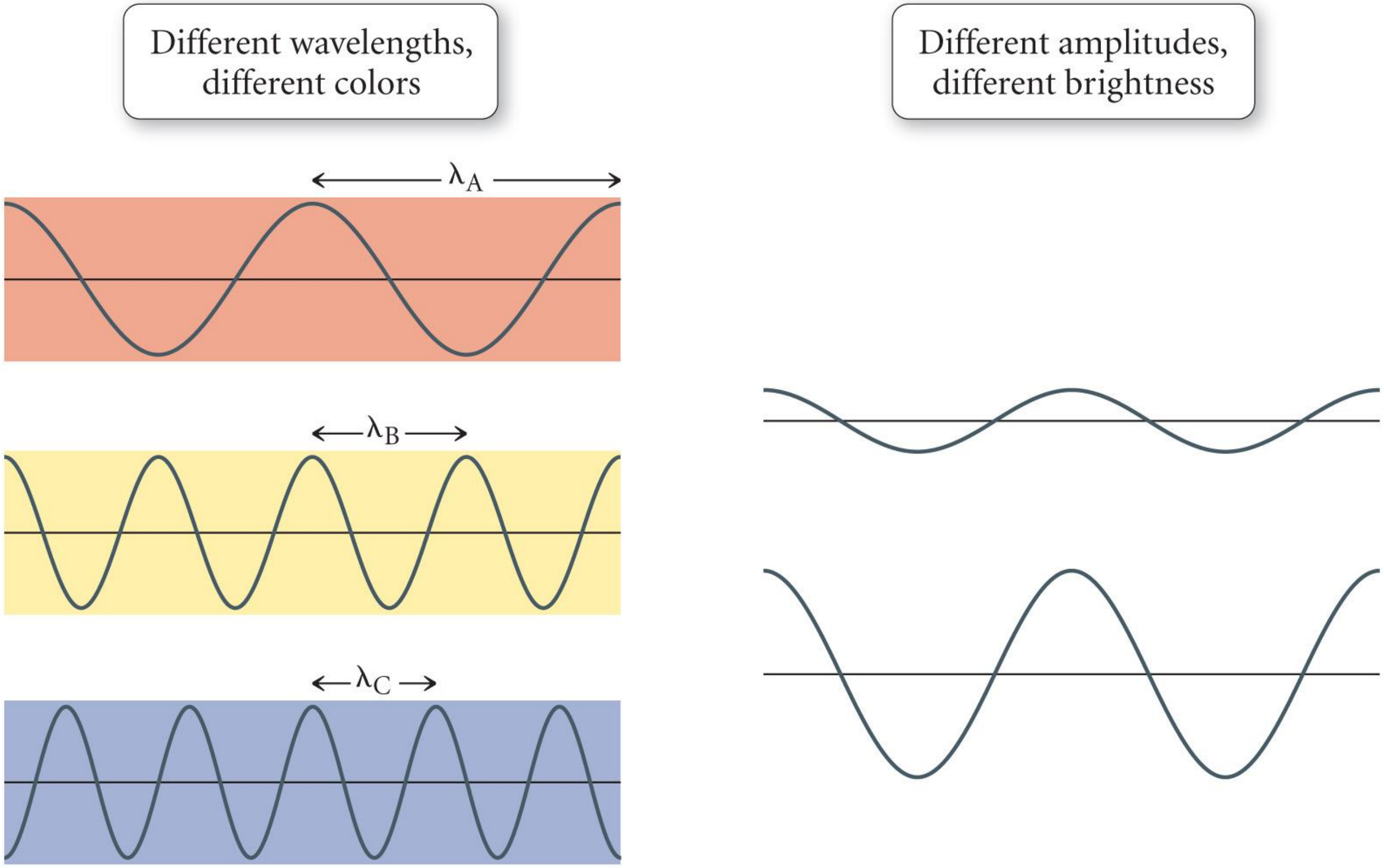




The Physics of Light



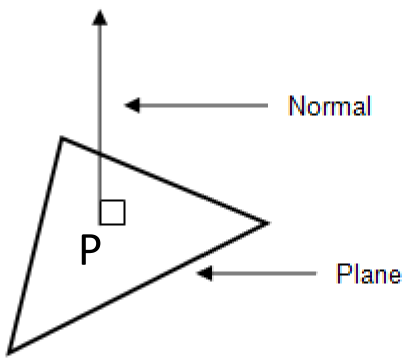
The Physics of Light

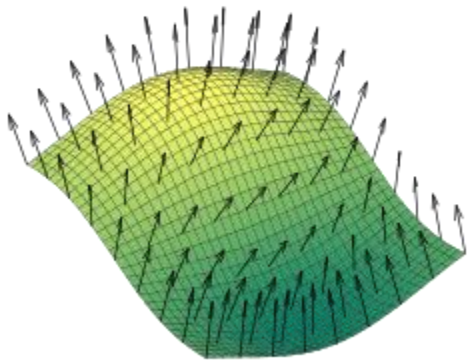


Surface Normals

- When we simulate light in computer graphics, the object's surface plays an important role. The surface normal vectors define how light interacts with the surface.

- To a surface at a point P, the normal is a vector that is perpendicular to the tangent plane to that surface at P.





Normals in Unity Shaders

- In order to access the surface normal in a Shader, we can add a field to the vertex structure.

```
struct VertexData {
  float4 position : POSITION;
  float3 normal : NORMAL;
};

struct VertexToFragment {
  float4 position : SV_POSITION;
  float3 normal : NORMAL;
};

VertexToFragment MyVertexProgram(VertexData vert) {
  VertexToFragment v2f;
  v2f.position = UnityObjectToClipPos(vert.position);
  v2f.normal = UnityObjectToWorldNormal(vert.normal);
  return v2f;
}
```

Transform the normal from local space to world space.

