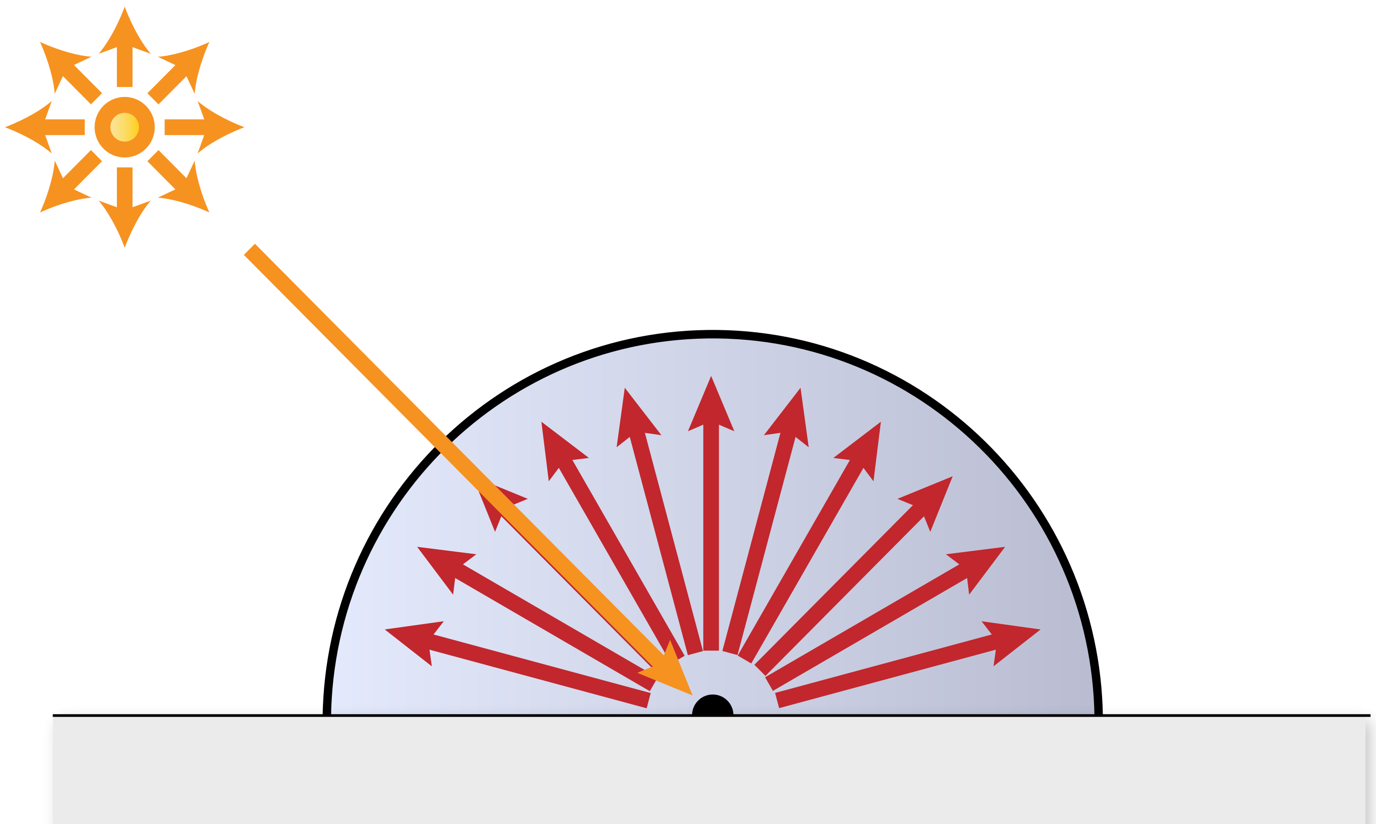
ECSE 446/546

Image Synthesis



Phenomenological Shading 1

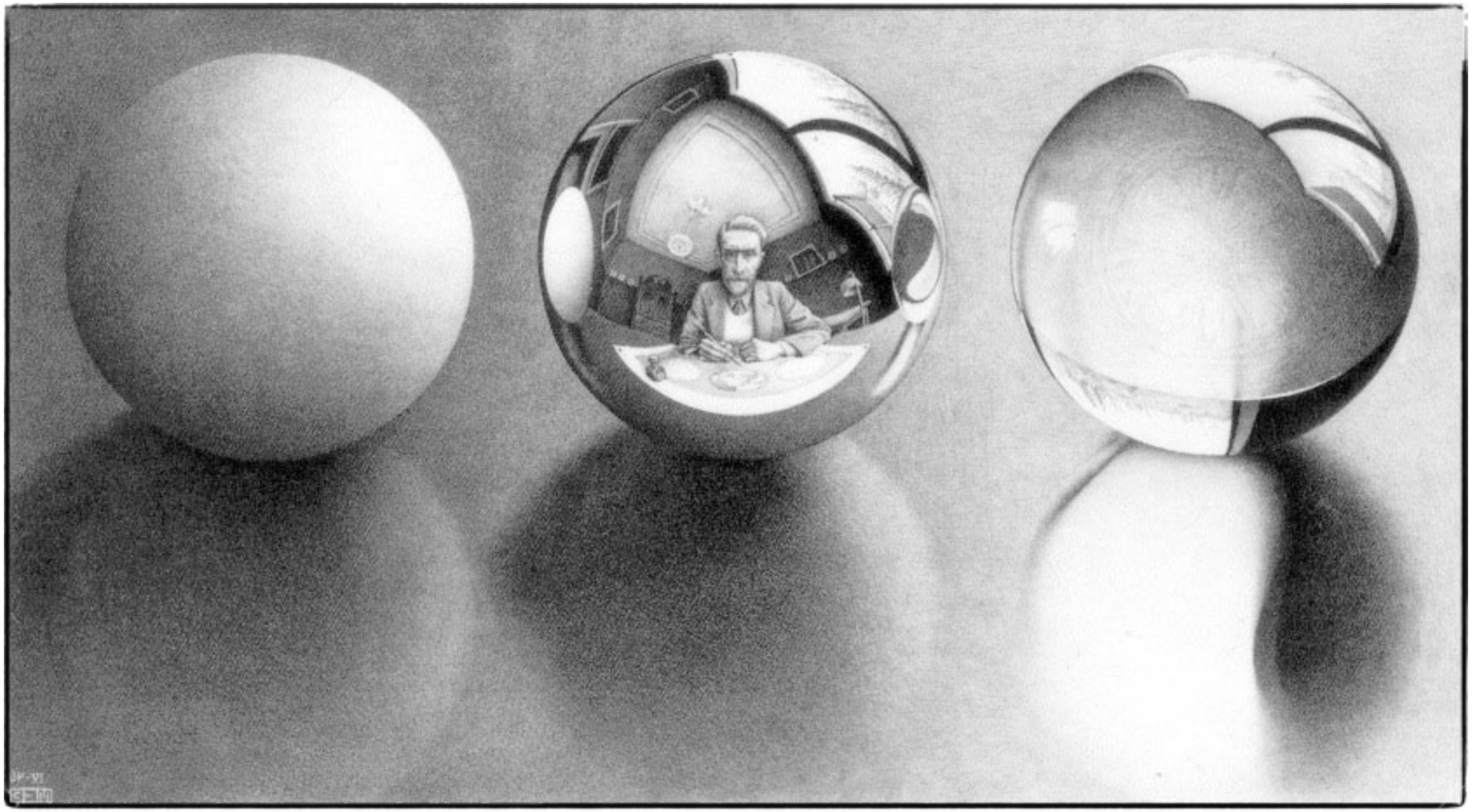
Prof. Derek Nowrouzezahrai
derek@cim.mcgill.ca

