

INFOGR – Computer Graphics

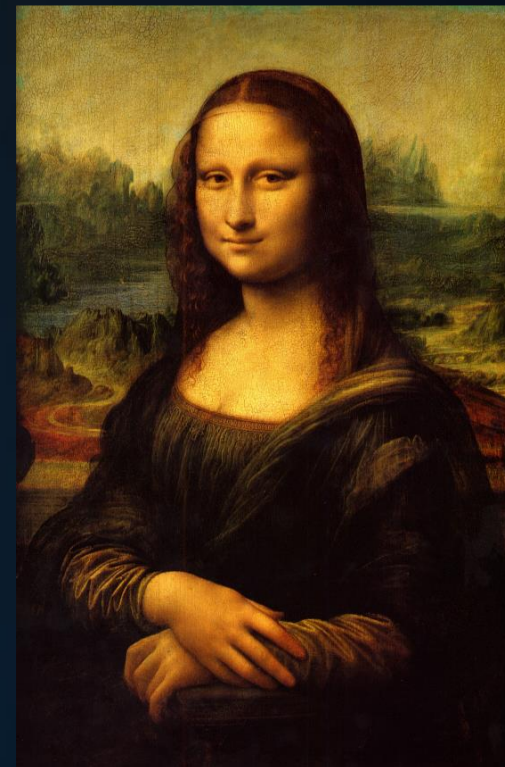
J. Bikker - April-July 2016 - Lecture 10: “Shading Models”

Welcome!



Today's Agenda:

- Introduction
- Light Transport
- Materials
- Sensors
- Shading



Introduction

The Quest for (Photo-)Realism

- Objective in modern games
- Important improvements when using ray tracing

The core algorithms of ray tracing and rasterization model light transport (with or without visibility):

$$L(p \rightarrow r) = L_e(p \rightarrow r) + \sum_{i=1}^{N_L} L(q_i \rightarrow p) f_r(q_i \rightarrow p \rightarrow r) G(q_i \leftrightarrow p)$$

Other factors:

- Material interactions
- Light models
- Sensor models



Material interactions



Introduction

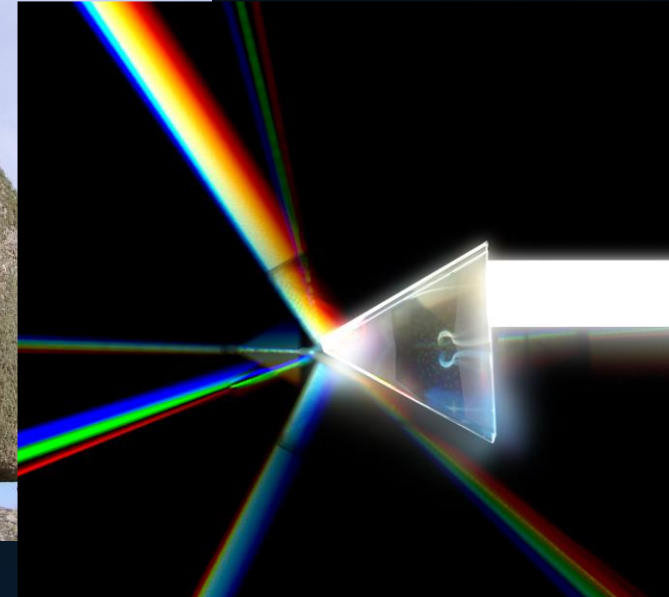
Material interactions

```
rics
& (depth < MAXD
c = inside / 1.5
nt = nt / nc; add
os2t = 1.0f - nnt
D, N );
0)
at a = nt - nc; b
at Tr = 1 - (R0 +
Tr) R = (D * nnt
E * diffuse;
= true;
efl + refr)) && (
D, N );
-refl * E * diffus
= true;
MAXDEPTH)
survive = Sur viva
estimation - doi
if;
-radiance = Sample
e.x + radiance.y
```

```
v = true;
at brdfPdf = EvaluateDiffuse( L, N ) * Psurvive;
at3 factor = diffuse * INVPI;
at weight = Mis2( directPdf, brdfPdf );
at cosThetaOut = dot( N, L );
E * ((weight * cosThetaOut) / directPdf) * (radiance
```

andom walk - done properly, closely following well-known algorithms (survive)

```
;
at3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf );
survive;
pdf;
n = E * brdf * (dot( N, R ) / pdf);
sion = true;
```



Introduction

Material interactions

```
ric  
& (depth < MAXD
```

```
t = inside / 1.0  
nt = nt / nc; add  
os2t = 1.0f - nnt
```

```
D, N );  
)
```

```
at a = nt -  
at Tr = 1 -  
Tr) R = (D
```

```
E * diffuse  
= true;
```

```
efl + refr)
```

```
D, N );  
refl * E *  
= true;
```

```
MAXDEPTH)
```

```
survive = S
```

```
estimation  
if;
```

```
radiance =  
e.x + radia
```

```
w = true;  
at brdfPdf
```

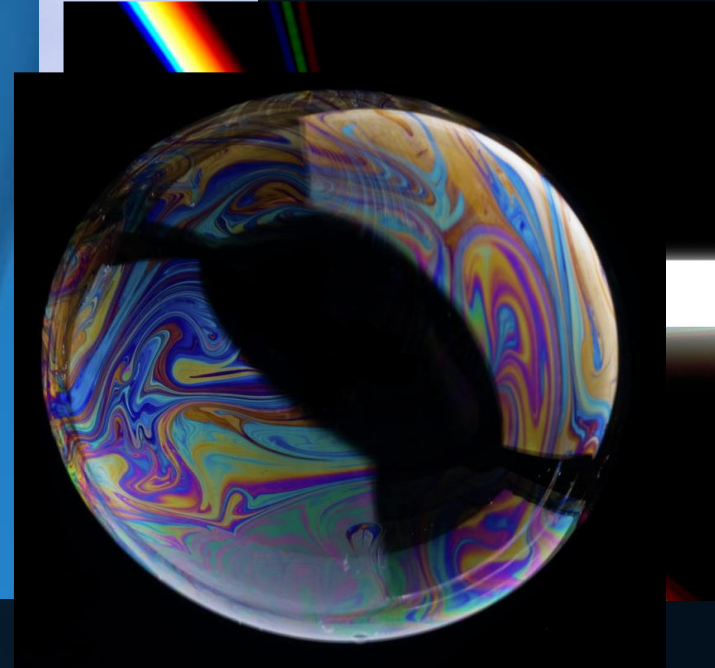
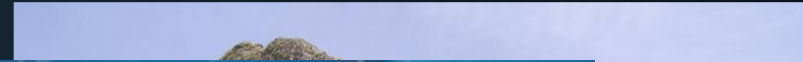
```
at3 factor = diffuse * INVPI;  
at weight = Mis2( directPdf, brdfPdf );
```

```
at cosThetaOut = dot( N, L );  
E * ((weight * cosThetaOut) / directPdf) * (radiance
```

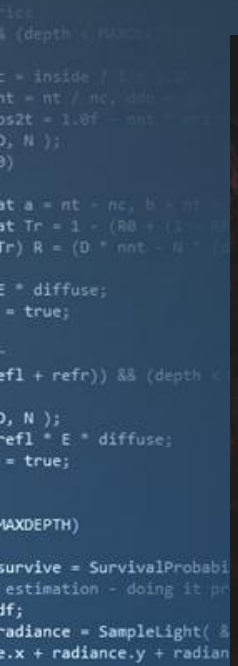
```
andom walk - done properly, closely following wall  
ive)
```

```
;
```

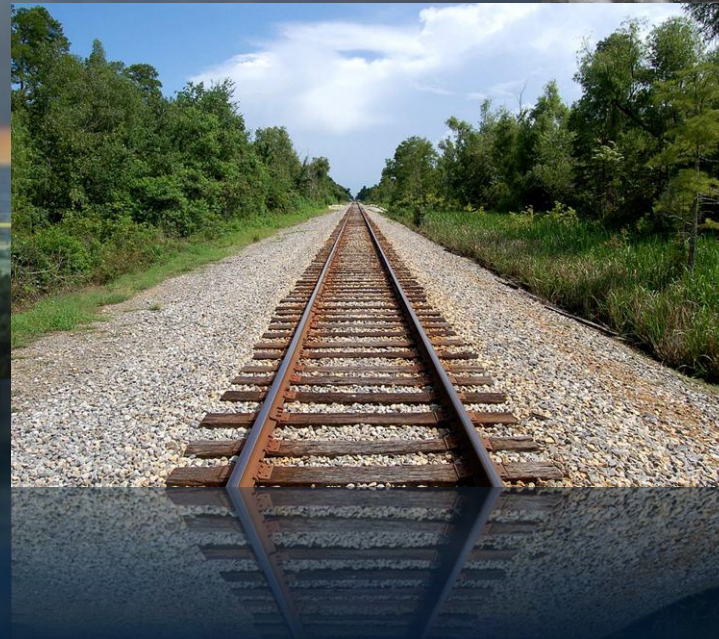
```
at3 brdf = SampleDiffuse( diffuse, N, r1, r2, BR, &pdf );  
survive;  
pdf;  
n = E * brdf * (dot( N, R ) / pdf);  
ion = true;
```