Lights in Unity Shaders

- Unity allows Shaders to have direct access to the light sources in the current scene through built-in variables:

```
_WorldSpaceLightPos0 : float4  - directional lights (world space
                                                      direction)

_LightColor0 : fixed4 - Light color multiplied by the intensity
```

```
float4 MyFragmentProgram(VertexToFragment v2f) : SV_TARGET {

  ...

  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float4 lightColor = _LightColor0.rgba;

  ...

}
```

Defined in "Lighting.cginc“, which must be included.

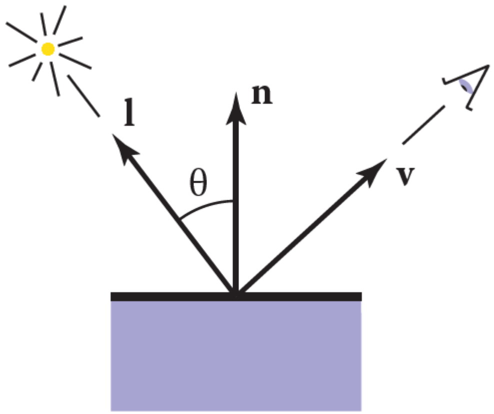
Diffuse Shading

- Many objects in the world have a surface appearance that is not at all shiny (e.g. newspaper, unfinished wood, and dry, unpolished stones).
  - Such objects do not have a color change with a change in viewpoint.


- These objects can be considered as behaving as Lambertian objects.

Lambertian Shading Model

- **Lambertian Shading (Diffuse):** the color of a surface is proportional to the cosine of the angle between the surface normal and the direction to the light (Lambert's cosine law).



$$c = c_r c_l max(0, n \cdot l)$$

- where:
  - c is the pixel color;
  - c_r is the diffuse coefficient, or the surface color;
  - c_l is the intensity of the light source;
  - $n \cdot l = \cos\theta$

Lambertian Shading in Unity

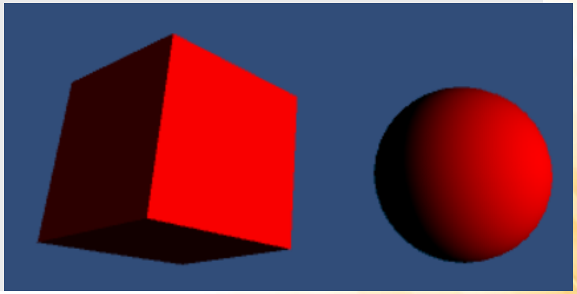
- In order to implement a Lambertian Shader we simply use the Lambertian equation to compute the color in the fragment program.

```
float4 MyFragmentProgram(VertexToFragment v2f) : SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float4 lightColor = _LightColor0.rgba;
  return _Color * lightColor * DotClamped(lightDir,
                                          normalize(v2f.normal));
}
```

Avoids negative dot products.

```
...
Pass{
  Tags{
    "LightMode" = "ForwardBase"
  }
  CGPROGRAM
  ...
```

We also need to specify the light mode used by the rendering pipeline. In this case: ForwardBase.



Ambient Shading

- One problem with the Lambertian shading is that any point whose normal faces away from the light will be black.
  – In real life, light is reflected all over, and some light is incident from every direction.

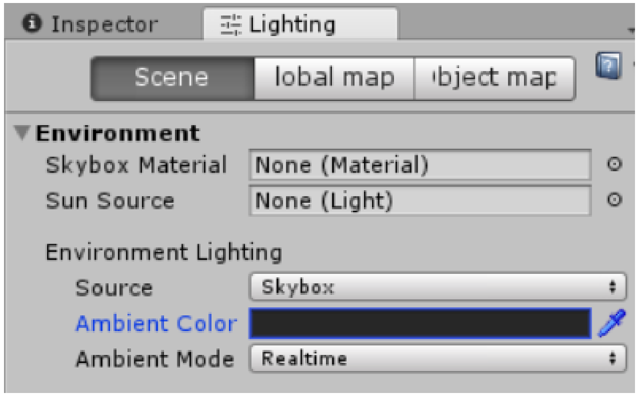
- A common approach to solve this is to add an ambient term to the equation:

$$c = c_r(c_a + c_l max(0, n \cdot l))$$

  – Where c_a is the ambient color.

Ambient Shading in Unity

- Unity has a built-in variable that defines the ambient color, which is defined in the Lightning Settings.
- We can add this variable to the Lambertian equation.




```
unity_AmbientSky : fixed4 - Sky ambient lighting color in gradient
                            ambient lighting case.
```

```
float4 MyFragmentProgram(VertexToFragment v2f) : SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float4 lightColor = _LightColor0.rgba;
  return _Color * (unity_AmbientSky + (lightColor *
                  DotClamped(lightDir, normalize(v2f.normal))));
}
```

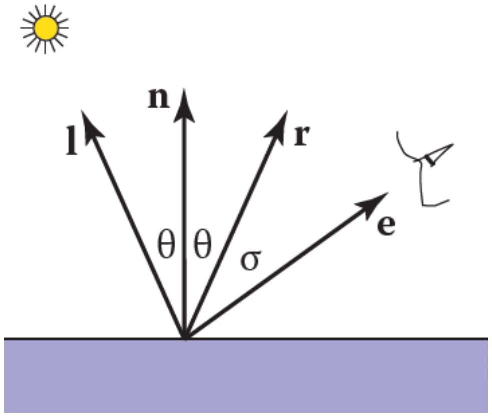
Specular Shading

- Some surfaces have <u>highlights</u> (e.g. polished tile floors, gloss paint, whiteboards). These highlights have the color of the light and move across the surface as the viewpoint moves.