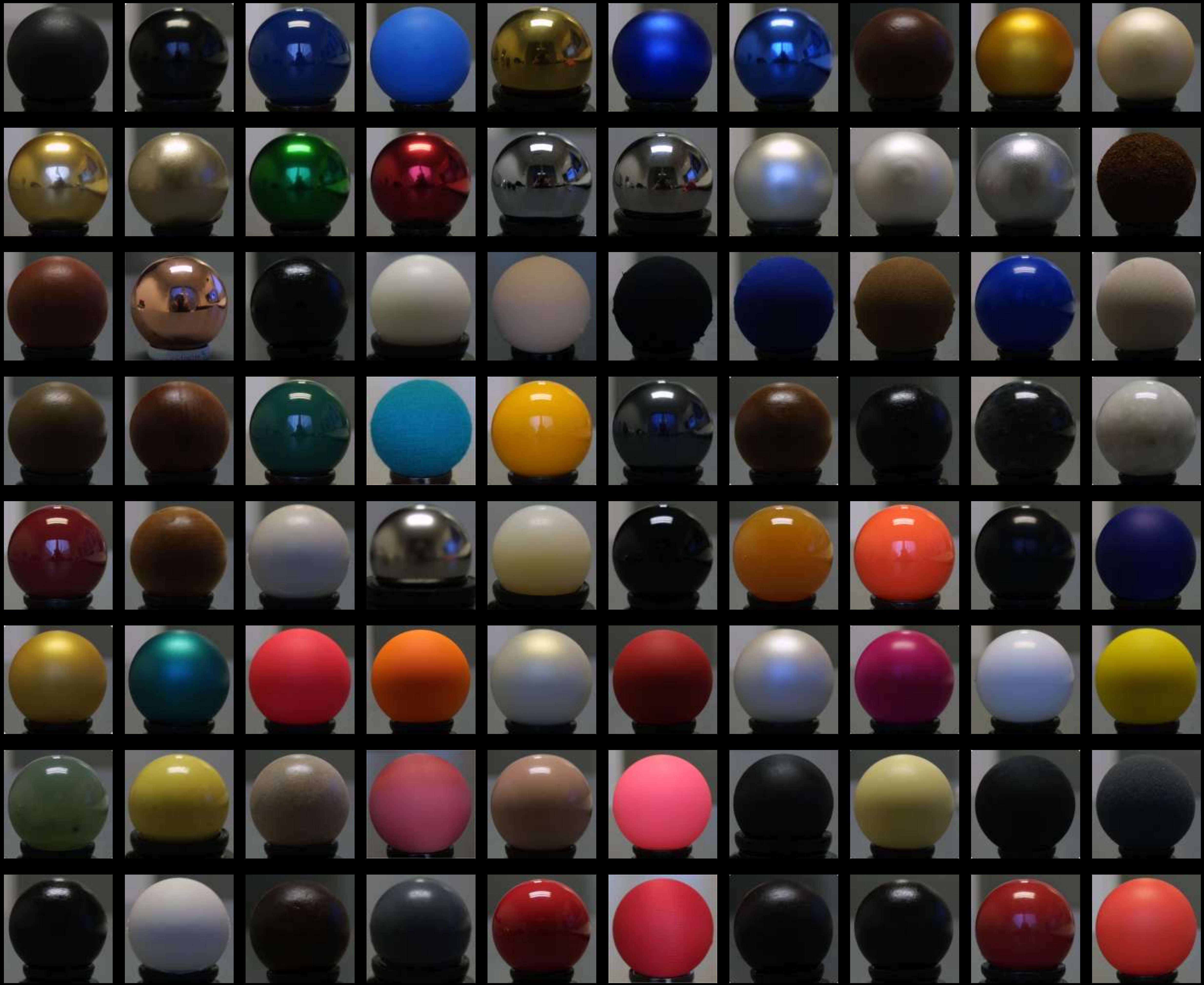
Shading

Shading =

Material x Lighting

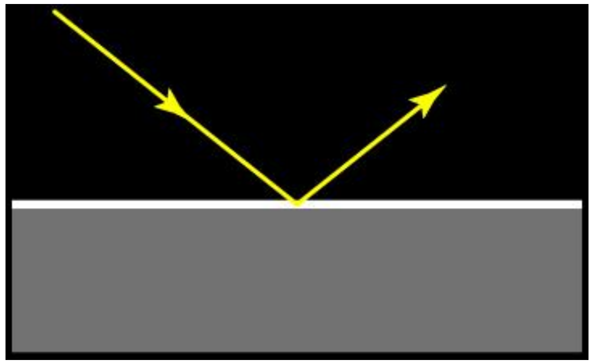
Motivation – Different Materials



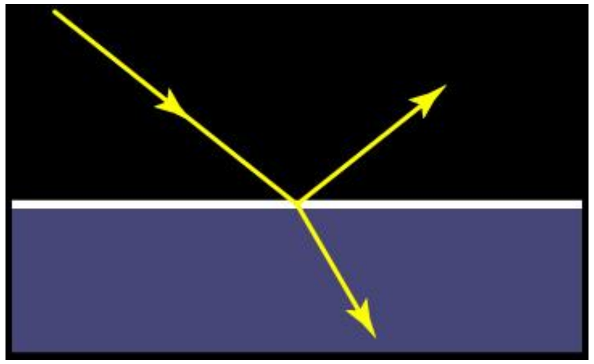


Real-world Materials

Metals

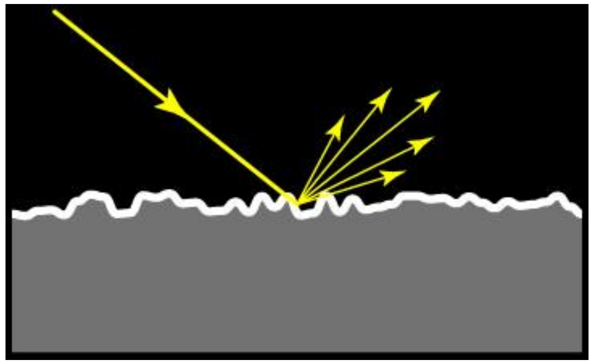


Dielectric

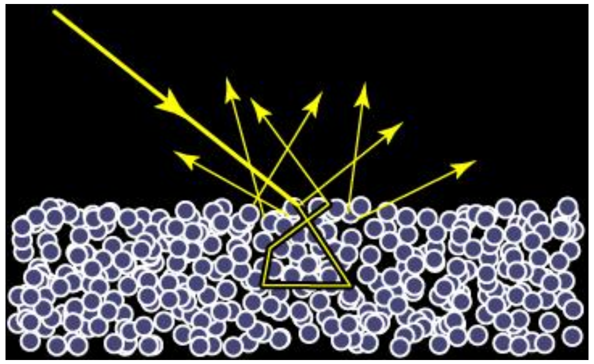


Real-world Materials

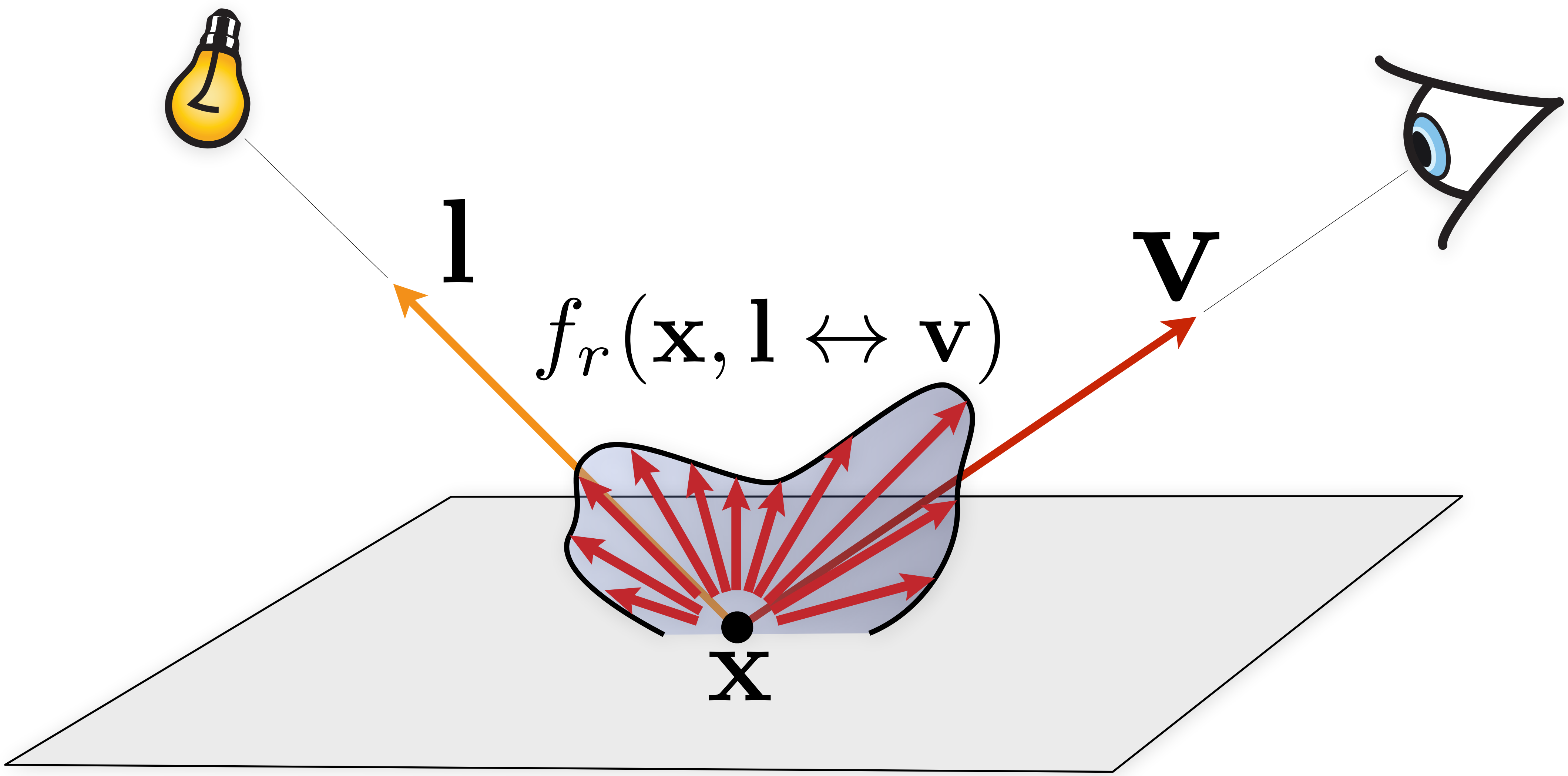
Metals



Dielectric



Light-Material Interactions



Material and Lighting Models

Empirical/phenomenological models:

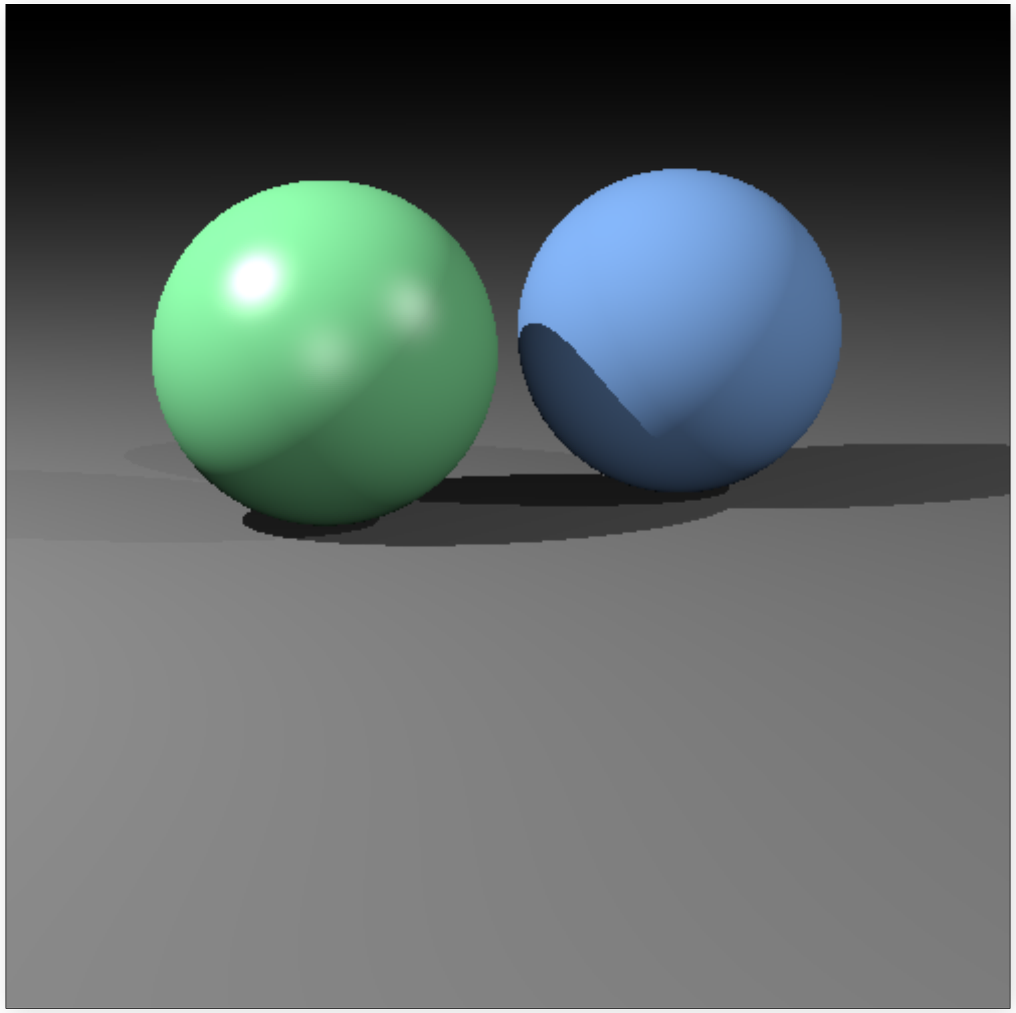
- produce believable images
- simple and efficient
- only for **simple materials** & **lights/emitters**

Physically-based shading models:

- can reproduce accurate effects
- more complex and expensive

Let's start with empirical models…

Shading – Circa 1970



After a slide by Steve Marschner

A Simple Empirical Material Model

Combines several effects:

1. Diffuse Reflection
   - light is reflected equally in every direction
   - shading is weighted by surface "color" property
2. Specular reflection/refraction (e.g., chrome, glass, glaze/varnish)
   - light reflected/refracted only in a single direction
3. Specular "highlights"
   - approximation of blurred reflection, **but only of the light source**