Light models



Light models



Light models



Introduction

Light models

```
...ics
& (depth < MAXDEPTH)
{
    // Inside / Outside
    nt = nt / nc; ddx = ddx / nc;
    pos2t = 1.0f - nnt * nnt;
    D, N );
}

// Diffuse
at a = nt - nc, b = nt * nc;
at Tr = 1 - (R0 + (1 - R0) * a);
Tr) R = (D * nnt - N * a);

E * diffuse;
= true;

refl + refr)) && (depth < MAXDEPTH)
{
    D, N );
    refl * E * diffuse;
    = true;

MAXDEPTH)

survive = SurvivalProbability( diffuse );
estimation - doing it properly, closely
if;
radiance = SampleLight( &rand, I, &t, &ll;
e.x + radiance.y + radiance.z) > 0) && (e
v = true;
at brdfPdf = EvaluateDiffuse( L, N ) * Pxum;
at3 factor = diffuse * INVPI;
at weight = Mix2( directPdf, brdfPdf );
at cosThetaOut = dot( N, L );
E * ((weight * cosThetaOut) / directPdf) * (radiance
random walk - done properly, closely following wall
survive)

;
at3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf );
survive;
pdf;
n = E * brdf * (dot( N, R ) / pdf);
sion = true;
```

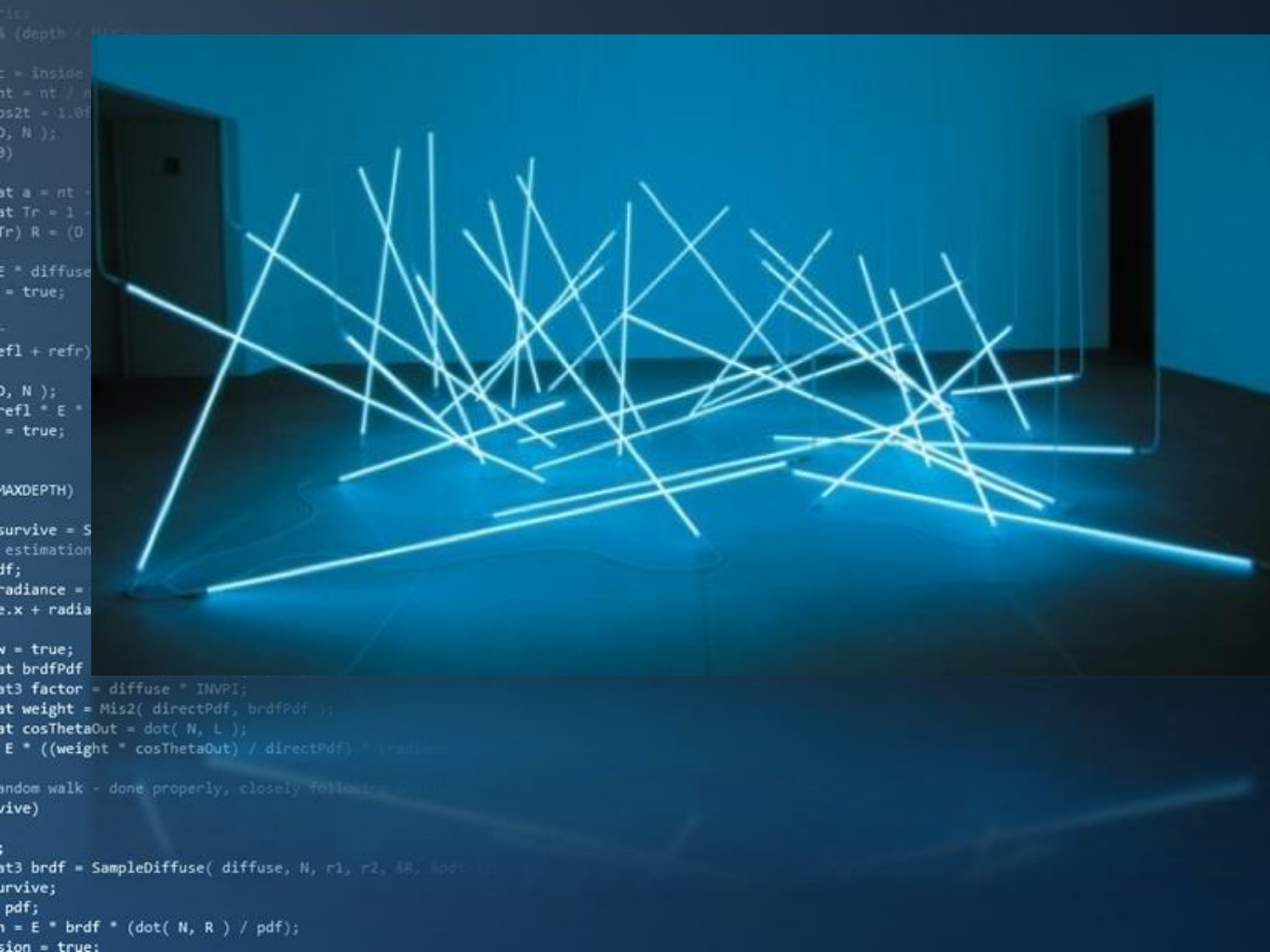


Light models



Introduction

Light models

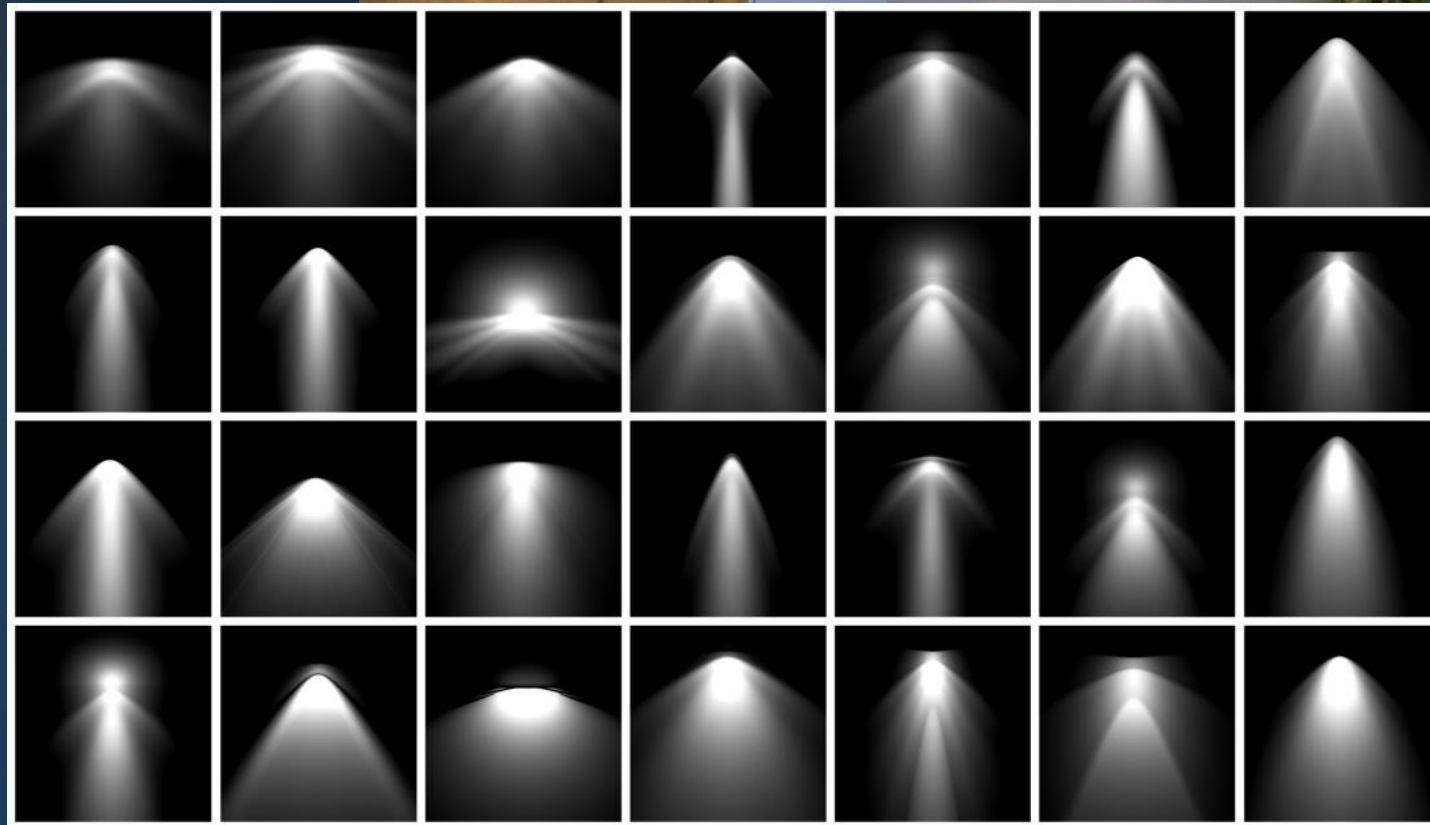


Light models



Introduction

Light models

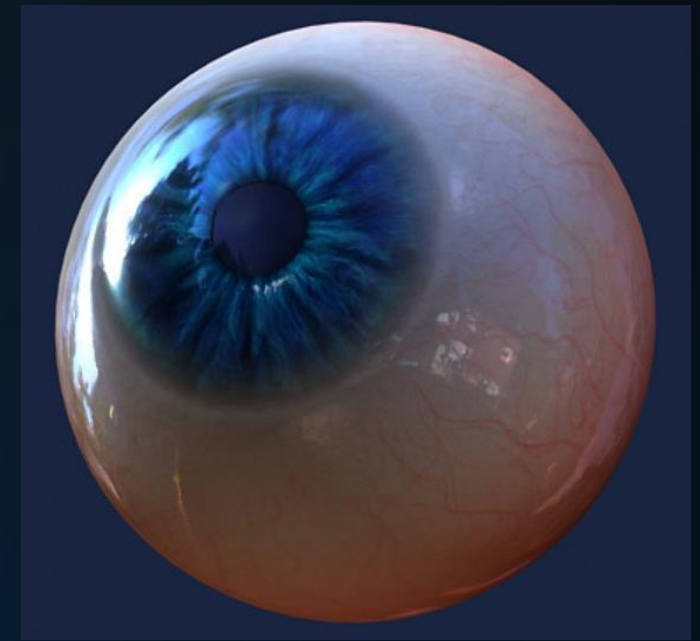
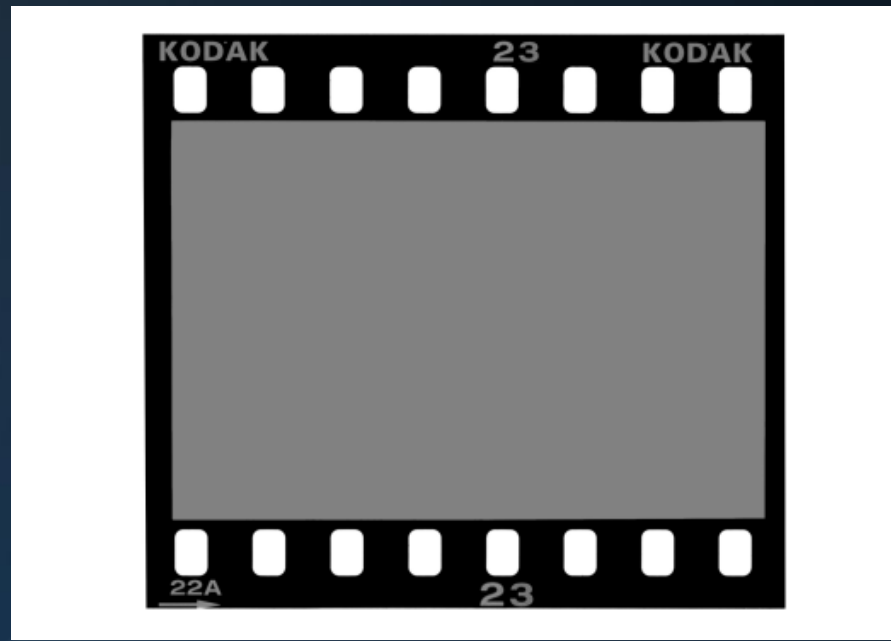
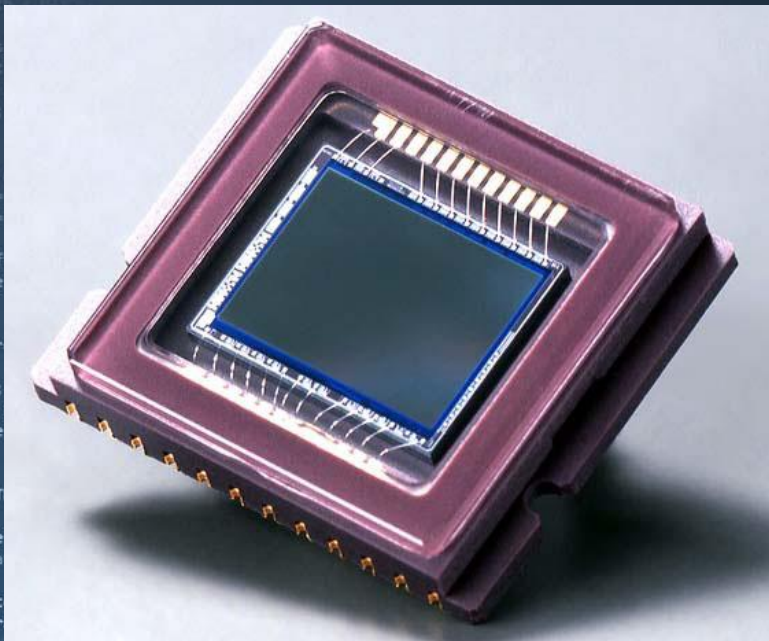


Light models



Introduction

Sensor models



```
...ics  
...A (depl  
...  
...t = ins  
...nt = nt  
...os2t =  
...D, N );  
...)  
...  
...at a =  
...at Tr =  
...Tr) R =  
...  
...E * dif  
...= true  
...  
...efl + r  
...D, N );  
...refl *  
...= true  
...  
...MAXDEPT  
...survive  
...estima  
...if;  
...radianc  
...e.x + r  
...  
...w = true;  