Phong Shading Model

- **Phong Shading (Specular):** describes the way a surface reflects light as a combination of the diffuse reflection of rough surfaces with the specular reflection of shiny surfaces.

$$c = c_l(h \cdot n)^p \qquad h = \frac{e + l}{\|e + l\|}$$



- where:
  - c is the pixel color;
  - c_l is the intensity of the light source;
  - e is the direction to the eye;
  - l is the direction of the light;
  - p is the phong exponent;

Phong Shading in Unity

- In order to implement a Phong Shader in Unity, we need to know the direction from the surface to the viewer. This requires the world-space position of the vertex.

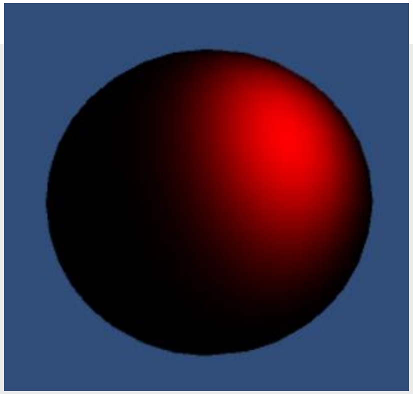
```
struct VertexToFragment {
  float4 position : SV_POSITION;
  float3 normal : NORMAL;
  float4 worldpos : TEXCOORD2;
};
```

```
VertexToFragment MyVertexProgram(VertexData vert) {
  VertexToFragment v2f;
  v2f.position = UnityObjectToClipPos(vert.position);
  v2f.normal = UnityObjectToWorldNormal(vert.normal);
  v2f.worldpos = mul(unity_ObjectToWorld, vert.position);
  return v2f;
}
```

Transform the vertex position from local space to world space.

Phong Shading in Unity

- With the vertex position in world space, we can use the Phong equation in fragment program:

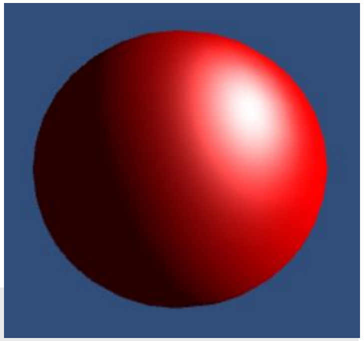


```
Properties
{
  _Color("Color", Color) = (1, 1, 1, 1)
  _Smoothness("Smoothness", Range(0, 1)) = 0.5
  _SpecularColor("Specular", Color) = (0.5, 0.5, 0.5)
}
...
float _Smoothness;
float4 _SpecularColor;
```

```
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float4 lightColor = _LightColor0.rgba;
  return lightColor * pow(DotClamped(normalize(lightDir + viewDir),
                        normalize(v2f.normal)), _Smoothness * 100);
}
```

Phong Shading in Unity

- We can also combine of the diffuse reflection of the Lambertian model with the specular reflection of the Phong model:



```
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float4 lightColor = _LightColor0.rgba;

  float4 difuse = _Color * (unity_AmbientSky + (lightColor *
                      DotClamped(lightDir, normalize(v2f.normal))));

  float4 specular = _SpecularColor * lightColor * pow(DotClamped(
                  normalize(lightDir + viewDir),
                  normalize(v2f.normal)), _Smoothness * 100);

  return difuse + specular;
}
```

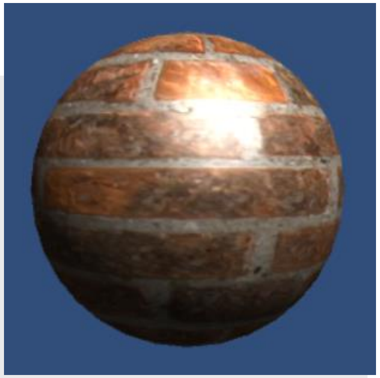
Phong Shading in Unity

- We can also add a texture to the shader:

```
Properties{
  ...
  _MainTex("Albedo", 2D) = "white" {}
}
...
sampler2D _MainTex;
float4 _MainTex_ST;

struct VertexData {
  float4 position : POSITION;
  float3 normal : NORMAL;
  float2 uv : TEXCOORD0;
};

struct VertexToFragment {
  float4 position : SV_POSITION;
  float2 uv : TEXCOORD0;
  float3 normal : NORMAL;
  float4 worldpos : TEXCOORD1;
};
```

Phong Shading in Unity

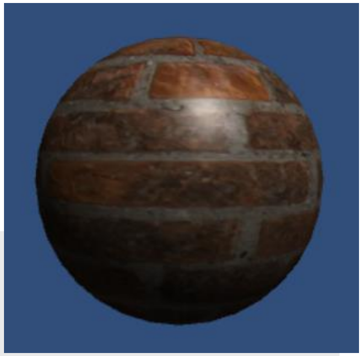
- We can also add a texture to the shader:



```
VertexToFragment MyVertexProgram(VertexData vert) {
  VertexToFragment v2f;
  v2f.position = UnityObjectToClipPos(vert.position);
  v2f.worldpos = mul(unity_ObjectToWorld, vert.position);
  v2f.normal = UnityObjectToWorldNormal(vert.normal);
  v2f.uv = TRANSFORM_TEX(vert.uv, _MainTex);
  return v2f;
}
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float4 lightColor = _LightColor0.rgba;
  float4 albedo = tex2D(_MainTex, v2f.uv).rgba * _Color;
  float4 difuse = albedo * (unity_AmbientSky + (lightColor *
                     DotClamped(lightDir, normalize(v2f.normal))));
  float4 specular = _SpecularColor * lightColor * pow(DotClamped(
                  normalize(lightDir + viewDir),
                  normalize(v2f.normal)), _Smoothness * 100);
  return difuse + specular;
}
```