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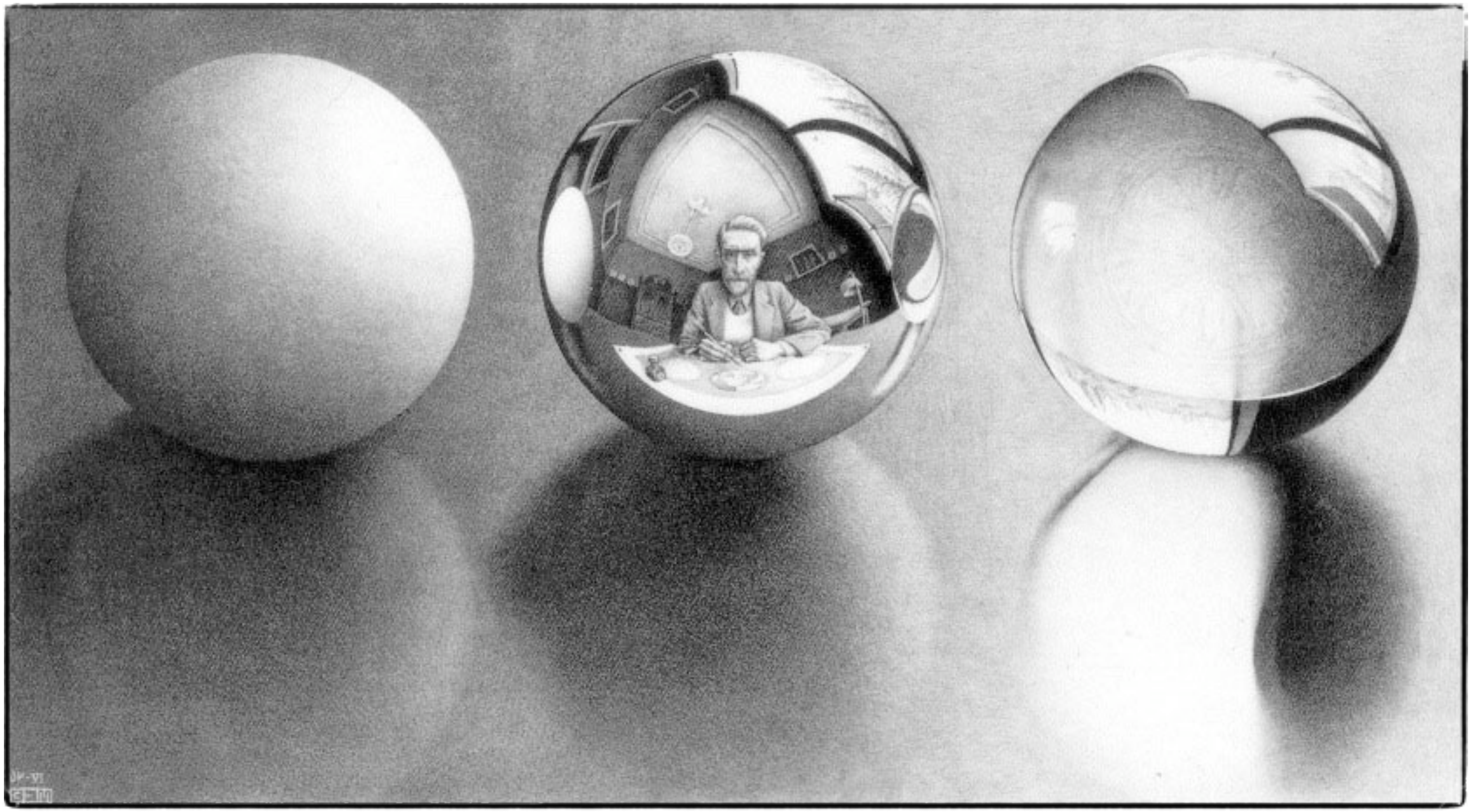
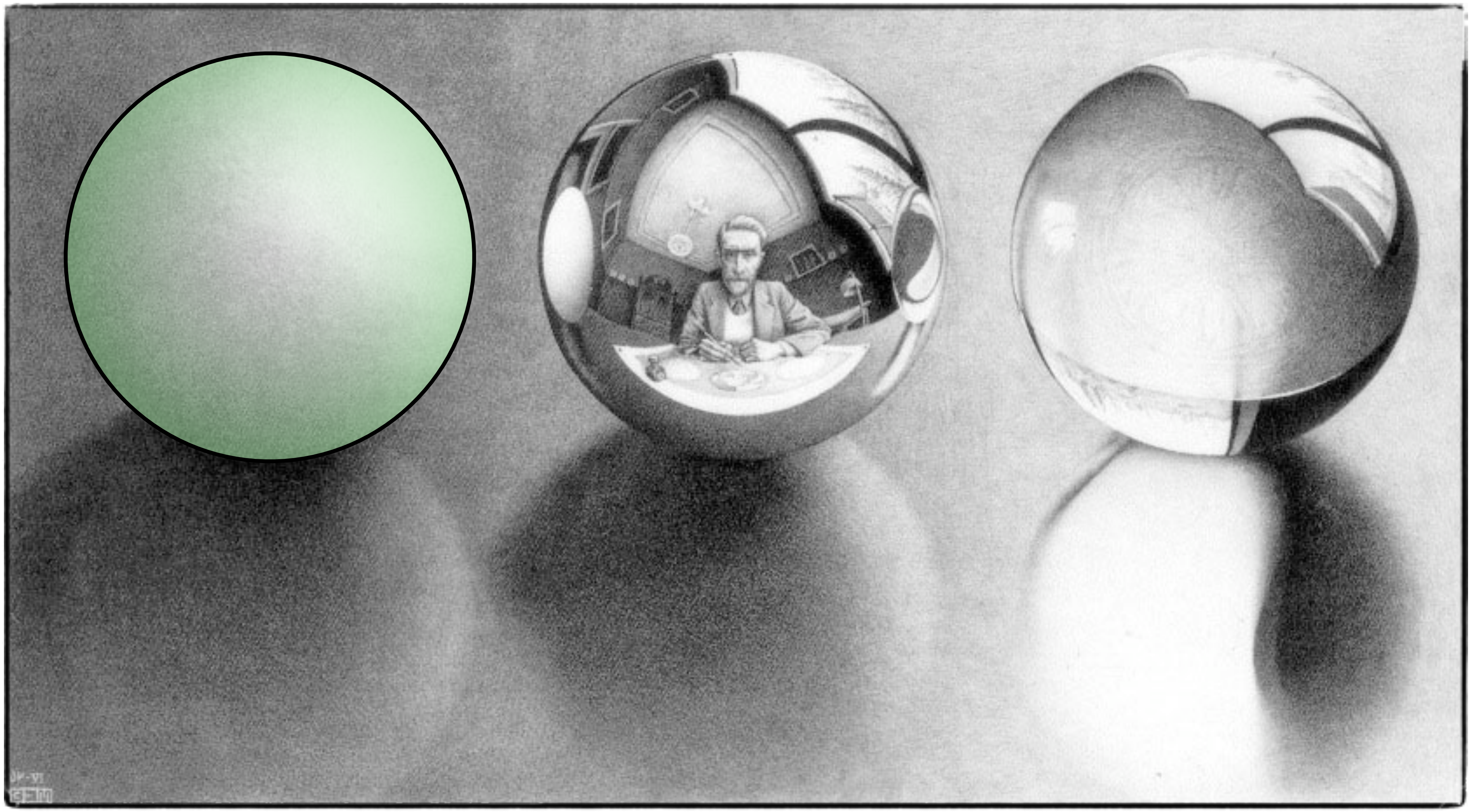
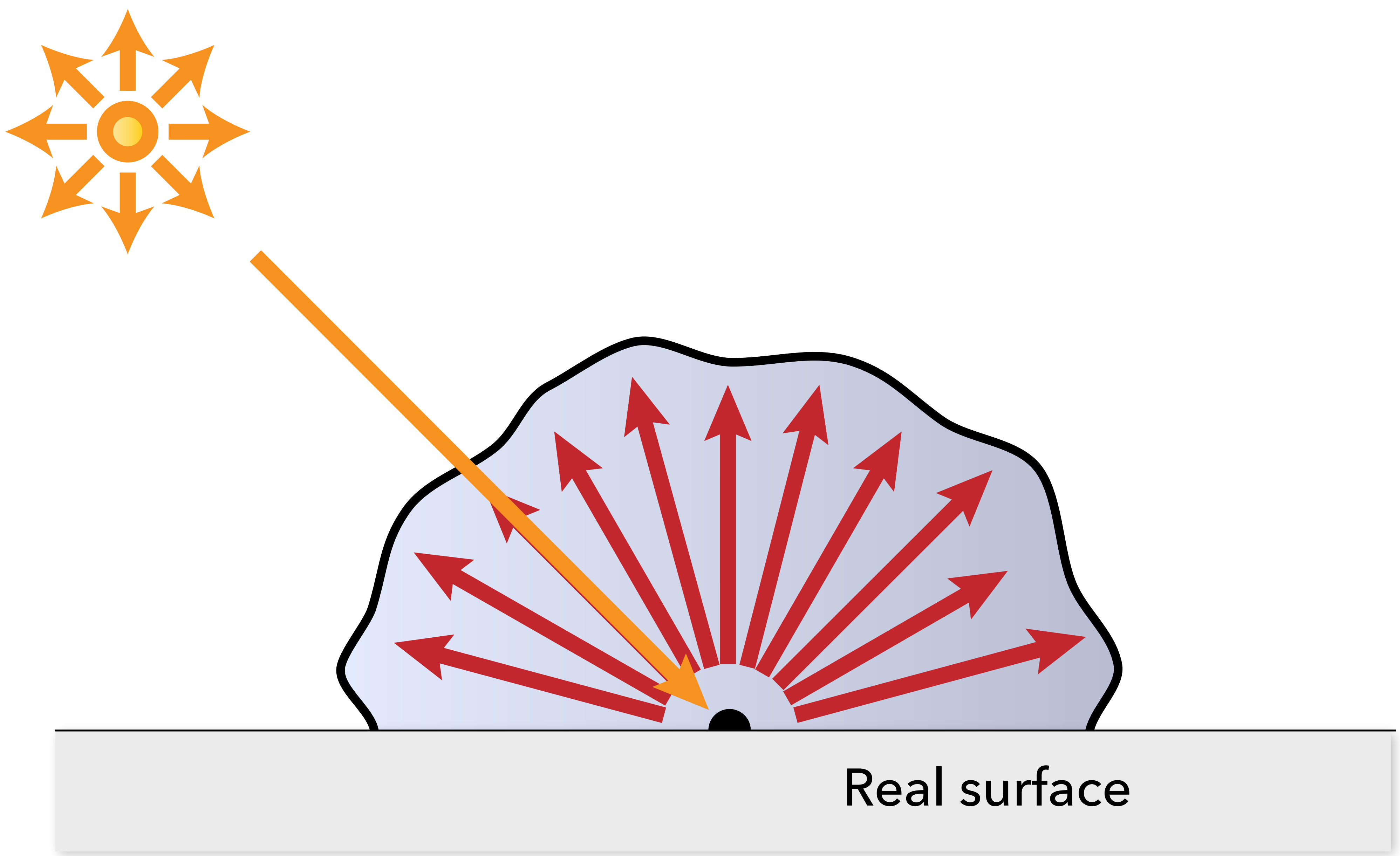
Idealized Materials