...at brdfPdf = EvaluateDiffuse( L, N ) * PI * r1 * r2;  
...at3 factor = diffuse * INVPI;  
...at weight = Mis2( directPdf, brdfPdf );  
...at cosThetaOut = dot( N, L );  
...E * ((weight * cosThetaOut) / directPdf) * PI * r1 * r2;  
...random walk - done properly, closely following  
...rive)  
...  
...at3 brdf = SampleDiffuse( diffuse, N, r1, r2, BR, &pdf );  
...survive;  
...pdf;  
...n = E * brdf * (dot( N, R ) / pdf);  
...ision = true;
```



Introduction

1. Light is emitted by a light source
2. Light interacts with the scene
3. Light is absorbed by a sensor

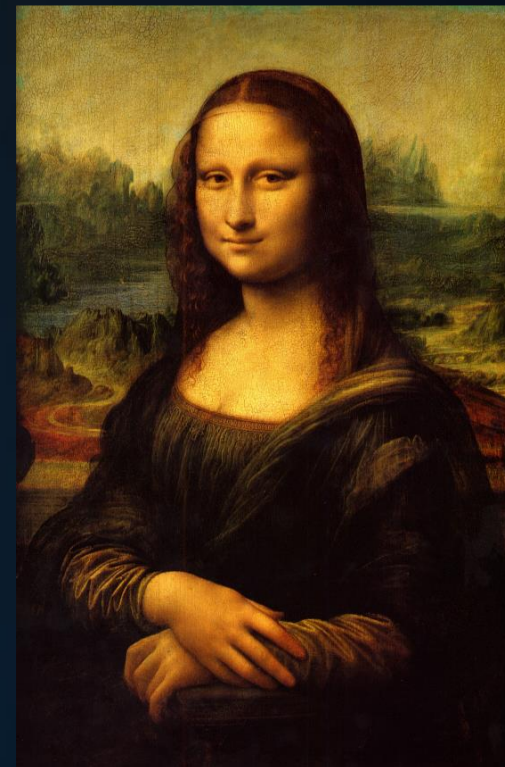
Absorption

Scattering



Today's Agenda:

- Introduction
- Light Transport
- Materials
- Sensors
- Shading



Light Transport

Light Transport Quantities

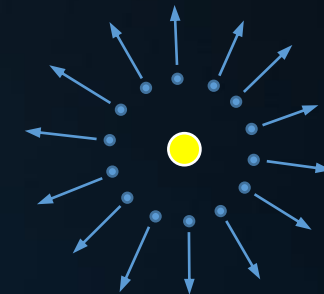
Radiant flux - Φ :

“Radiant energy emitted, reflected, transmitted or received, per unit time.”

Units: watts = joules per second

$$W = J s^{-1}.$$

Simplified particle analogy:
number of photons.



Note: photon energy depends on electromagnetic wavelength:

$E = \frac{hc}{\lambda}$, where h is Planck's constant, c is the speed of light, and λ is wavelength. At $\lambda = 550\text{nm}$ (yellow), a single photon carries 3.6×10^{-19} joules.



Light Transport

Light Transport Quantities

In a vacuum, radiant flux emitted by a point light source remains constant over distance:

A point light emitting 100W delivers 100W to the surface of a sphere of radius r around the light. This sphere has an area of $4\pi r^2$; energy per surface area thus decreases by $1/r^2$.

In terms of photons: the density of the photon distribution decreases by $1/r^2$.