Phong Shading in Unity

- <u>Energy conservation</u> problem: when light hits a surface, only part of it bounces off as specular light.



```
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float3 lightColor = _LightColor0.rgb;
  float3 albedo = tex2D(_MainTex, v2f.uv).rgb * _Color;
  float oneMinusReflectivity;
  albedo = EnergyConservationBetweenDiffuseAndSpecular(albedo,
                              _SpecularColor, oneMinusReflectivity);
  float3 difuse = albedo * (unity_AmbientSky + (lightColor *
                      DotClamped(lightDir, normalize(v2f.normal))));
  float3 specular = _SpecularColor * lightColor * pow(DotClamped(
                      normalize(lightDir + viewDir),
                      normalize(v2f.normal)), _Smoothness * 100);
  return float4(difuse + specular, 1);
}
```

Energy conservation correction.

Physically Based Shading

- **Physically Based Shading** is a model that seeks to render computer graphics in a way that more accurately simulates the flow of light of the real world.
  - Phong has been used by the game industry for a long time, but nowadays is being replaced by physically-based shading.
  - Unity introduced Physically Based Shading in Unity 5 (2015)

Physically Based Shading in Unity

- Unity provides some functions that allow us to easy use the physically based lightning computations in our shaders.

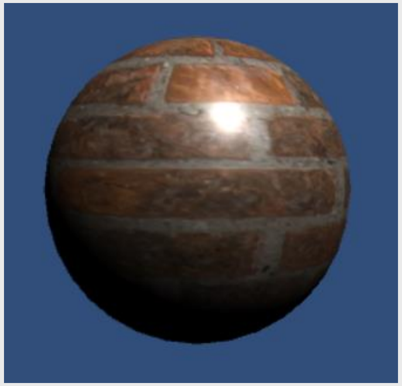
```
CGPROGRAM

#pragma target 3.0

...

#include "UnityPBSLighting.cginc"
```

Just to make sure that Unity selects an appropriated shader level (3.0)

```
half4 UNITY_BRDF_PBS(half3 diffColor, half3 specColor,
                     half oneMinusReflectivity, half smoothness,
                     half3 normal, half3 viewDir,
                     UnityLight light, UnityIndirect gi)
```

Physically Based Shading in Unity

```
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
  float3 lightDir = _WorldSpaceLightPos0.xyz;
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float3 lightColor = _LightColor0.rgb;
  float3 albedo = tex2D(_MainTex, v2f.uv).rgb * _Color;
  float oneMinusReflectivity;
  albedo = EnergyConservationBetweenDiffuseAndSpecular(albedo,
                           _SpecularColor, oneMinusReflectivity);
  UnityLight light;
  light.color = lightColor;
  light.dir = lightDir;
  light.ndotl = DotClamped(normalize(v2f.normal),
                         lightDir);
  UnityIndirect indirectLight;
  indirectLight.diffuse = 0;
  indirectLight.specular = 0;

  return UNITY_BRDF_PBS(albedo, _SpecularColor, oneMinusReflectivity,
                     _Smoothness, normalize(v2f.normal), viewDir,
                     light, indirectLight);
}
```



Multiple Lights

- In order to add support for multiple lights, we need to add more passes to the shader.

- These passes will have nearly identical code, so it is better to move the shader code to an include file.
  - The include file must have the extension ".cginc". Then it can be included in the main shader program:

```
#include "LightShader.cginc"
```

  - When writing an include file is always important to prevent redefinitions of inclusions:

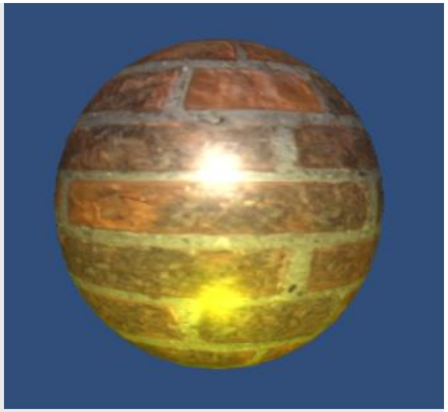
```
#if !defined(LIGHTSHADER_INCLUDED)
#define LIGHTSHADER_INCLUDED
...
#endif
```

Include file: LightShader.cginc

```
#if !defined(LIGHTSHADER_INCLUDED)
#define LIGHTSHADER_INCLUDED

#include "UnityPBSLighting.cginc"

float4 _Color;
...

struct VertexData {
   ...
};
struct VertexToFragment {
   ...
};
VertexToFragment MyVertexProgram(VertexData vert) {
   ...
}
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
   ...
}
#endif
```

Multiple Lights – Main Shader

```
SubShader{
  Pass{
    Tags{"LightMode" = "ForwardBase"}
    CGPROGRAM
    #pragma target 3.0
    #pragma vertex MyVertexProgram
    #pragma fragment MyFragmentProgram
    #include "LightShader.cginc"
    ENDCG
  }
  Pass{
    Tags{"LightMode" = "ForwardAdd"}
    Blend One One
    ZWrite Off
    CGPROGRAM
    #pragma target 3.0
    #pragma vertex MyVertexProgram
    #pragma fragment MyFragmentProgram
    #include "LightShader.cginc"
    ENDCG
  }
}
```



The second pass will be added to the base pass.

Combines the results of the passes through a additive blending.

The second pass don't need to write the z-buffer.