Diffuse Reflection

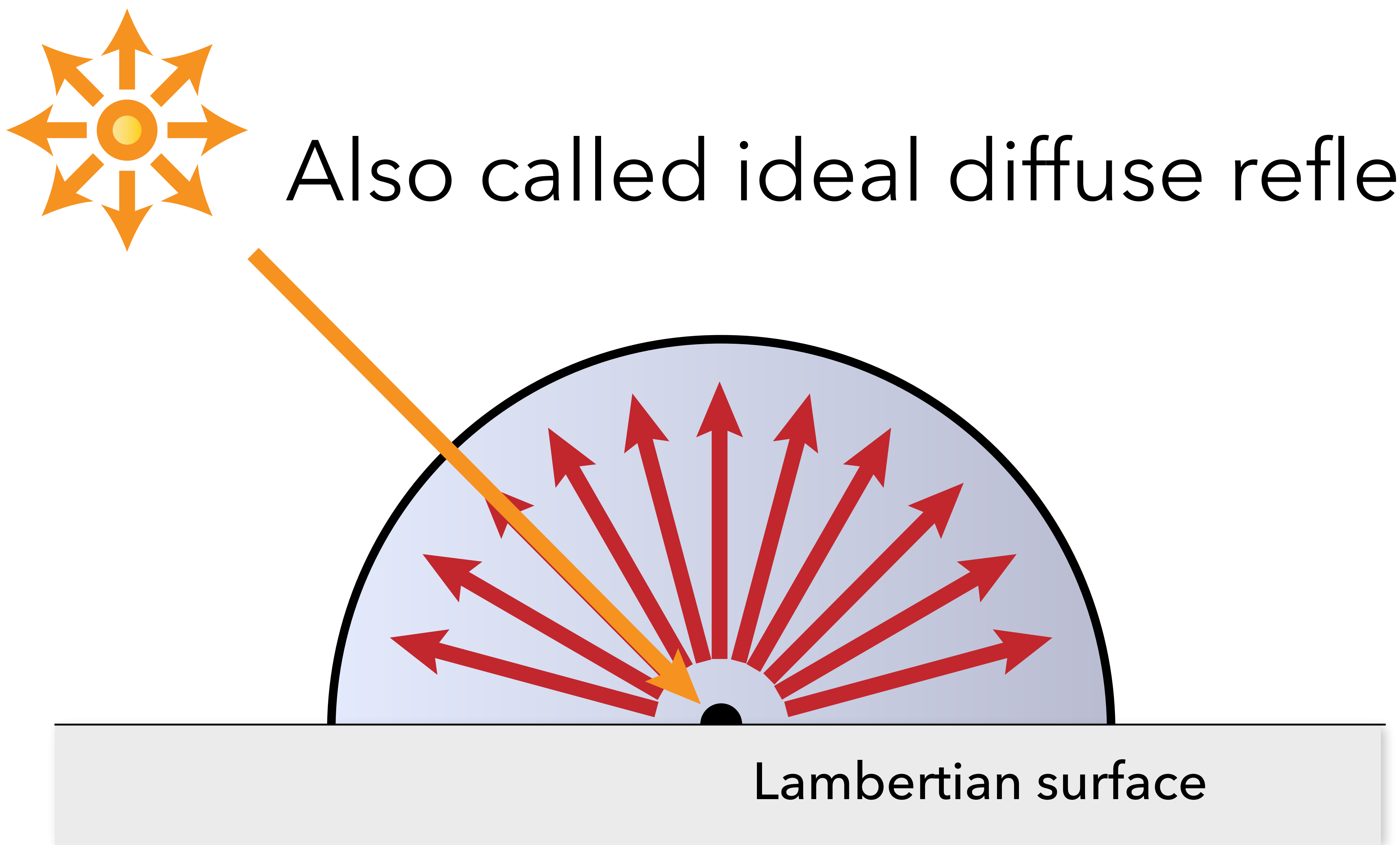


Diffuse/Lambertian Reflection



Basic Shading – Diffuse Material

Also called ideal diffuse reflection

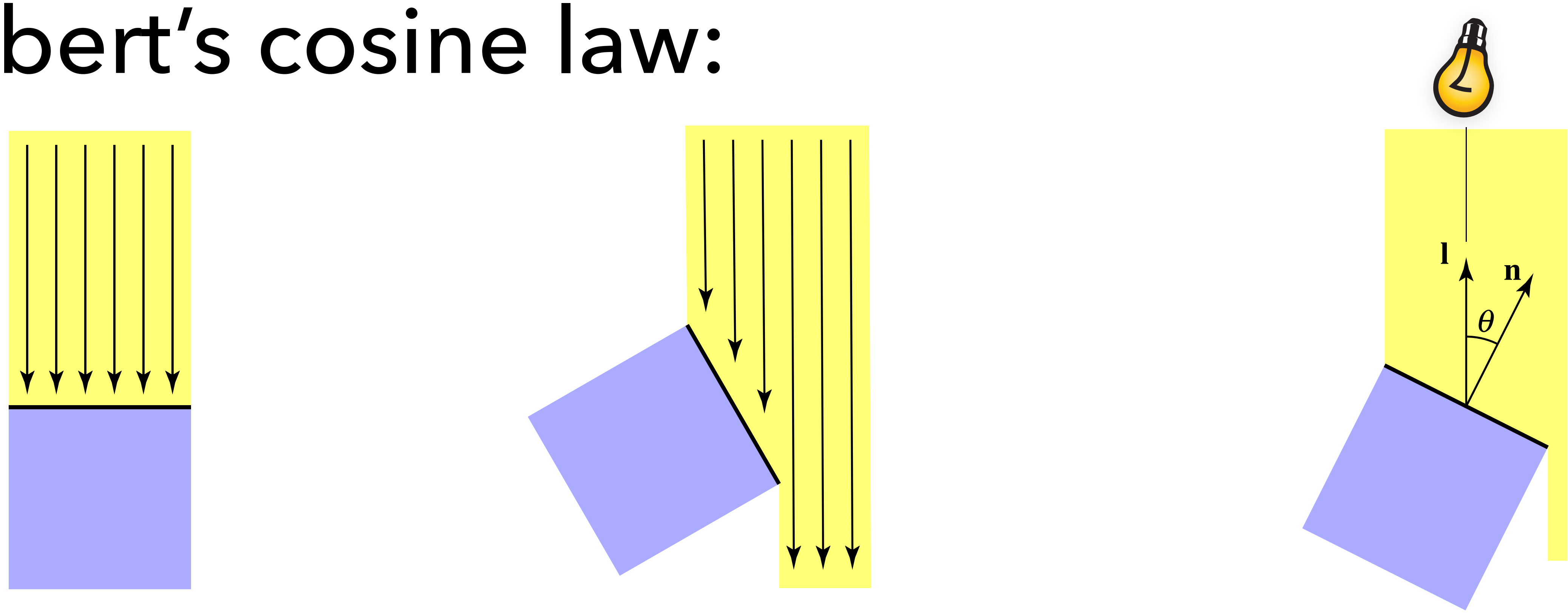


Basic Shading – Diffuse Material

Light is scattered uniformly in all directions

- shading is constant for all viewing directions

Lambert's cosine law:



Top face of cube receives a certain amount of light

Top face of 60° rotated cube intercepts half the light

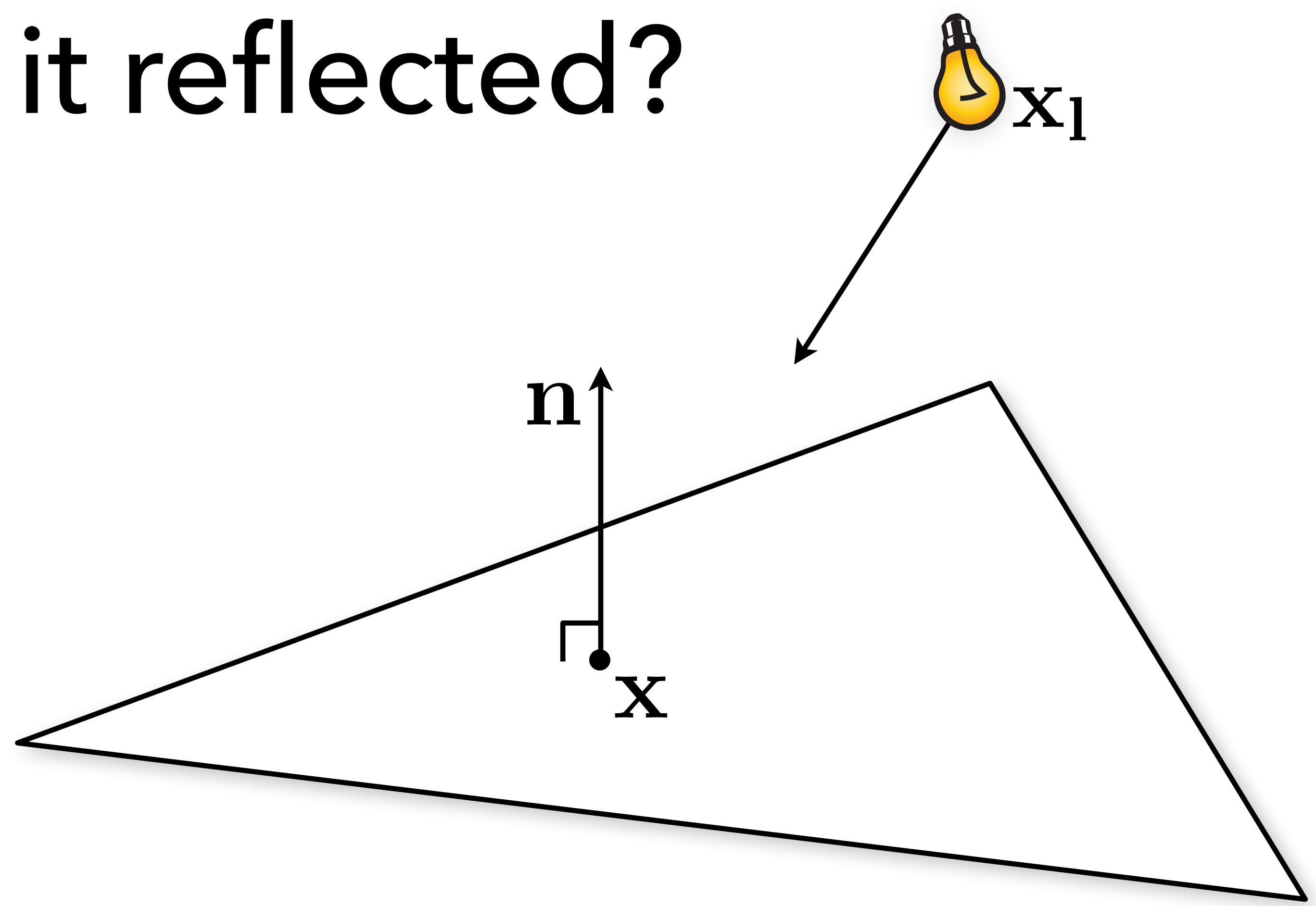
In general, light per unit area is proportional to $\cos\theta = \mathbf{l} \cdot \mathbf{n}$