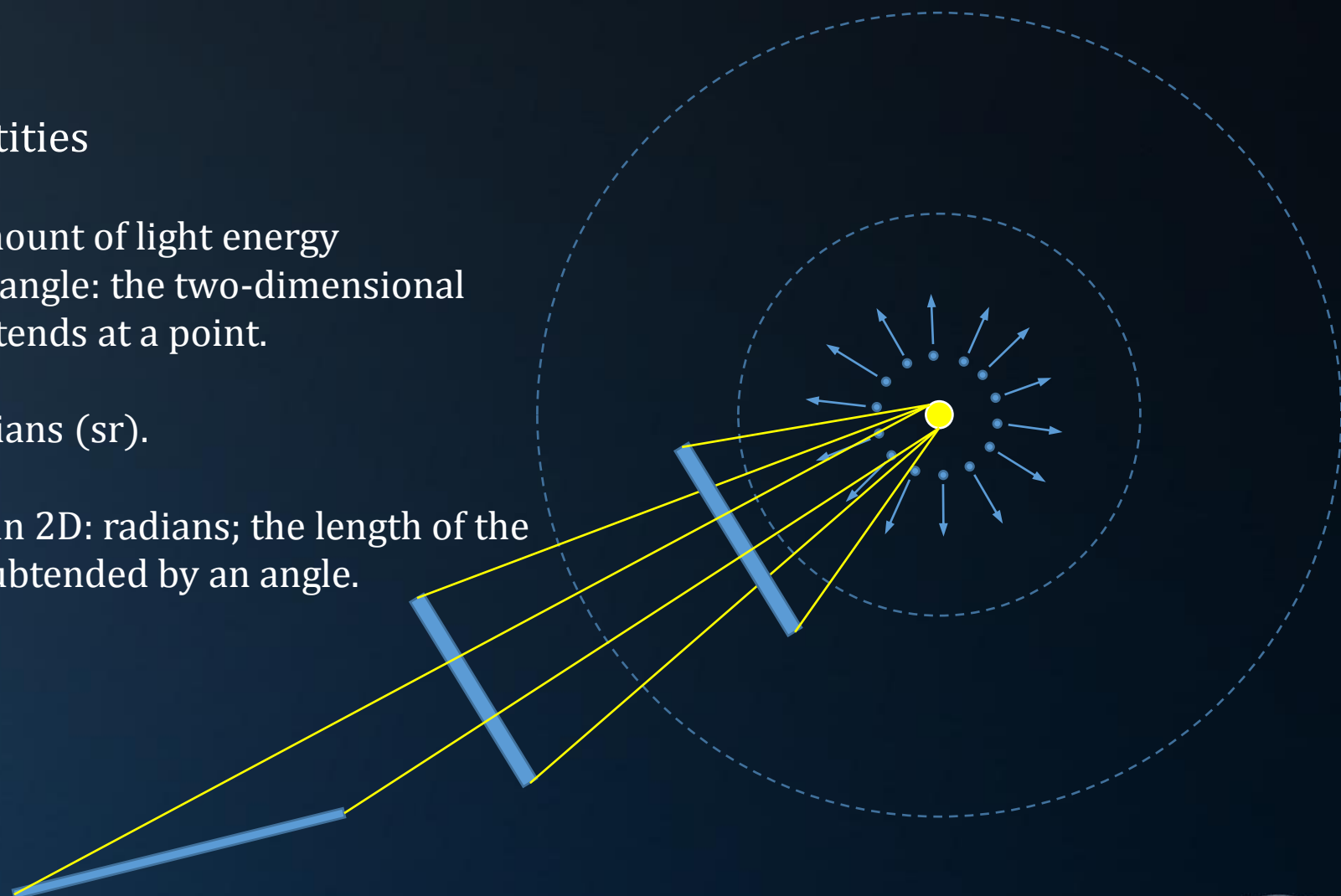
Light Transport

Light Transport Quantities

A surface receives an amount of light energy proportional to its solid angle: the two-dimensional space that an object subtends at a point.

Solid angle units: steradians (sr).

Corresponding concept in 2D: radians; the length of the arc on the unit sphere subtended by an angle.



Light Transport

Light Transport Quantities

Radiance - L :

“The power of electromagnetic radiation emitted, reflected, transmitted or received per unit projected area per unit solid angle.”

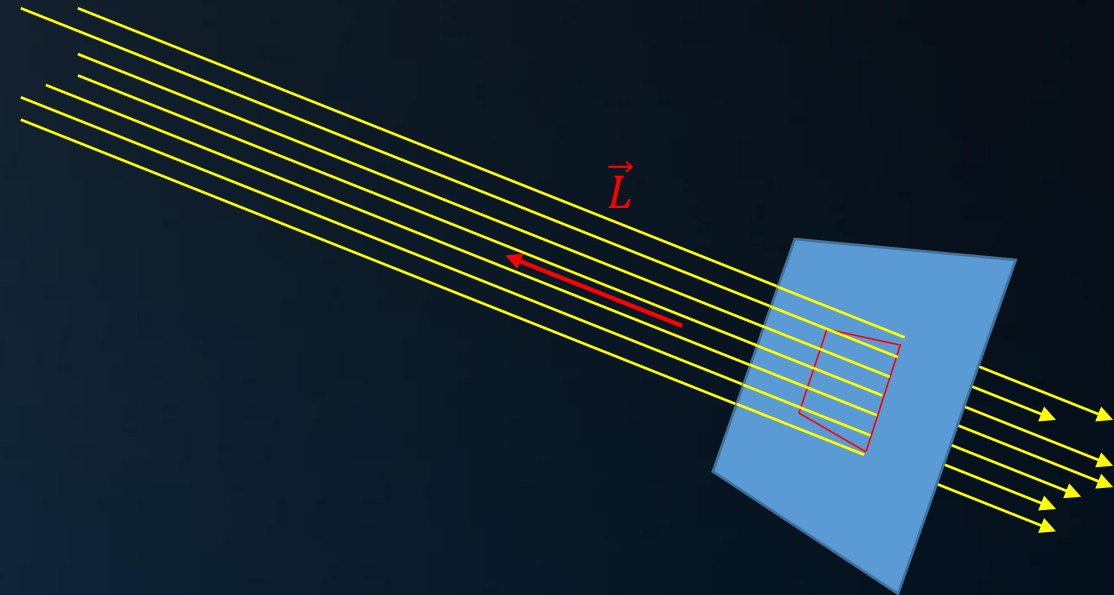
Units: $Wsr^{-1}m^{-2}$

Simplified particle analogy:

Amount of particles passing through a pipe with unit diameter, per unit time.

Note: radiance is a continuous value:

while flux at a point is 0 (since both area and solid angle are 0), we can still define flux per area per solid angle for that point.



Light Transport

Light Transport Quantities

Irradiance - E :

“The power of electromagnetic radiation per unit area incident on a surface.”

Units: Watts per m^2 = joules per second per m^2
 $Wm^{-2} = Jm^{-2}s^{-1}$.

Simplified particle analogy:
 number of photons arriving per unit area per unit time, from all directions.

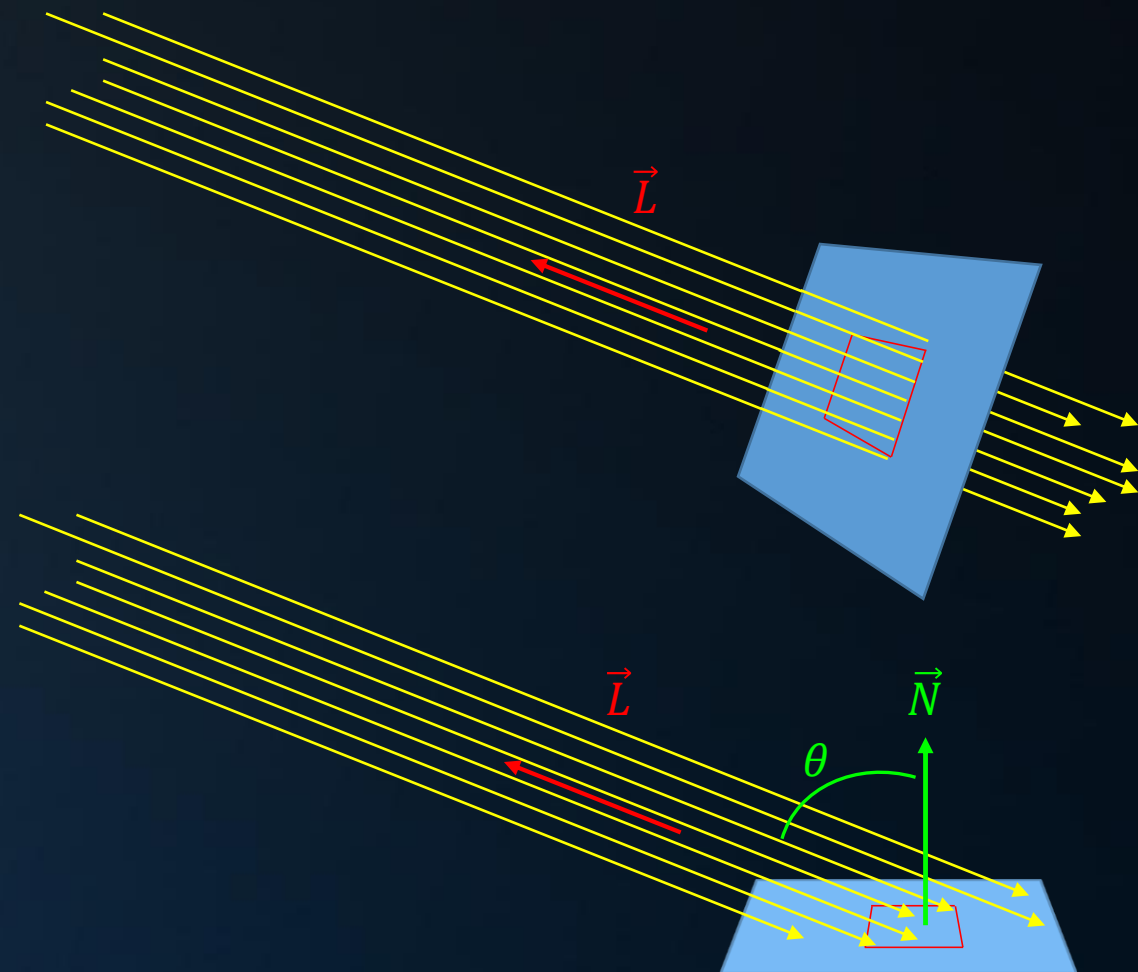


Light Transport

Light Transport Quantities

Converting radiance to irradiance:

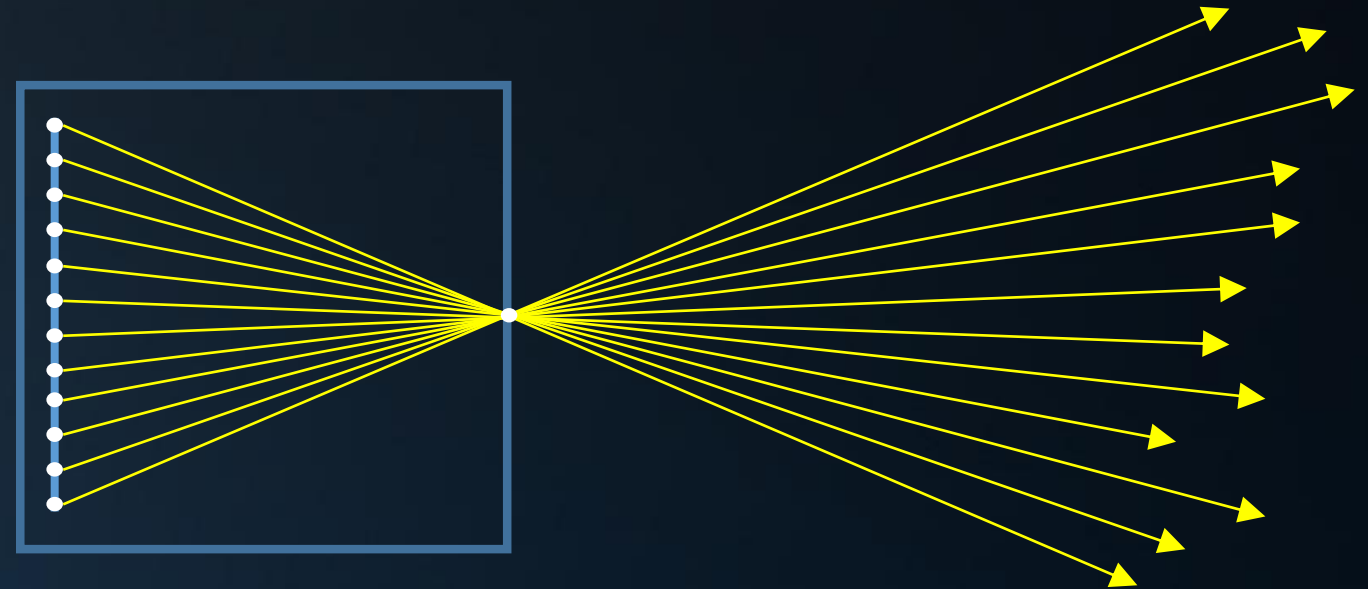
$$E = L \cos \theta$$



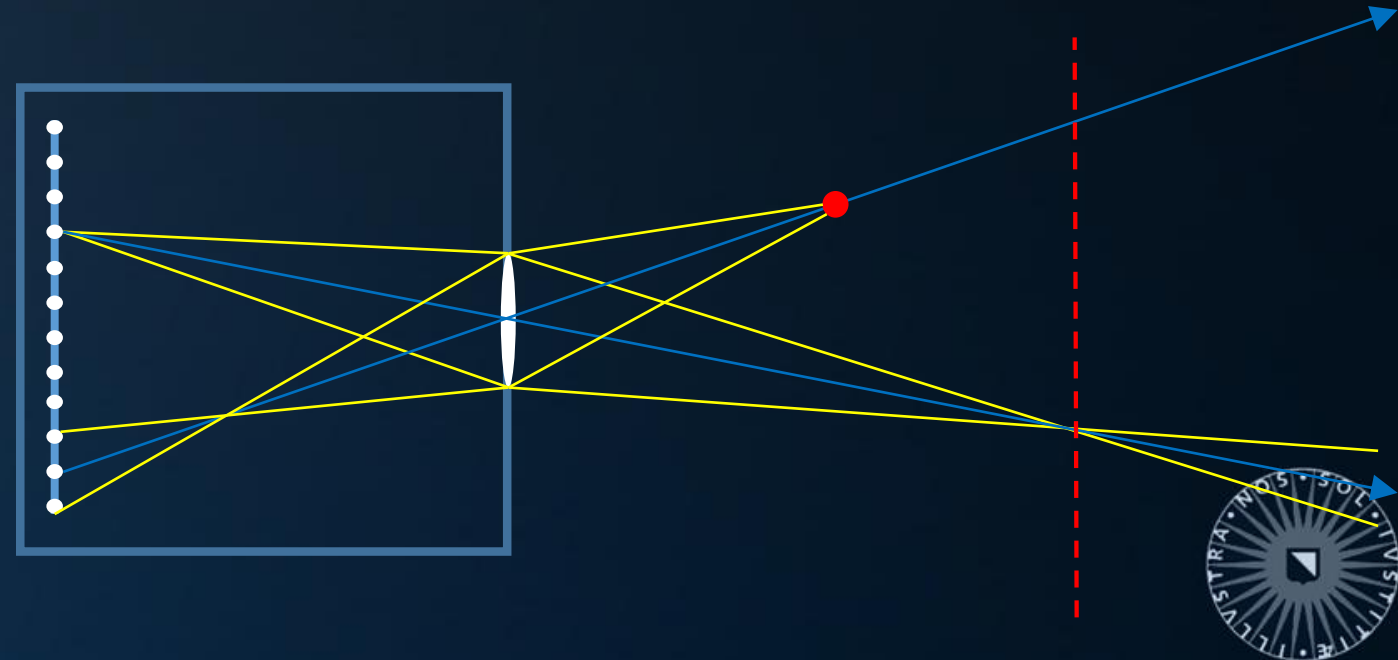
Light Transport

Pinhole Camera

A camera should not accept light from all directions for a particular pixel on the film. A pinhole ensures that only a single direction is sampled.

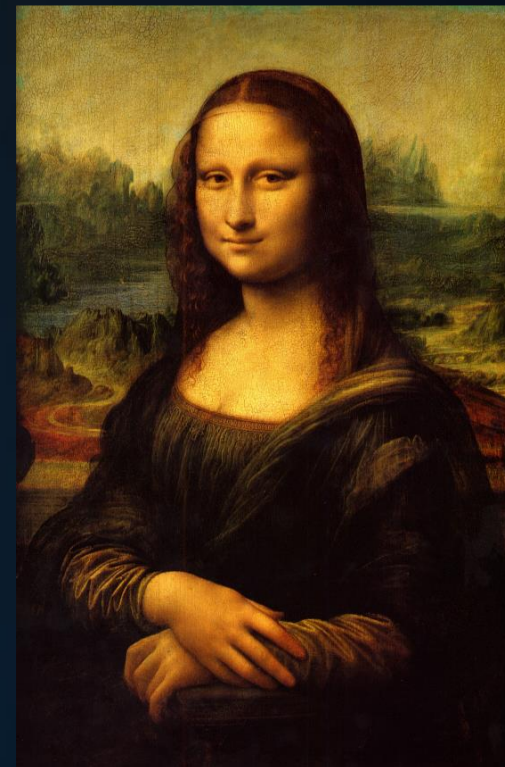


In the real world, an aperture with a lens is used to limit directions to a small range, but only on the focal plane.



Today's Agenda:

- Introduction
- Light Transport
- Materials
- Sensors
- Shading



Materials

Material properties:

- Texture + detail texture
- Shader
- Normal map
- Specular map
- Color
- ...

Used to simulate the interaction of light with a material.

Interaction:

- Absorption
- Scattering



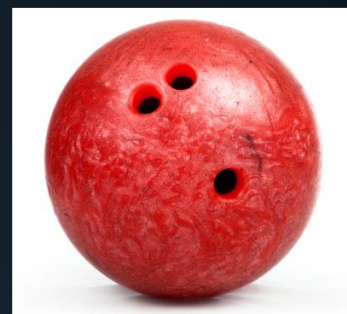
Materials

Absorption:

Happens on ‘optical discontinuities’.

Light energy is converted in other forms of energy (typically heat), and disappears from our simulation.

Materials typically absorb light with a certain wavelength, altering the color of the scattered light. This is how we perceive material color.



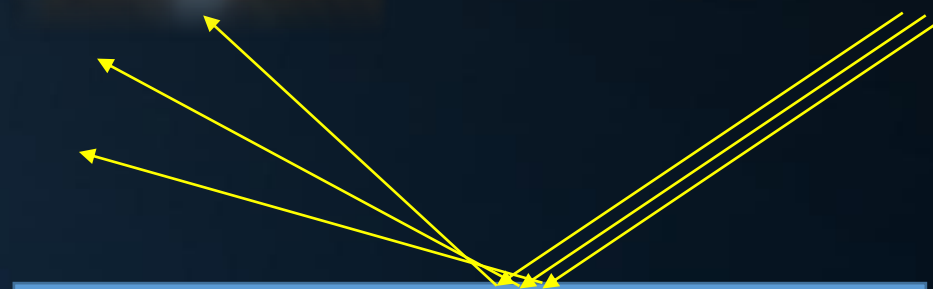
Materials

Scattering

Happens on ‘optical discontinuities’.

Scattering causes light to change direction.
Note that the amount of energy does not change due to scattering.

Light leaving the hemisphere can never exceed light entering the hemisphere, unless the material is emissive.

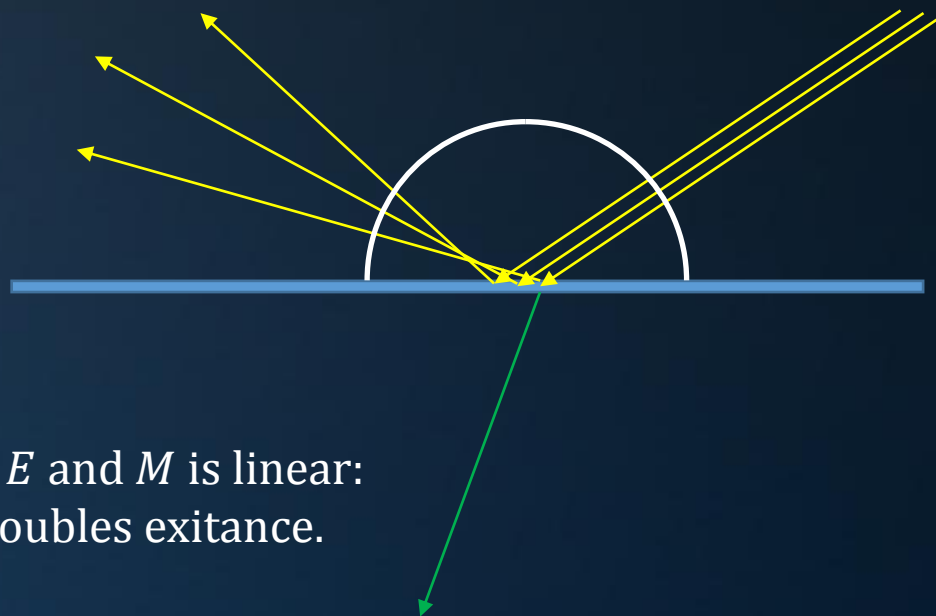


Materials

Light / surface interaction

In: irradiance (E), from all directions over the hemisphere.