Point Lights

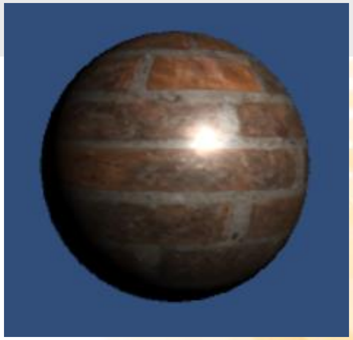
- When we use directional light, _WorldSpaceLightPos0 contains the direction of the light. But when we have a point light, the variable represents the actual position of the light.

```
_WorldSpaceLightPos0 : float4  - Directional lights: (world
                                 space direction, 0).
                                 Other lights: (world space
                                 position, 1).
```

- So we need to compute the direction of the point light:

```
float3 lightDir = normalize(_WorldSpaceLightPos0.xyz -
                            v2f.worldpos);
```

Note: the base pass only renders directional lights.
Point lights must be render in other passes.



Point Lights

- To simplify and organize our shader, we can create a function to create the light:

```
UnityLight CreateLight(VertexToFragment v2f) {
  UnityLight light;
  light.dir = normalize(_WorldSpaceLightPos0.xyz - v2f.worldpos);
  light.color = _LightColor0.rgb;
  light.ndotl = DotClamped(normalize(v2f.normal), light.dir);
  return light;
}
```

Point Lights

- Now we simply call the CreateLight function in the fragment program:

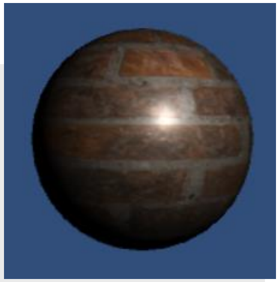
```
float4 MyFragmentProgram(VertexToFragment v2f) :SV_TARGET{
  float3 viewDir = normalize(_WorldSpaceCameraPos - v2f.worldpos);
  float3 albedo = tex2D(_MainTex, v2f.uv).rgb * _Color;
  float oneMinusReflectivity;
  albedo = EnergyConservationBetweenDiffuseAndSpecular(albedo,
                            _SpecularColor, oneMinusReflectivity);

  UnityIndirect indirectLight;
  indirectLight.diffuse = 0;
  indirectLight.specular = 0;

  return UNITY_BRDF_PBS(albedo, _SpecularColor,
                        oneMinusReflectivity, _Smoothness,
                        normalize(v2f.normal), viewDir,
                        CreateLight(v2f), indirectLight);
}
```

Point Lights – Attenuation and Range

- **Point lights have two additional properties:**
  - Light Attenuation: the distance of the light to the object's surface effects the intensity of the light that hits the surface.
  - Light Range: in real life, photons keep moving until they hit something. But with distance, they become so weak that we can no longer see it.
- Unity provides a macro that simplifies the process to calculate the correct attenuation factor:

```
UNITY_LIGHT_ATTENUATION(attenuation, shadowcoord, vertexWorldPos);
```

Point Lights – Attenuation and Range



```
#include "AutoLight.cginc"

UnityLight CreateLight(VertexToFragment v2f) {
  UnityLight light;
  light.dir = normalize(_WorldSpaceLightPos0.xyz - v2f.worldpos);
  UNITY_LIGHT_ATTENUATION(attenuation, 0, v2f.worldpos);
  light.color = _LightColor0.rgb * attenuation;
  light.ndotl = DotClamped(normalize(v2f.normal), light.dir);
  return light;
}
```

- We also have to change the second pass of the main shader program:

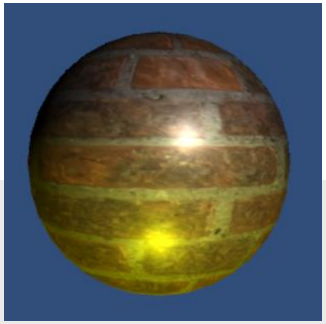
```
    ...
    #pragma vertex MyVertexProgram
    #pragma fragment MyFragmentProgram
    #define POINT
    #include "LightShader.cginc"
    ENDCG
    ...
```

Used by the attenuation macro to know when a point light is being rendered.

Point Light and Directional Light

- In order to combine a point light with a directional light, our shader must know how to correctly compute the light direction depending on the type of light that is being rendered.

- We can use the POINT keyword:



```
UnityLight CreateLight(VertexToFragment v2f) {
  UnityLight light;
  #if defined(POINT)
    light.dir = normalize(_WorldSpaceLightPos0.xyz - v2f.worldpos);
  #else
    light.dir = _WorldSpaceLightPos0.xyz;
  #endif
  UNITY_LIGHT_ATTENUATION(attenuation, 0, v2f.worldpos);
  light.color = _LightColor0.rgb * attenuation;
  light.ndotl = DotClamped(normalize(v2f.normal), light.dir);
  return light;
}
```

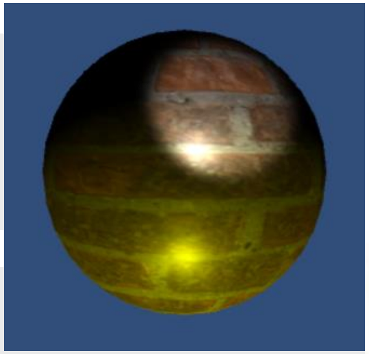
Point Light and Directional Light

- **Problem with keywords**: they are applied during compilation time.
- If we want our shader to work with all combinations of directional and point lights, we need to compile multiple versions of the shader.
  - This can be done with the multi_compile command:

```
...
Blend One One
ZWrite Off
CGPROGRAM
#pragma target 3.0
#pragma multi_compile DIRECTIONAL POINT
#pragma vertex MyVertexProgram
#pragma fragment MyFragmentProgram
#include "LightShader.cginc"
ENDCG
...
```

Spot Lights

- Spot lights are very similar to point lights. In addition, the UNITY_LIGHT_ATTENUATION macro already takes care of the computations to create the light cone shape.
- We can simply add the SPOT keyword to our shader:



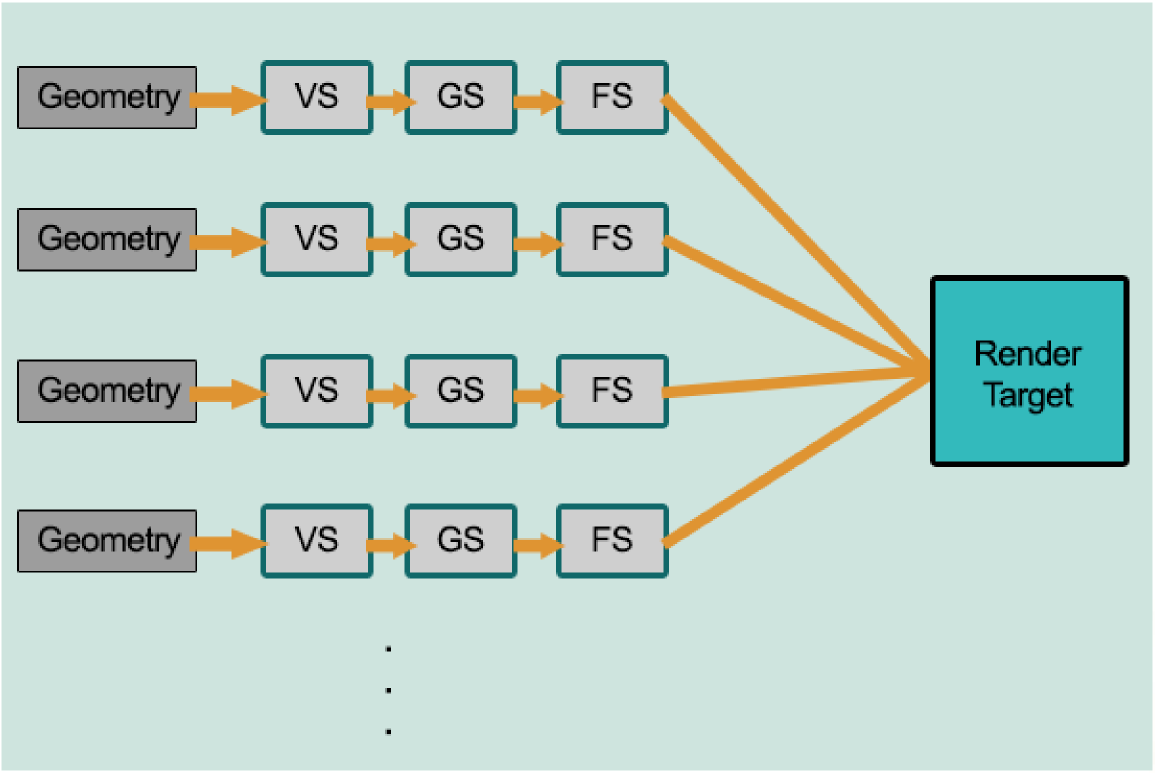
```
...
#pragma multi_compile DIRECTIONAL POINT SPOT
...
```

```
...
#if defined(POINT) || defined(SPOT)
  light.dir = normalize(_WorldSpaceLightPos0.xyz - v2f.worldpos);
#else
  light.dir = _WorldSpaceLightPos0.xyz;
#endif
...
```

Unity Rendering Pipeline

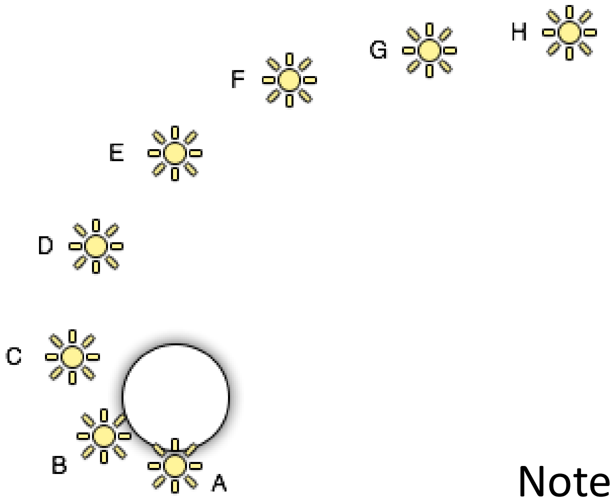
- Unity supports two main rendering paths:
  - **Forward Rendering:** renders each object in one or more passes, depending on lights that affect the object.
    - Is based on the traditional linear graphics pipeline, where each geometry is processed by the pipeline (one at a time) to produce the final image.
  - **Deferred Rendering:** renders each object once on the first pass and stores shading information into G-buffer textures. Additional passes compute lighting based on G-buffer and depth in screen space.
    - The rendering is "deferred" until all of the geometries have been processed by the pipeline. The final image is produced by applying shading/lightning at the end.