After a slide by Steve Marschner

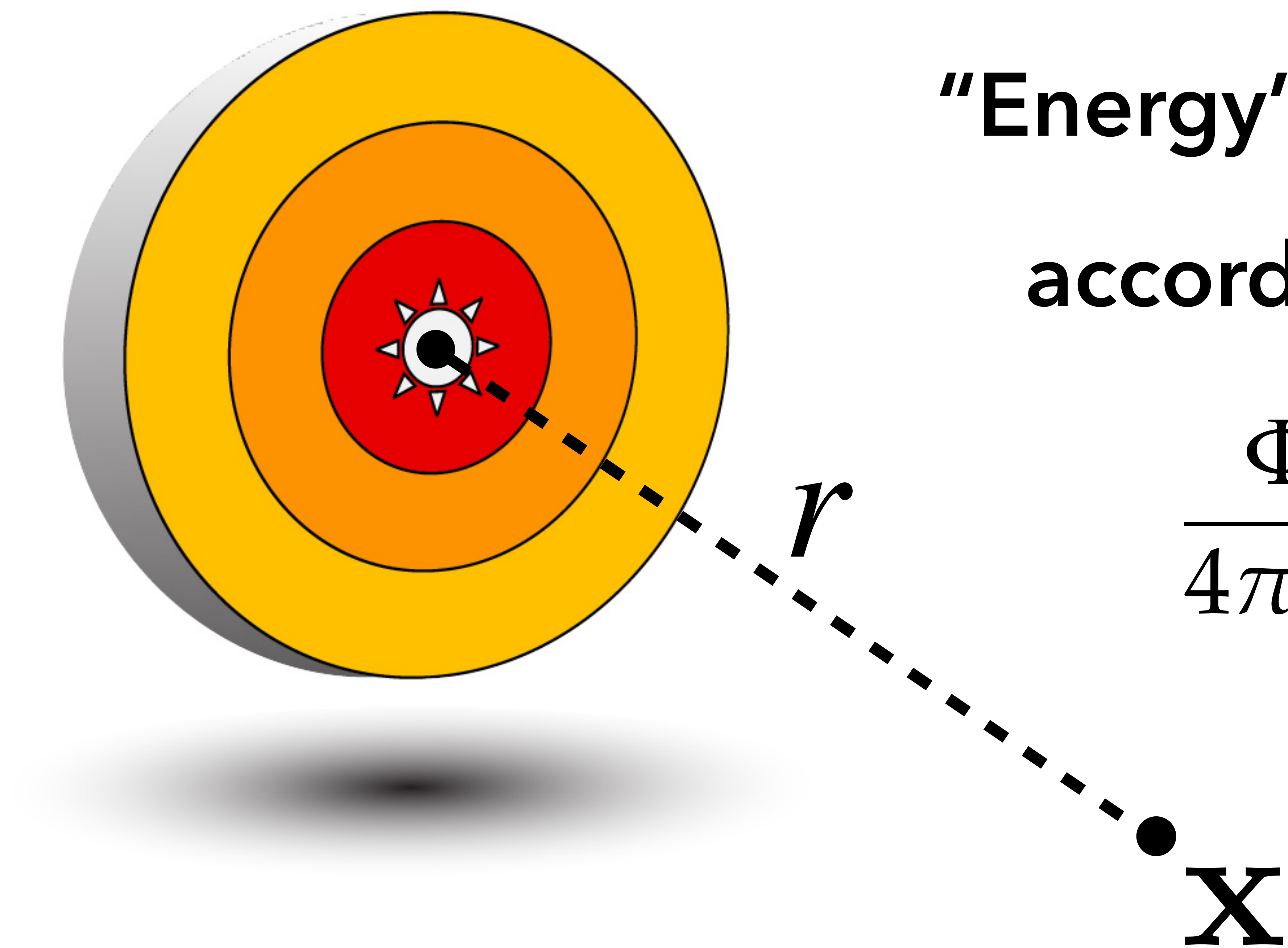
Basic Shading – Point Light

How much light hits this triangle?

How is it reflected?



Basic Shading – Point Light

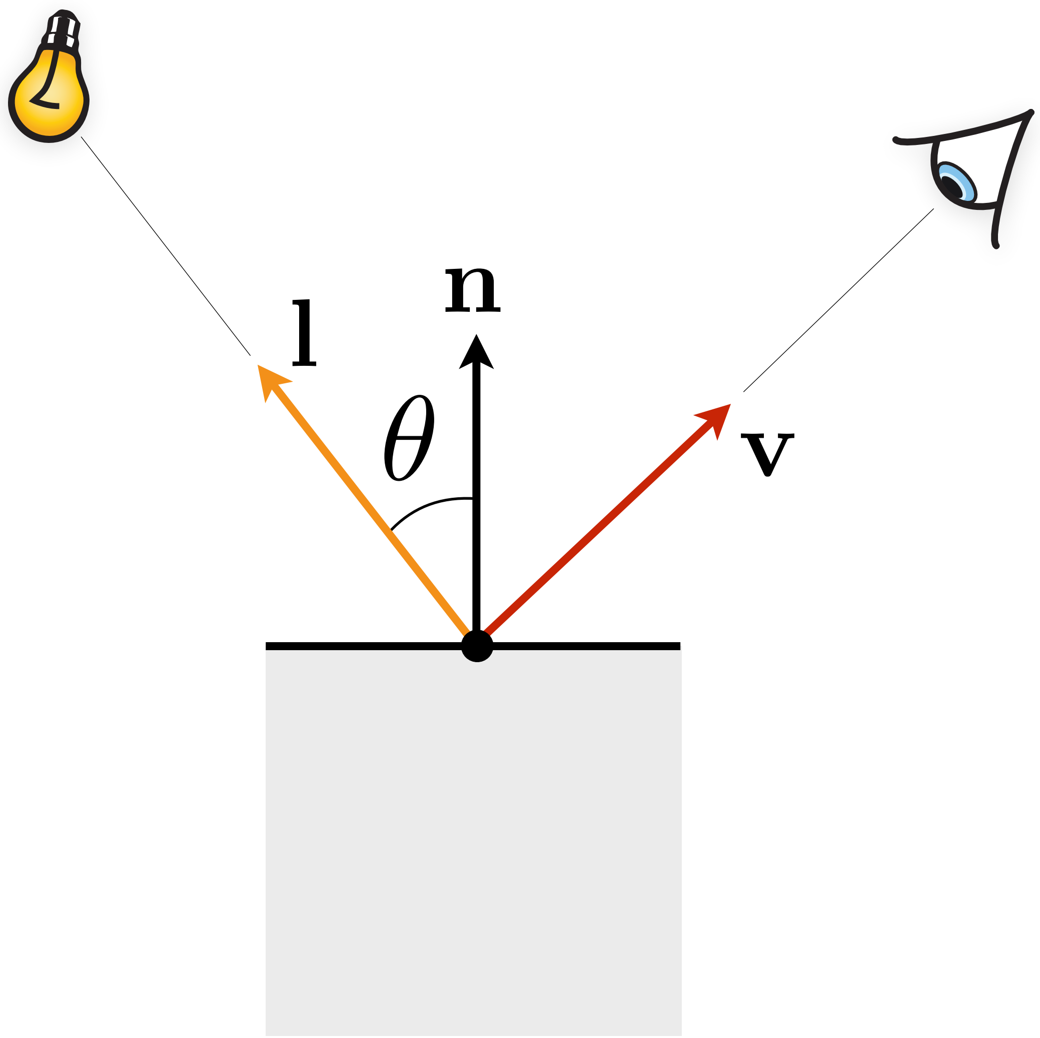


"Energy" falls off according to

$$\frac{\Phi}{4\pi r^2}$$

Diffuse Shading with a Point Light

Shading independent of view direction



incident light (e.g., coming from source)

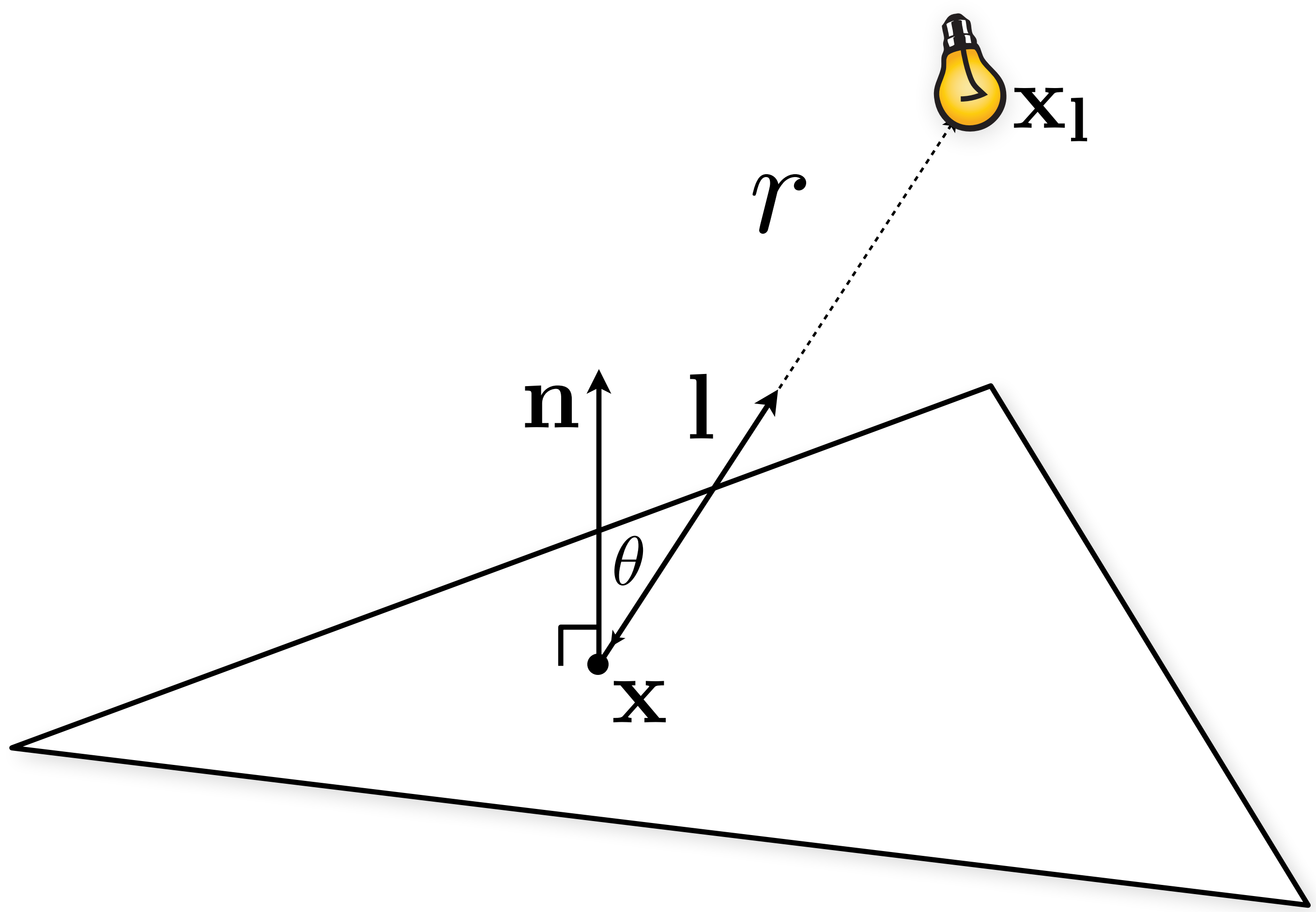
$$L_d = \frac{\rho}{\pi} L_i \max(0, \mathbf{n} \cdot \mathbf{l})$$