Out: exitance (M), in all directions over the hemisphere.



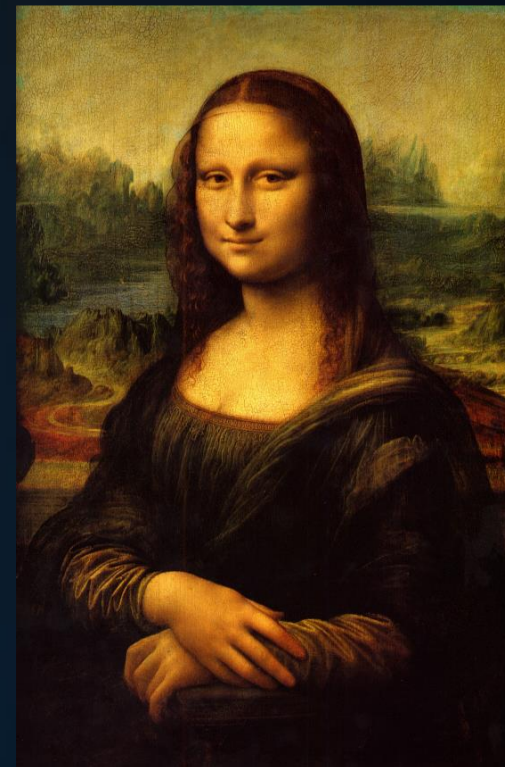
The relation between E and M is linear:
doubling irradiance doubles exitance.

$\frac{M}{E}$ must be in the range 0..1.



Today's Agenda:

- Introduction
- Light Transport
- Materials
- Sensors
- Shading



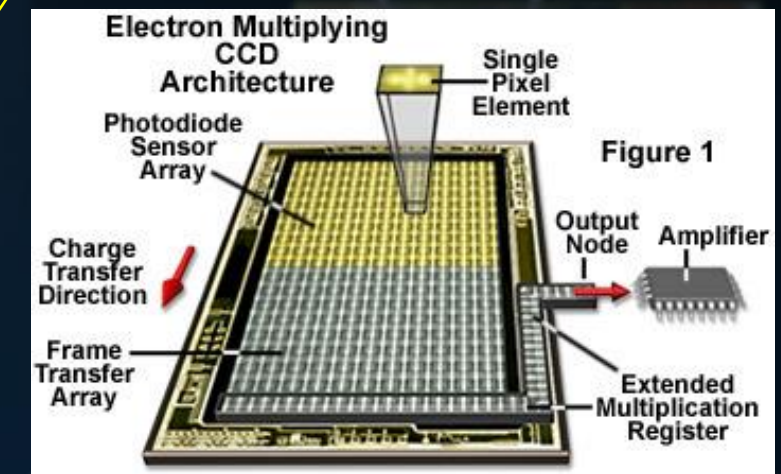
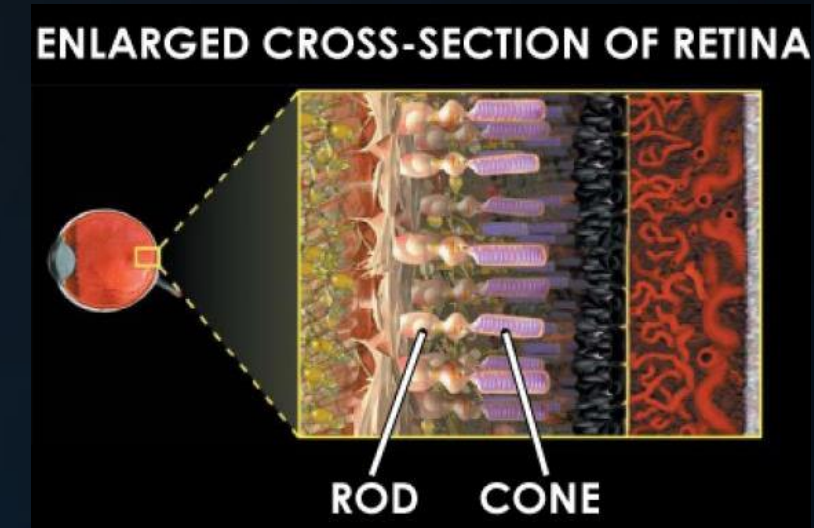
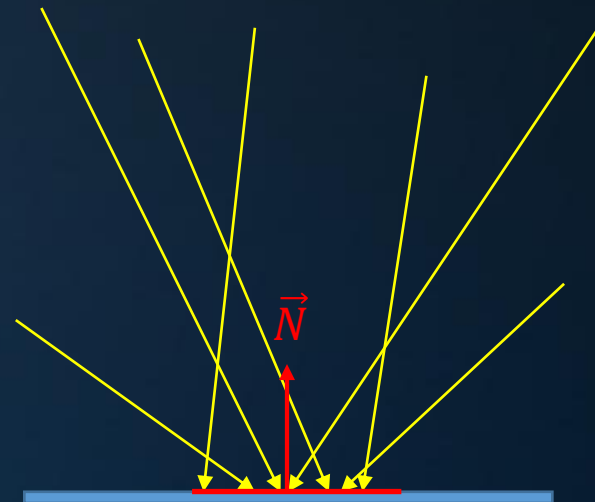
Sensors

Sensors typically consists of many small sensors:

- Rods and cones in the eye
- Dye particles in the film
- Pixel elements in a CCD
- A ray in a ray tracer
- A fragment in a rasterizer

Note that we cannot use irradiance to generate an image:

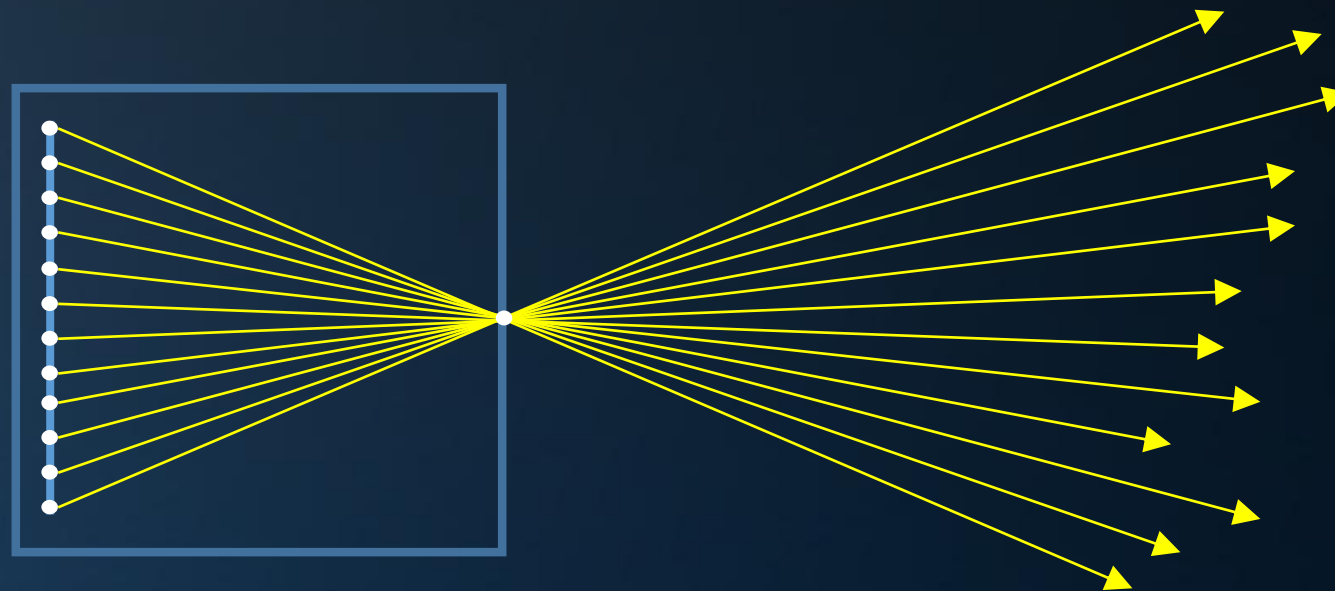
irradiance is a measure for light arriving from all directions.



Sensors

Pinhole camera

To capture light from a specific direction, we use a camera with a small opening (the aperture), so that each sensor can ‘see’ a small set of incoming directions.



Sensors

Radiance

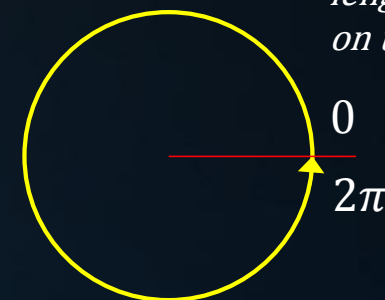
Using a pinhole camera, the sensors become directionally specific:

they average light over a small area, and a small set of incoming directions.

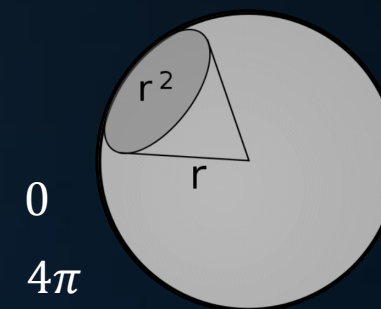
Recall that this is referred to as *radiance* (L):

The density of light flow per area per incoming direction, in $W\ m^{-2}sr^{-1}$.