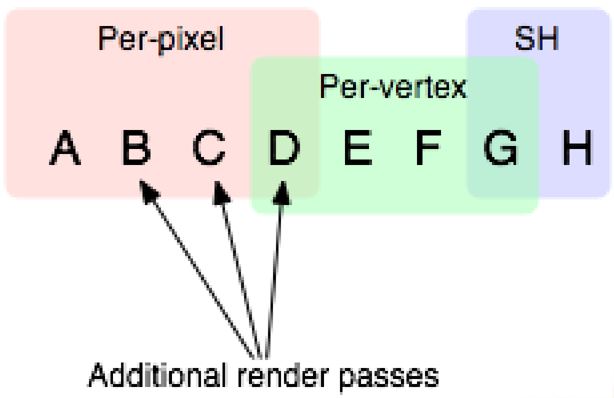
Forward Rendering



Forward Rendering

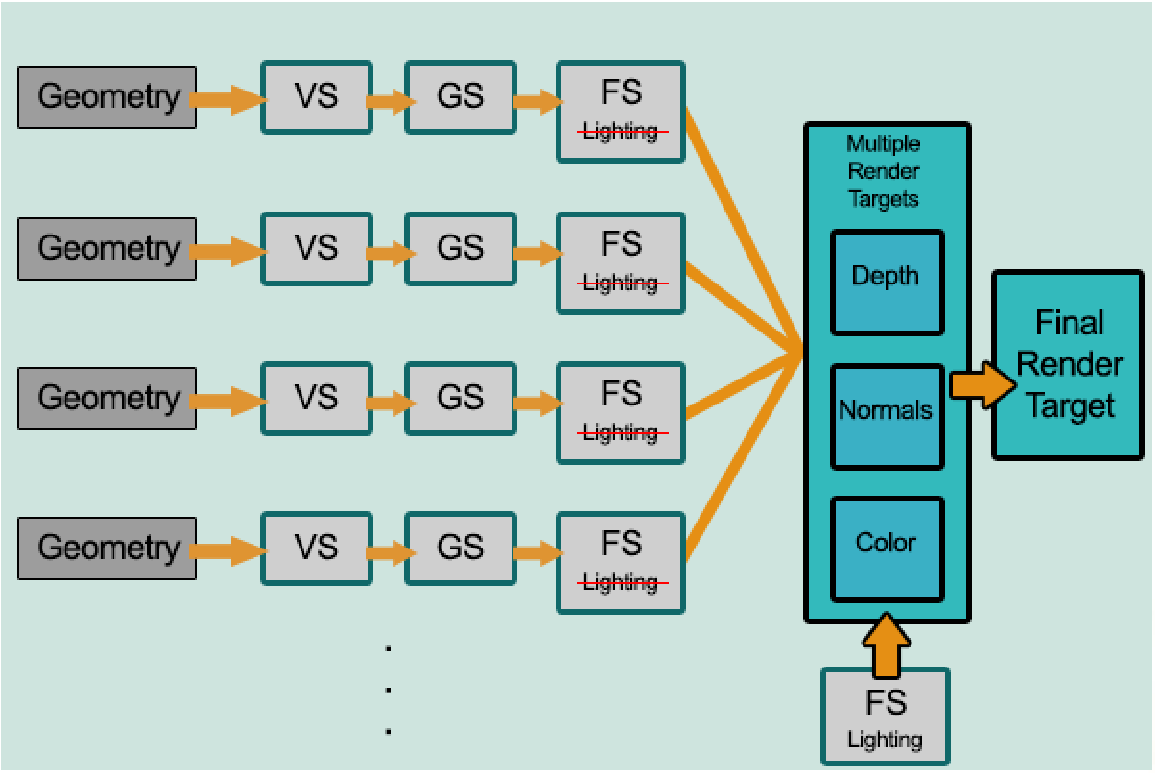
- In Forward Rendering, lights can be rendered in 3 different ways:
  - Some lights that affect each object are rendered in fully **per-pixel** mode (number defined by the Pixel Light Count – Quality Setting).
  - Up to 4 point lights are calculated **per-vertex**.
  - The other lights are computed as **spherical harmonics** (SH – faster method, but is only an approximation).





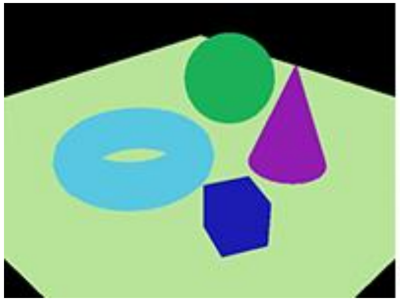
Note: groups overlap reduces the "light popping" effect.

Deferred Rendering

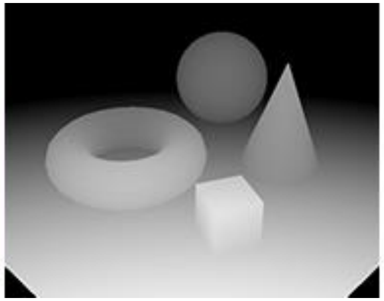


Deferred Rendering

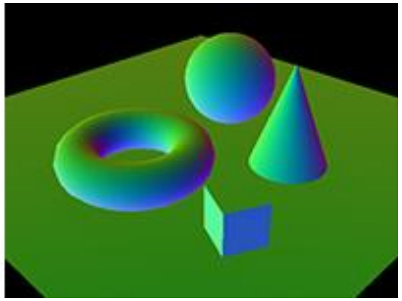
- In Deferred Rendering, each object is rendered once on the first pass and shading information is stored into G-buffer textures using *multiple render targets* (MRT).



Color

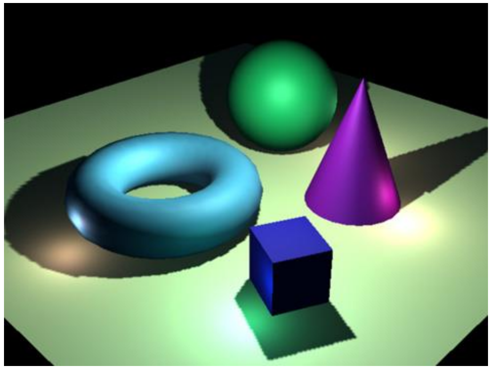


Depth



Normal

- Additional passes compute lighting based on G-buffer information in screen space:



Deferred Shaders

- The main difference between a forward shader and deferred shader is the output of the fragment program:

```
struct FragmentOutput{
  #if defined(DEFERRED_PASS)
    float4 gBuffer0 : SV_Target0;
    float4 gBuffer1 : SV_Target1;
    float4 gBuffer2 : SV_Target2;
    float4 gBuffer3 : SV_Target3;
  #else
    float4 color : SV_Target;
  #endif
};
FragmentOutput MyFragmentProgram (Interpolators i) {
  FragmentOutput output;
  #if defined(DEFERRED_PASS)
    //fill the buffers
  #else
    output.color = color;
  #endif
  return output;
}
```

Diffuse albedo and the surface occlusion.