diffuse coefficient

diffusely reflected light

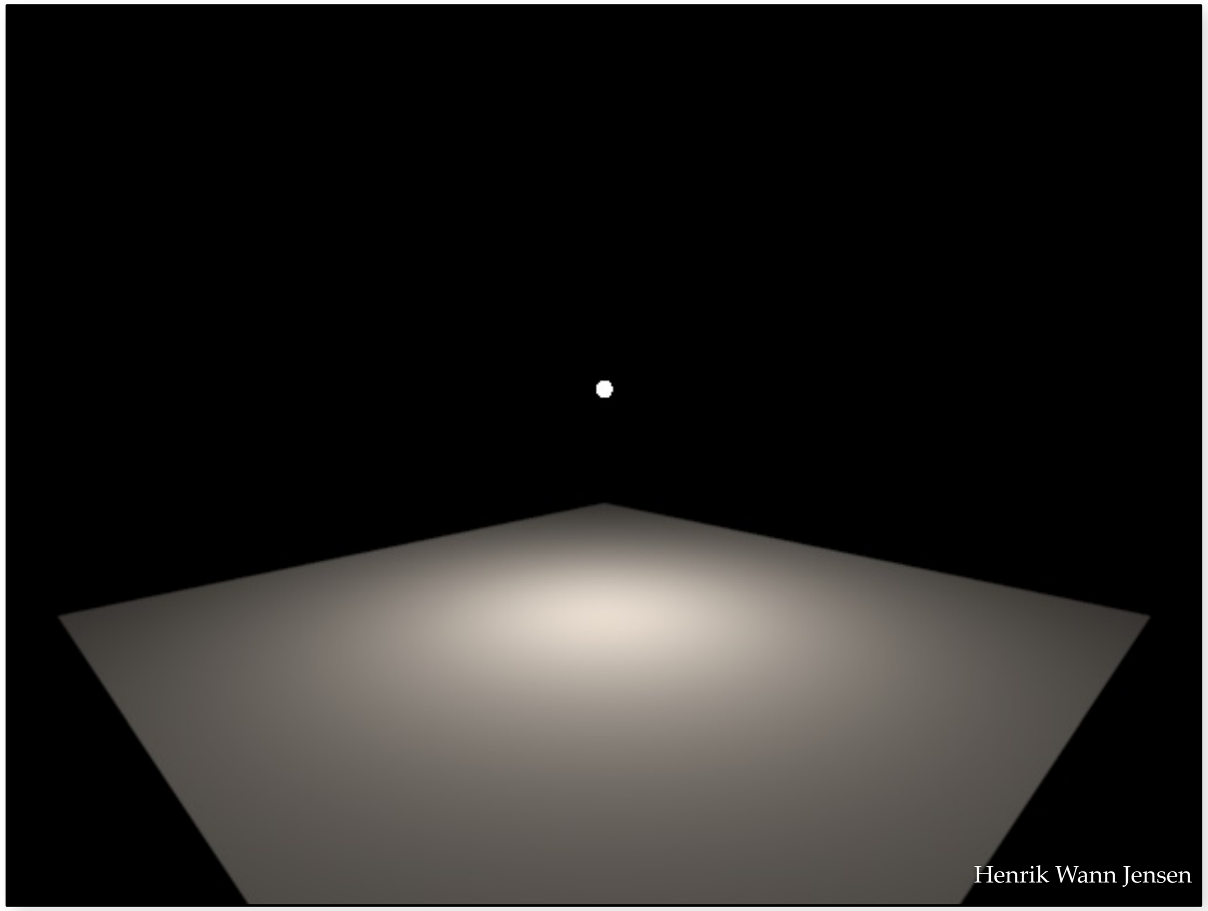
After a slide by Steve Marschner

Diffuse Shading with a Point Light



$$L_d = \frac{\rho}{\pi} L_i \max(0, \mathbf{n} \cdot \mathbf{l})$$

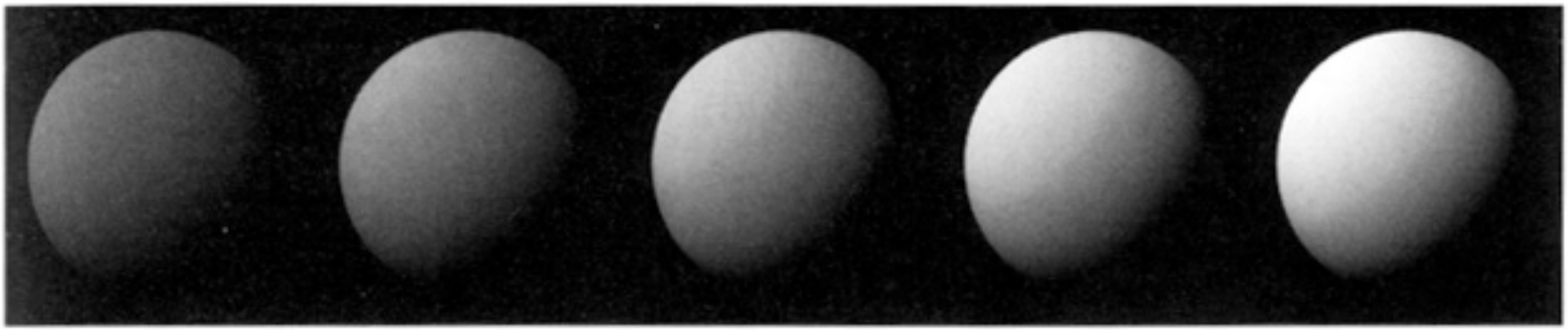
Diffuse Shading with a Point Light



$$L_d = \frac{\rho}{\pi} L_i \max(0, \mathbf{n} \cdot \mathbf{l}) = \frac{\rho}{\pi} \left(\frac{\Phi}{4\pi r^2} \right) \max(0, \mathbf{n} \cdot \mathbf{l})$$

Diffuse Shading with a Point Light

Produces matte, 3D appearance



ρ

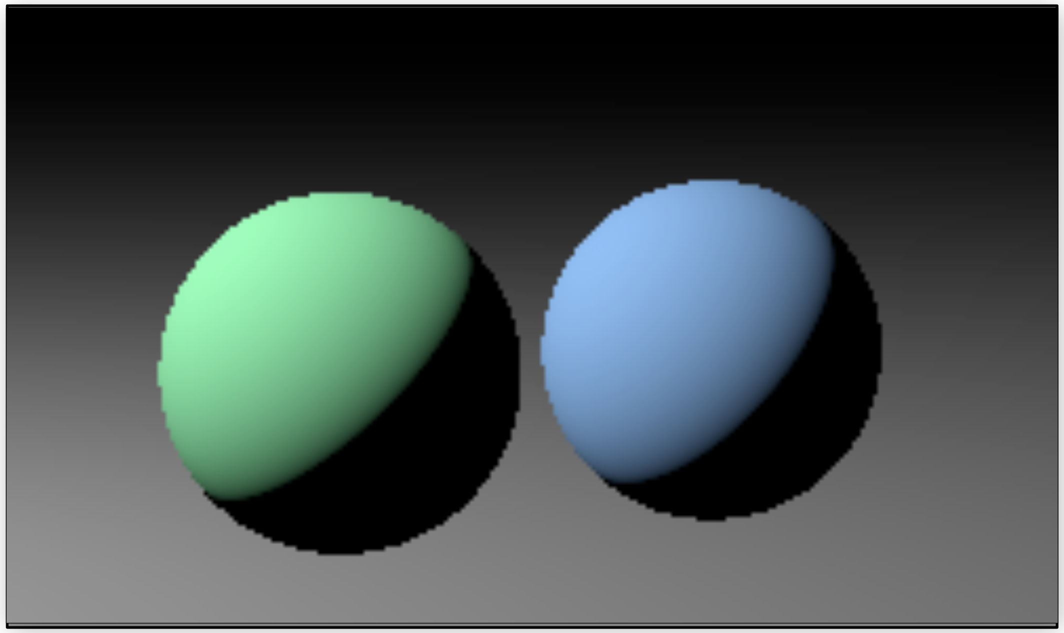
[Foley et al.]

After a slide by Steve Marschner

Image so far

```
Scene::trace(Ray ray, tMin, tMax)
   hit = surfaces.intersect(ray, tMin, tMax);
   if hit
      return hit.material.shade(hit, light);
   else
      return backgroundColor;

Material::shade(hit, light)
   l = normalize(light.pos - hit.pos);
   // compute shading...
```

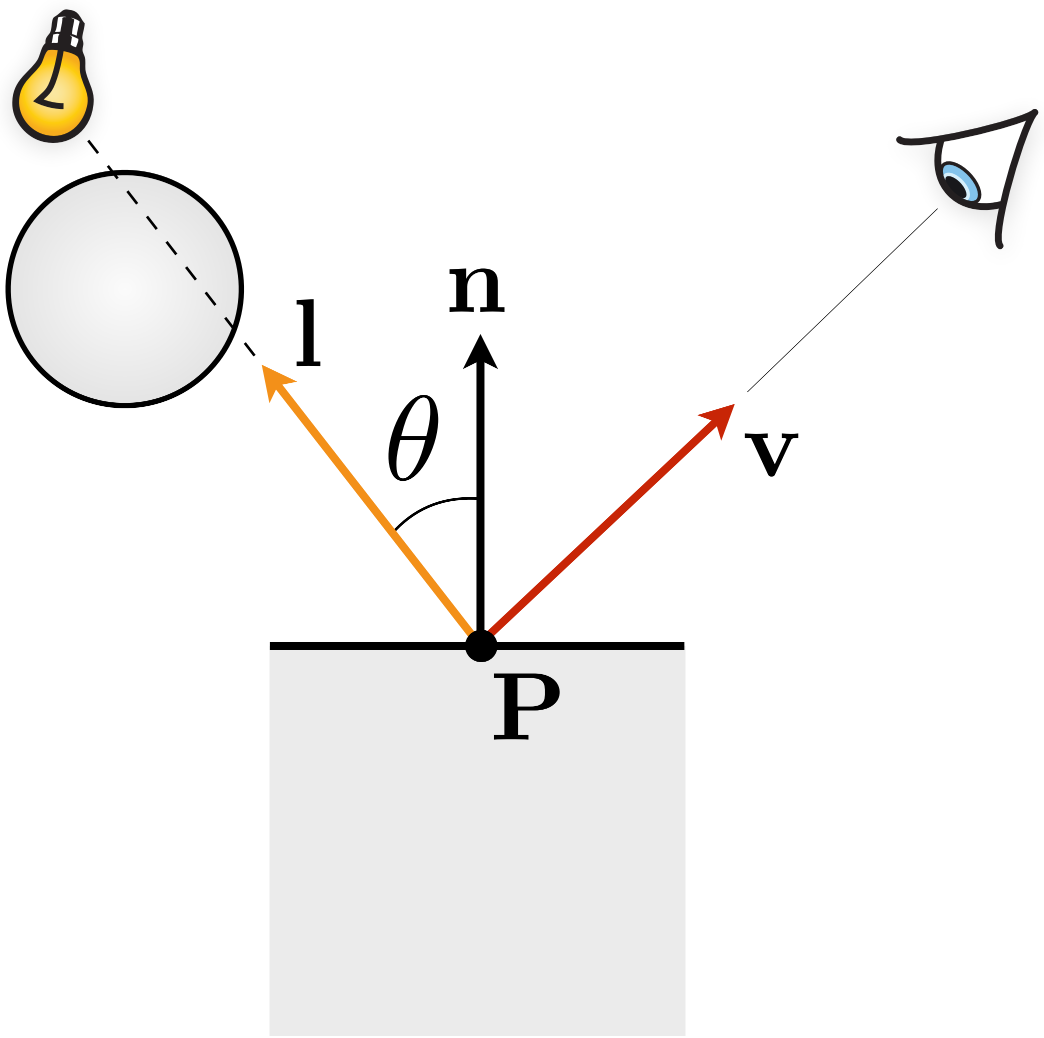


Shadows

Surface only illuminated if nothing blocks its "view" of the light

With ray tracing it's easy to check!