Radians:
*length of arc
on unit circle*



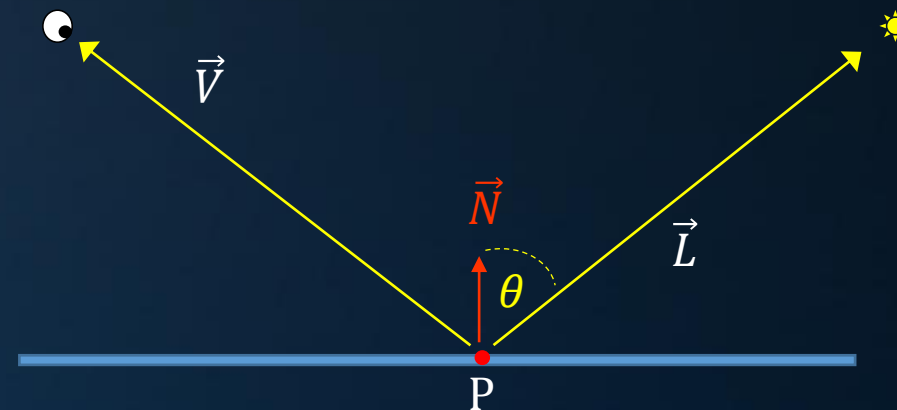
Steradians:
*area of surface
on unit sphere*



Sensors

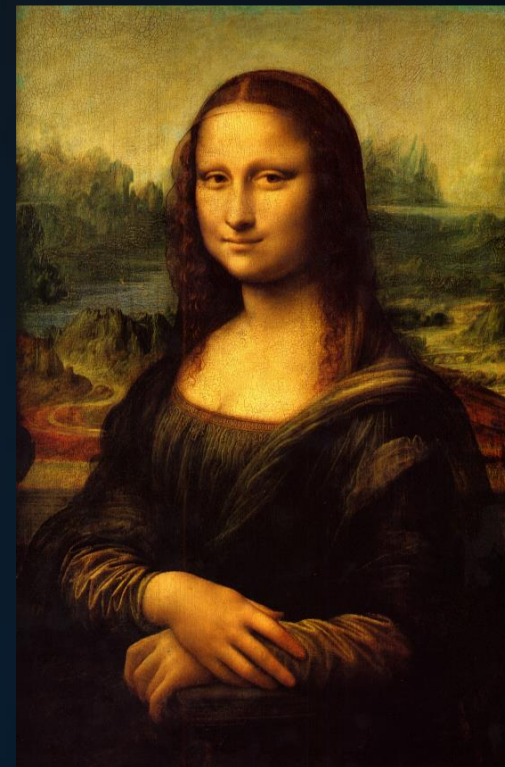
Summing it up:

- Light arrives from all light sources on point P ;
- The energy flow per unit area, perpendicular to \vec{L} is projected on a surface perpendicular to \vec{N} . This is *irradiance*, or: E .
- Exitant light M is scattered over all directions on the hemisphere.
- Light scattered towards the eye arrives at a sensor.
- The sensor detects radiance: light from a specific set of directions.



Today's Agenda:

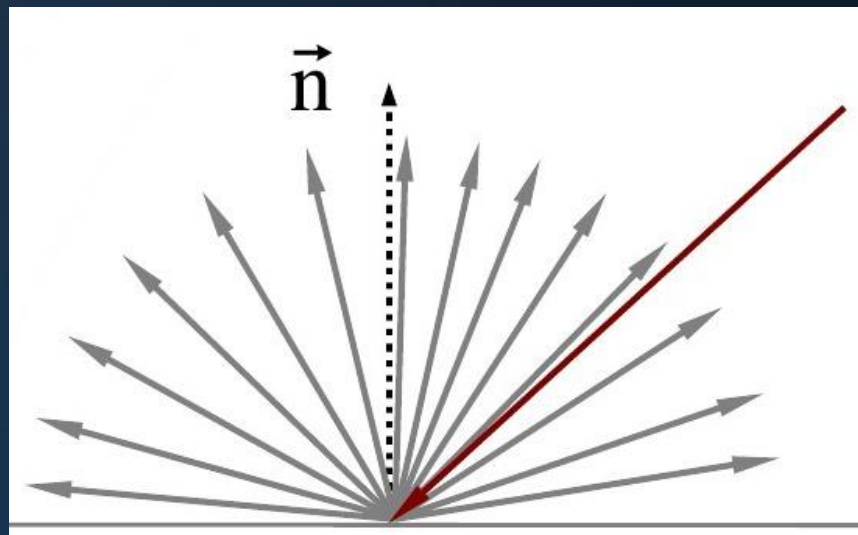
- Introduction
- Light Transport
- Materials
- Sensors
- Shading



Shading

Definition

Shading: the process of using an equation to compute the outgoing radiance along the view ray \vec{V} , based on material properties and light sources.



Diffuse or Lambert BRDF, also called “N dot L shading”



Shading

Lambert shading model

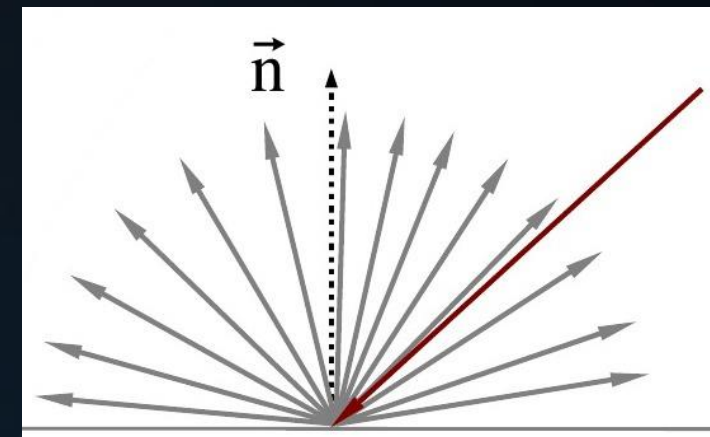
The diffuse shading model is:

$$M_{diff} = \frac{c_{diff}}{\pi} L \overline{\cos\theta_i}$$

This takes into account:

- Projection of the direction of the incoming light on the normal;
- Absorption due to material color c_{diff} .

Distance attenuation is represented in L .



Practical implementation:

```
dist=light.pos-fragment.pos;
L=normalize(light.pos-fragment.pos);
N=fragment_normal; // interpolated
radiance=light.color/(dist*dist);
irradiance=radiance*dot(N,L);
M=(material.color / PI)*irradiance;
```

The reflected energy M is what the camera will receive via the ray arriving at the fragment (i.e., the ‘color’ of the fragment).



Shading

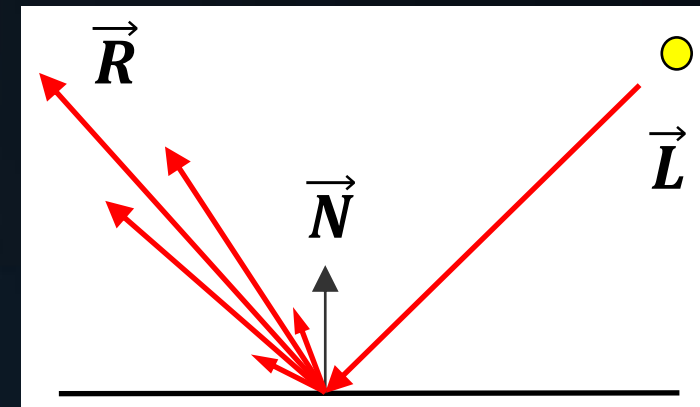
Phong shading model

The Phong shading model combines a diffuse reflection with a glossy one, and adds an ambient factor.

$$M_{\text{phong}} = c_{\text{ambient}} + c_{\text{diff}}(\vec{N} \cdot \vec{L})L_{\text{diff}} + c_{\text{spec}}(\vec{V} \cdot \vec{R})^s L_{\text{spec}}$$

The Phong shading model is an ‘empirical model’, and has many problems:

- It doesn’t guarantee that $M \leq E$;
- It doesn’t take irradiance as input;
- It requires many (unnatural) parameters;
- That ambient factor...



Shading

BRDF – Bidirectional Reflectance Distribution Function

Defines the relation between *irradiance* and *radiance*.

Or, more accurately:

The BRDF represents the ratio of reflected radiance exiting along \vec{V} , to the irradiance incident on the surface from direction \vec{L} .

Note that the BRDF takes two parameters: an incoming and an outgoing direction.

$$f_r(\vec{L}, \vec{V}) = \frac{dL_{reflected}(\vec{V})}{dE_{incoming}(\vec{L})}$$



Shading

BRDF – Bidirectional Reflectance Distribution Function

Diffuse BRDF:

$$f_r(\vec{L}, \vec{V}) = \frac{dL_{reflected}(\vec{V})}{dE_{incoming}(\vec{L})} = \frac{material\ color}{\pi}$$

where $E_{incoming}(\vec{L})$ is irradiance arriving from the light source, i.e. light color, times attenuation, times N dot L.

The diffuse BRDF scatters light equally in all directions. \vec{V} is *not* used in the equation. The diffuse BRDF is *view independent*.

Also note that \vec{N} and \vec{L} do not occur in this equation: N dot L is simply used to convert from radiance to irradiance.

Practical use of the BRDF:

Input for a BRDF is irradiance.

This means that we already have processed attenuation and N dot L.