Specular color.

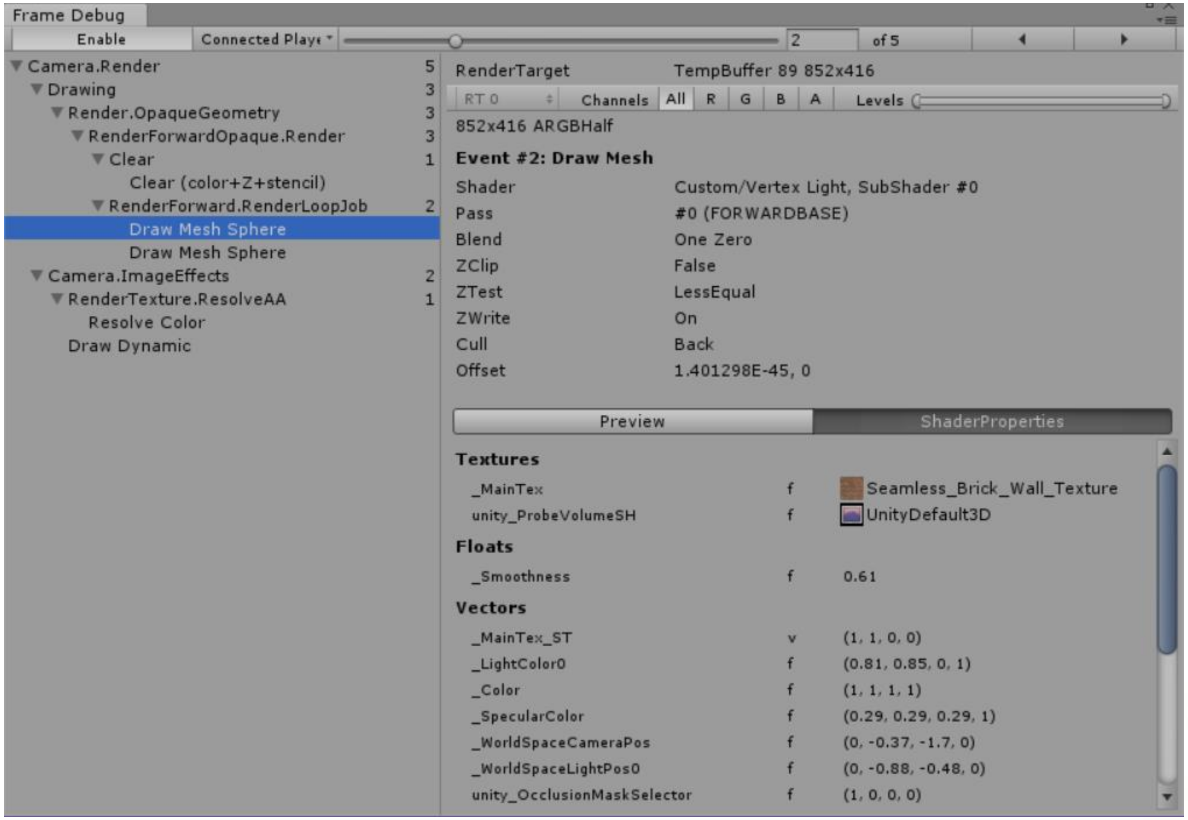
World-space normal vectors.

Emission lighting.

Implementation Tutorial: http://catlikecoding.com/unity/tutorials/rendering/part-13/

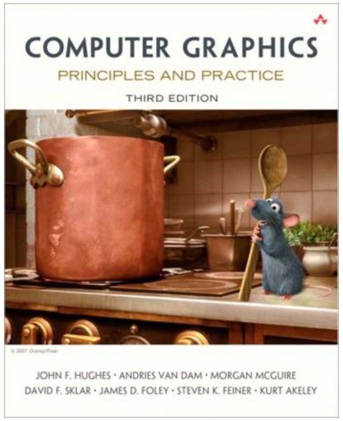
Frame Debugger

- Window->Frame Debugger

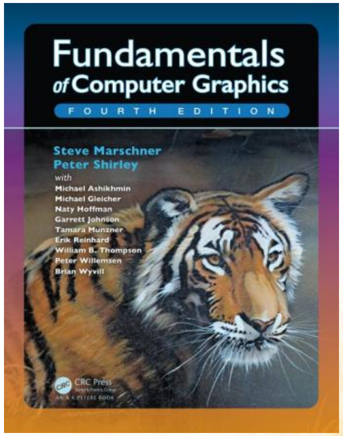


Further Reading

- Hughes, J. F., et al. (2013). **Computer Graphics: Principles and Practice** (3rd ed.). Upper Saddle River, NJ: Addison-Wesley Professional. ISBN: 978-0-321-39952-6.
  - **Chapter 26: Light**
  - **Chapter 27: Materials and Scattering**



- Marschner, S., et al. (2015). **Fundamentals of Computer Graphics** (4th ed.). A K Peters/CRC Press. ISBN: 978-1482229394.
  - **Chapter 10: Surface Shading**
  - **Chapter 18: Light**



- **Web:**
  - http://catlikecoding.com/unity/tutorials/rendering/part-4/
  - http://catlikecoding.com/unity/tutorials/rendering/part-5/