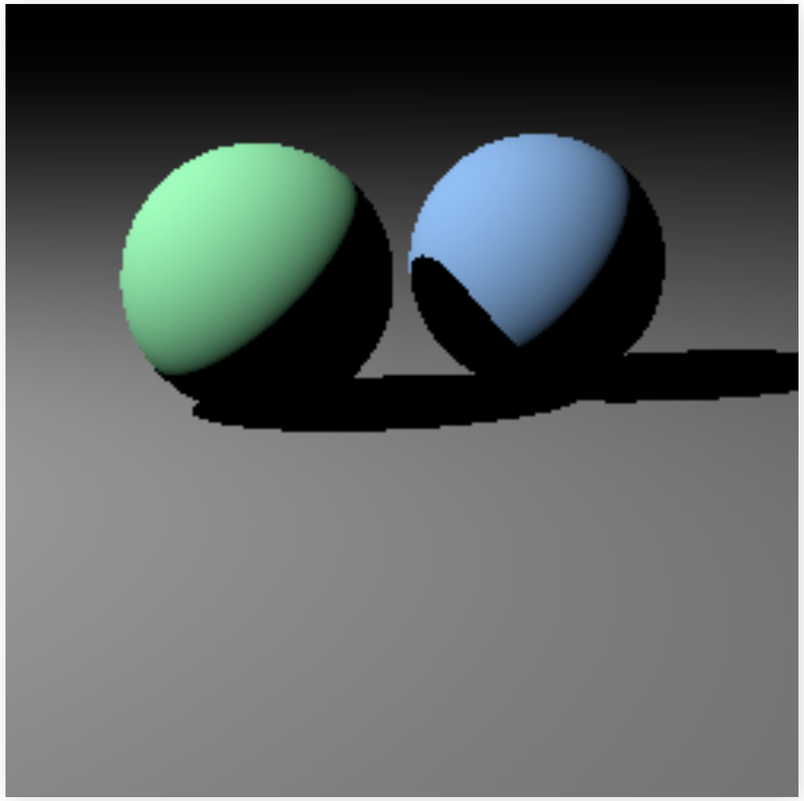
- just intersect a ray with the scene!
- send shadow ray – checks if light is visible



After a slide by Steve Marschner

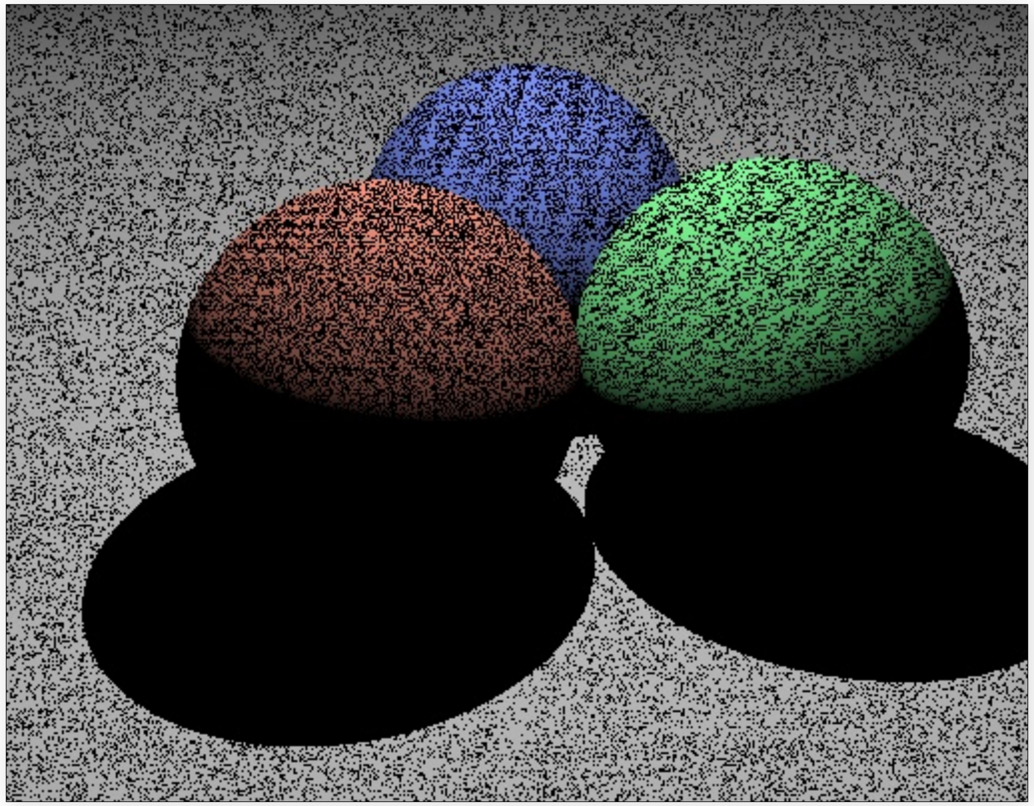
Image so far

```
Material::shade(hit, light)
   Ray shadRay(hit.pos, light.pos - hit.pos);
   if (shadRay not blocked)
      l = normalize(light.pos - hit.pos);
      // compute shading
   return black;
```



Shadow – Numerical Issues

Don't fall victim to one of the classic blunders:



affectionately called "shadow acne"

What's going on?

- *hint*: at what t does the shadow ray intersect **the surface you're shading**?

After a slide by Steve Marschner

Shadow – Numerical Issues

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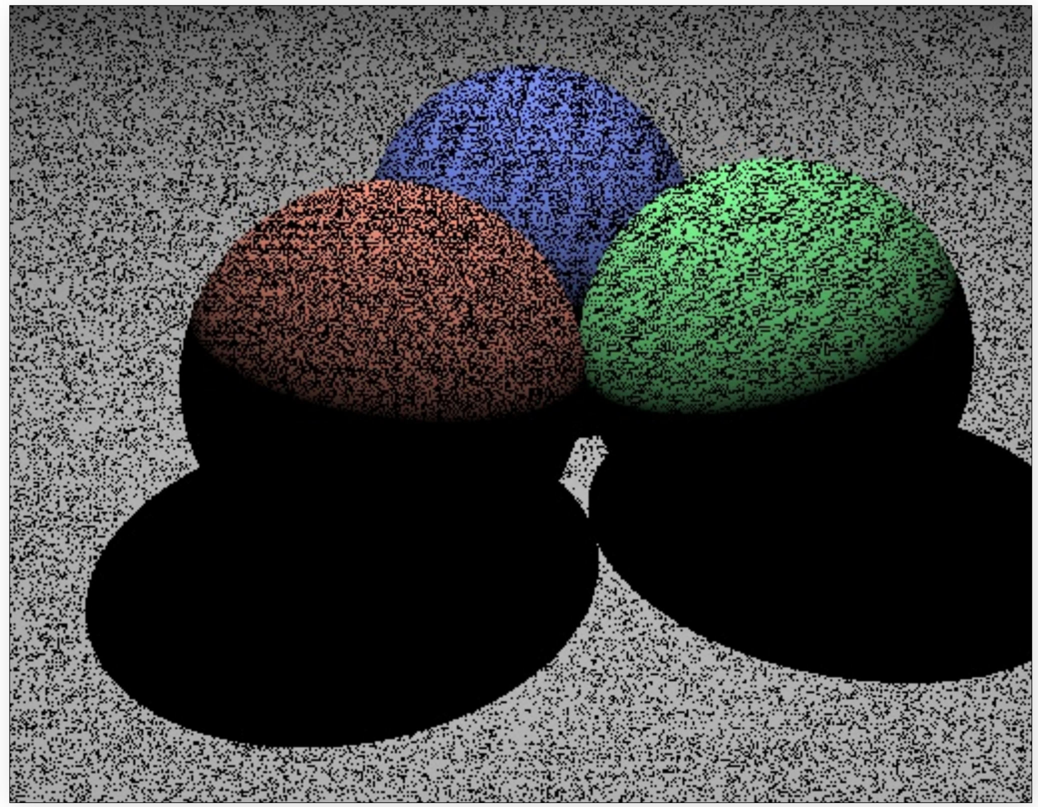
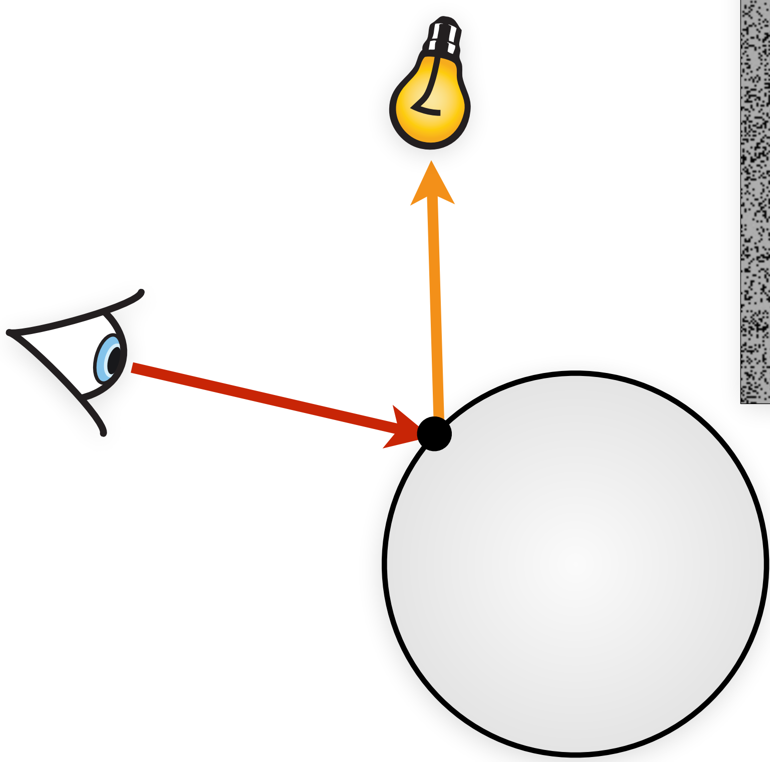
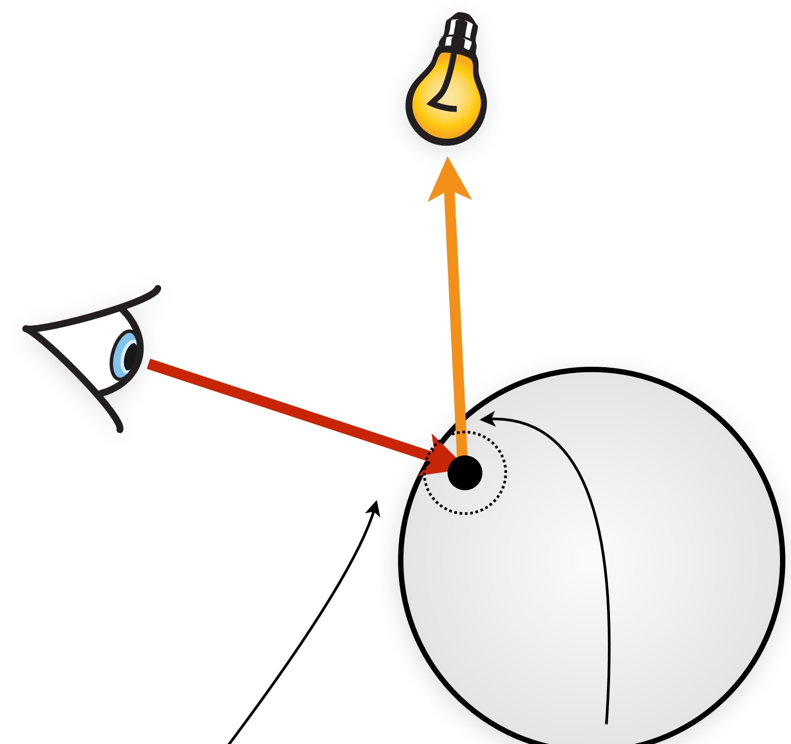