The fragment color, using a BRDF and a point light at distance r is thus:

$$M = f_r(\vec{L}, \vec{V}) \overline{\cos \theta_i} \frac{light\ color}{r^2}$$



Shading

BRDF – Bidirectional Reflectance Distribution Function

Phong BRDF:

$$f_r(\vec{L}, \vec{V}) = \frac{dL_{reflected}(\vec{V})}{dE_{incoming}(\vec{L})} = color + color \overline{\cos \alpha}^m$$

Where α is the angle between \vec{V} and \vec{R} , \vec{R} is \vec{L} reflected in \vec{N} , and m is the Phong exponent.

Note that the division by π is missing; it doesn't make sense for the specular reflection...

Also note that the ambient color is missing: this factor is constant and does not depend on irradiance.



Shading

BRDF – Bidirectional Reflectance Distribution Function

BRDFs formalize the interaction of light / surface interaction, and allow us to do so in a physically correct way.

Games are switching to physically based models rapidly:

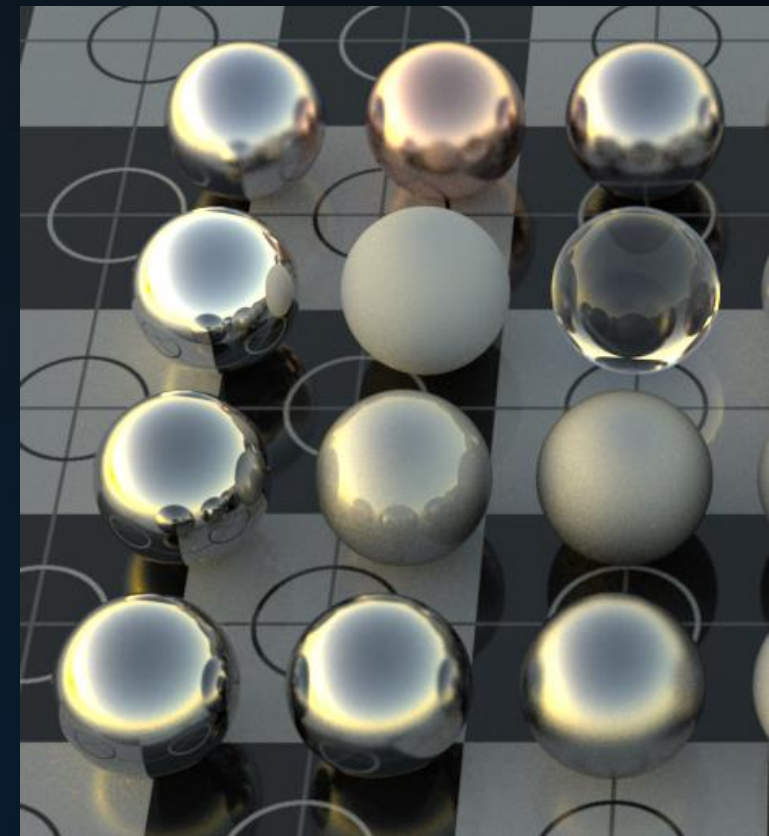
- To increase realism;
- To reduce the number of parameters in shaders;
- To have uniform shaders for varying lighting conditions.

More on this in Advanced Graphics!

```

    if (depth < MAXDEPTH)
    {
        if (inside) // inside sphere
        {
            nt = nt / nc; add = add * nc;
            cos2t = 1.0f - nnt * nnt;
            D, N );
        }
        else // outside sphere
        {
            at = nt - nc; b = nt + nc;
            at Tr = 1 - (R0 + (1 - R0) * cos2t);
            Tr) R = (D * nnt - N * (cos2t > 0 ? 1 : -1));
        }
        E * diffuse;
        = true;
    }
    refl + refr)) && (depth < MAXDEPTH)
    {
        D, N );
        refl * E * diffuse;
        = true;
    }
    MAXDEPTH)
    survive = SurvivalProbability( diffuse );
    estimation - doing it properly, closely following
    if;
    radiance = SampleLight( &rand, I, &t, &light );
    e.x + radiance.y + radiance.z) > 0) && (depth <
    v = true;
    at brdfPdf = EvaluateDiffuse( L, N ) * Psurvive;
    at3 factor = diffuse * INVPI;
    at weight = Mis2( directPdf, brdfPdf );
    at cosThetaOut = dot( N, L );
    E * ((weight * cosThetaOut) / directPdf) * (radiance
    random walk - done properly, closely following walk
    vive)
    ;
    at3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf );
    survive;
    pdf;
    n = E * brdf * (dot( N, R ) / pdf);
    ion = true;

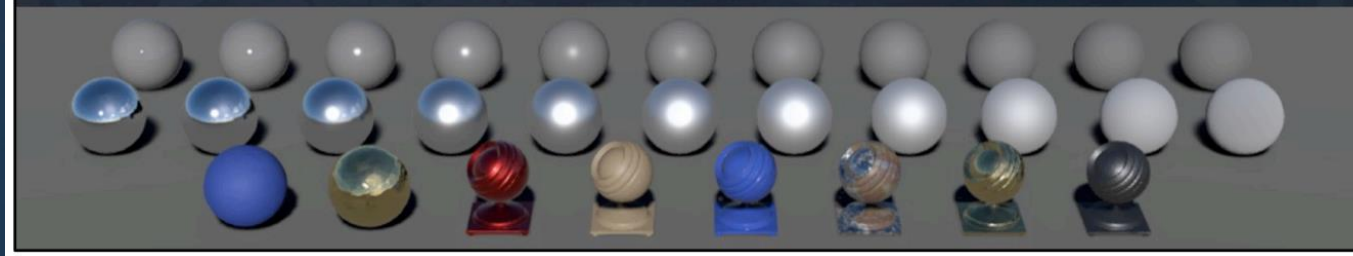
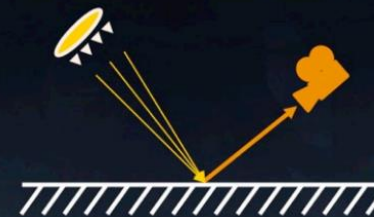
```



Shading

Lighting – Analytical Lights

- **Sun** light
 - **Units:** Illuminance (lux)
 - Facing disk with non-null solid angle



“Moving Frostbite to PBR”

http://www.frostbite.com/wp-content/uploads/2014/11/s2014_pbs_frostbite_slides.pdf




```

10;
11 (depth < MAXDC)
12 {
13     nt = inside / l * 0.5;
14     nt = nt / nc; ddn = dot(N, N);
15     cos2t = 1.0f - nnt * ddn;
16     D, N );
17 }
18
19 at a = nt - nc, b = nt + nc;
20 at Tr = 1 - (R0 + (1 - R0) * a);
21 Tr) R = (D * nnt - N * (ddn
22
23 E * diffuse;
24 = true;
25
26
27 refl + refr)) && (depth < MAXDEPTH)
28 {
29     D, N );
30     refl * E * diffuse;
31     = true;
32
33 MAXDEPTH)
34
35 survive = SurvivalProbability( diffuse,
36 estimation - doing it properly, closely following
37 if;
38 radiance = SampleLight( &rand, I, &l, &align,
39 e.x + radiance.y + radiance.z) > 0) && (cos(N
40
41 w = true;
42 at brdfPdf = EvaluateDiffuse( L, N ) * Psurvive;
43 at3 factor = diffuse * INVPI;
44 at weight = Mis2( directPdf, brdfPdf );
45 at cosThetaOut = dot( N, L );
46 E * ((weight * cosThetaOut) / directPdf) * (radiance
47
48 random walk - done properly, closely following
49 (survive)
50
51
52 at3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf);
53 survive;
54 pdf;
55 n = E * brdf * (dot( N, R ) / pdf);
56 sion = true;

```

Guerrilla Games

```

Random walk - done properly, closely following world
(archive)

;
mat3 brdf = SampleDiffuse( diffuse, N, r1, r2, &R, &pdf);
R = RandomVec();
pdf;
n = E * brdf * (dot( N, R ) / pdf);
return n;
}

```



Shading



Lighting Conditions

Want same content to look good

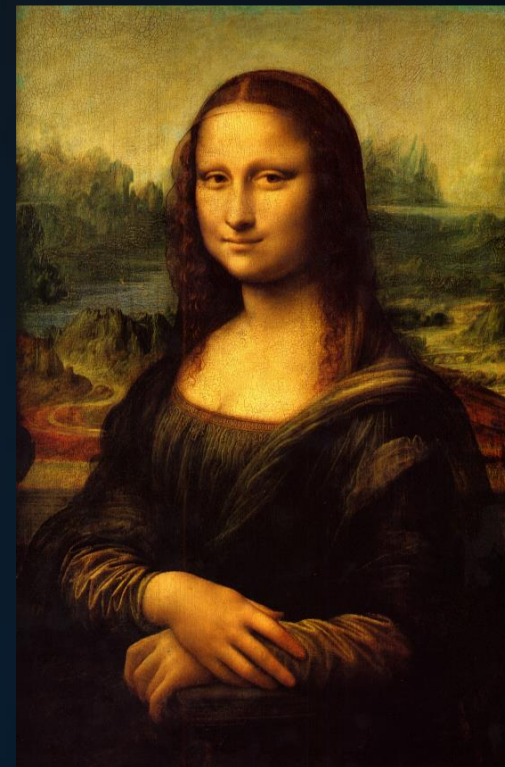
“Physically Based Shading in Unity”

http://aras-p.info/texts/files/201403-GDC_UnityPhysicallyBasedShading_notes.pdf



Today's Agenda:

- Introduction
- Light Transport
- Materials
- Sensors
- Shading



INFOGR – Computer Graphics

J. Bikker - April-July 2016 - Lecture 10: “Shading Models”

END of “Shading Models”

next lecture: “Visibility”