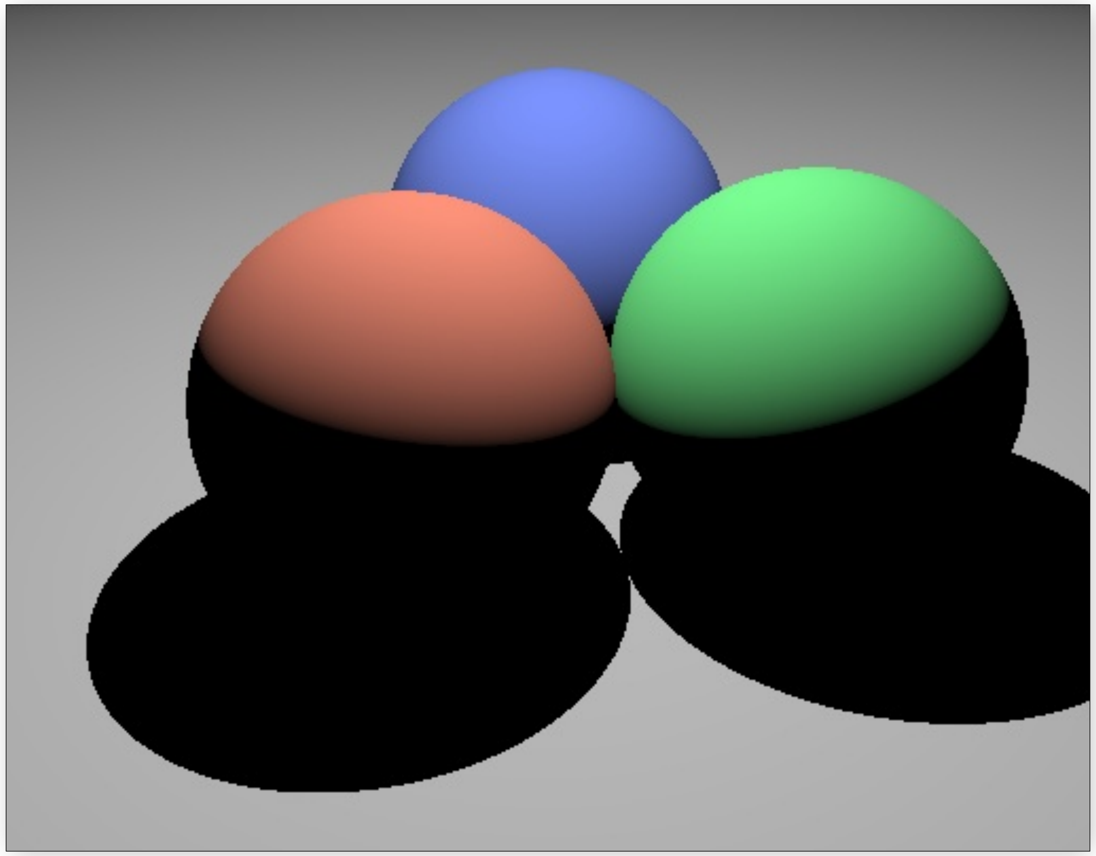


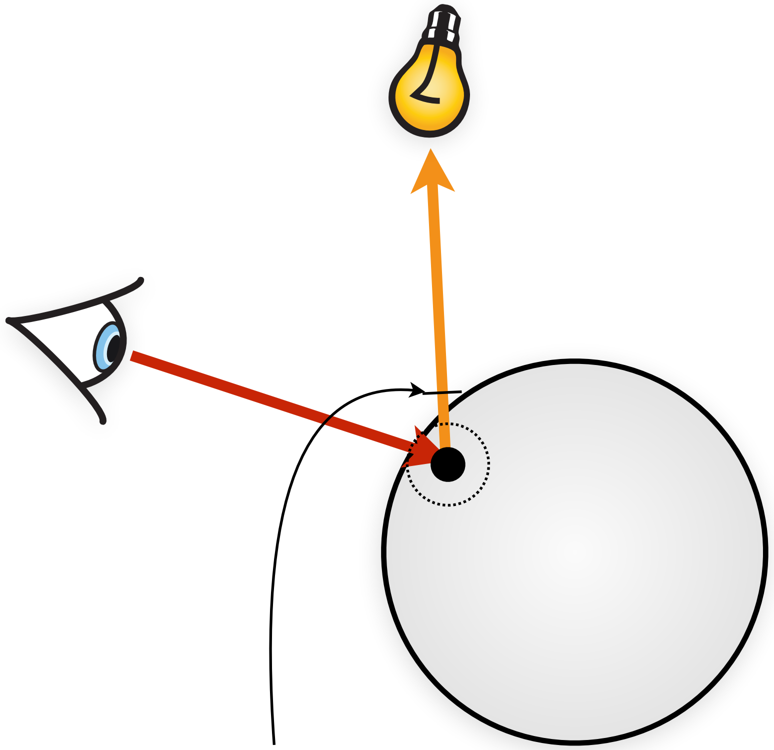
Shadow – Numerical Issues

Solutions:

- shadow rays start a tiny distance from the surface, or
- only consider intersections in a specific *t* range

After a slide by Steve Marschner





Basic Shading – Diffuse Material, Point Light & Shadows

Questions?

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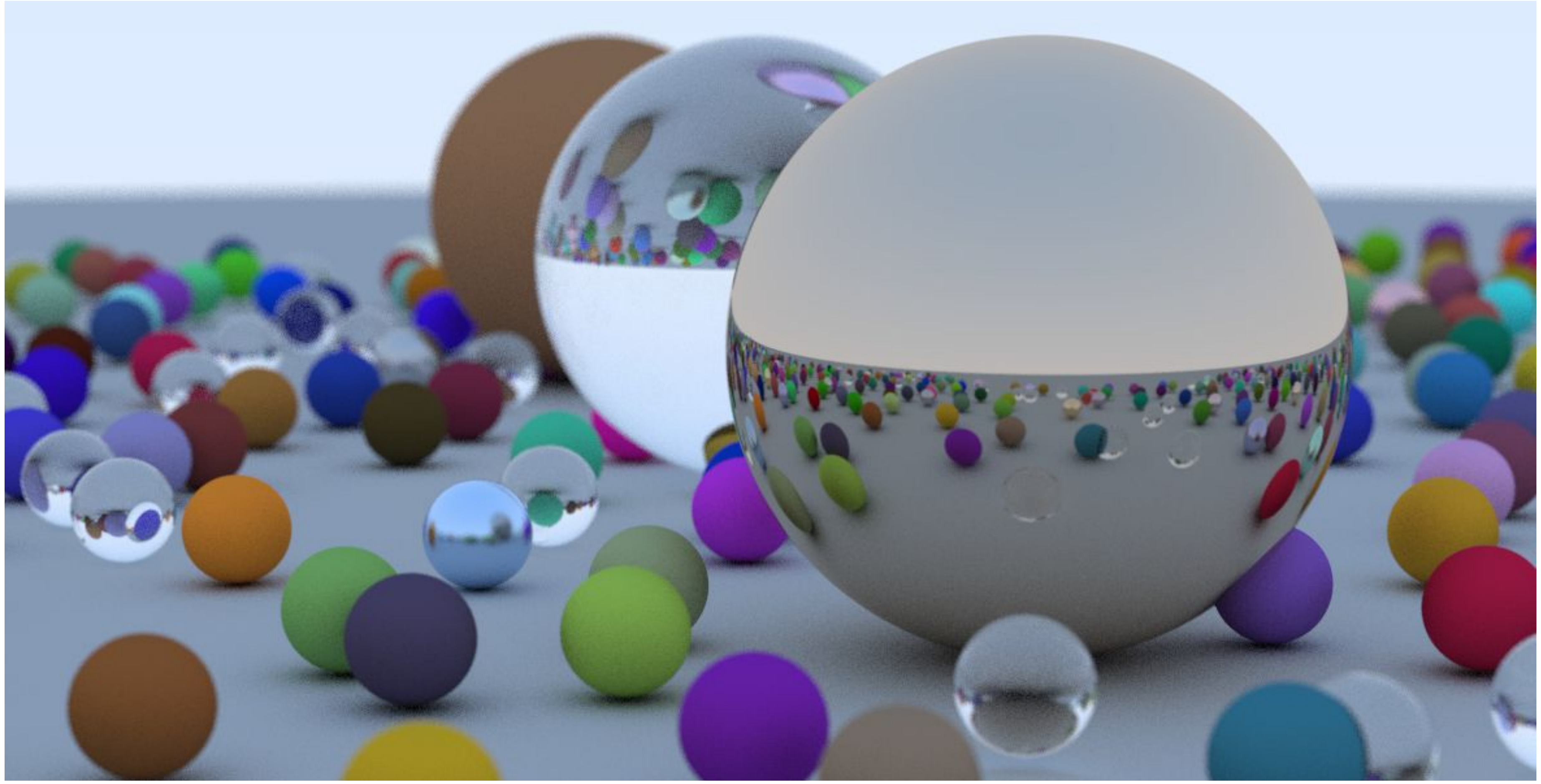
Image Synthesis



Phenomenological Shading 2

Prof. Derek Nowrouzezahrai
derek@cim.mcgill.ca

A Simple Empirical Material Model

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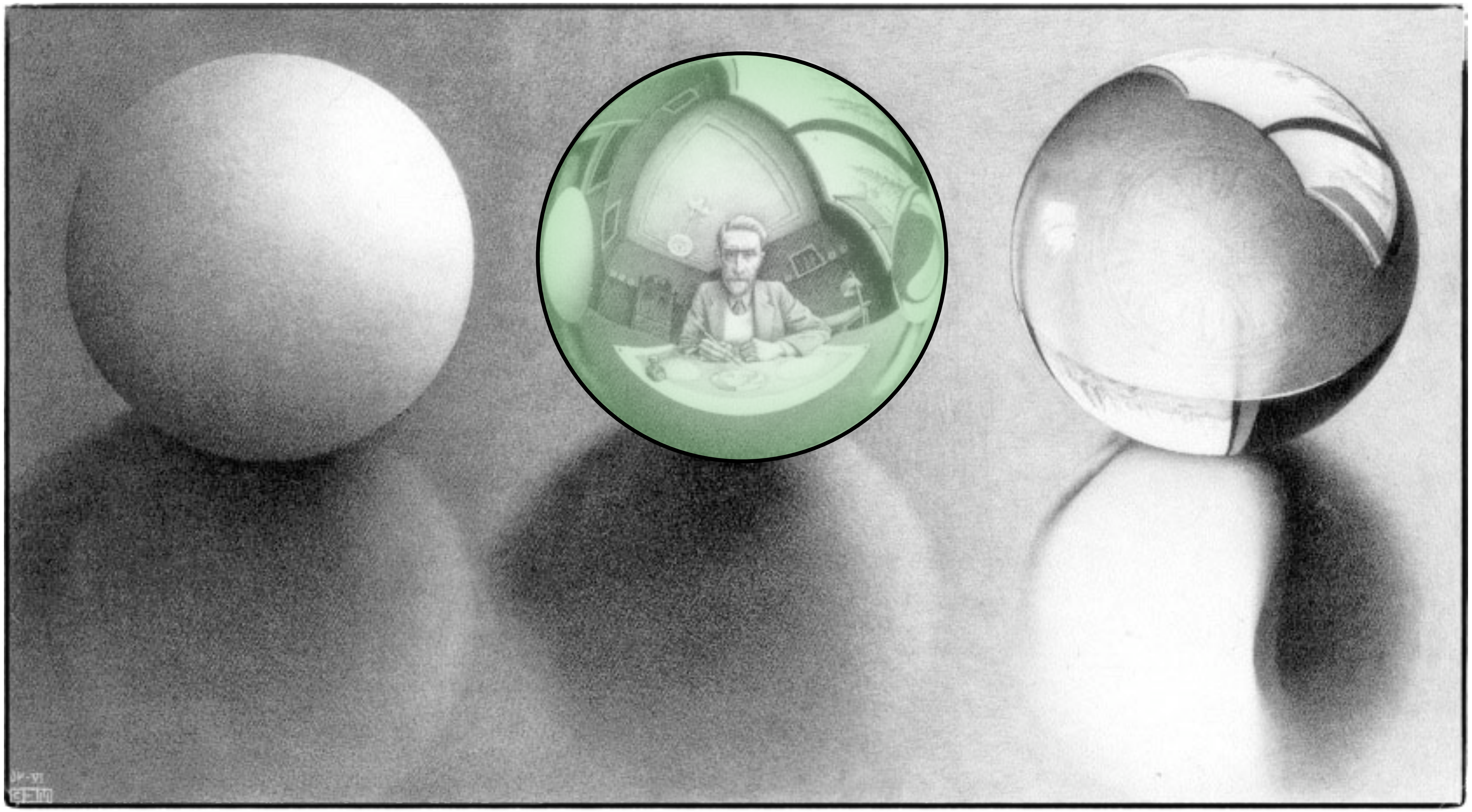
Specular/Mirror reflection



Mirror reflection

Consider perfectly shiny surface

- there's a reflection of other objects

Can render this using recursive ray tracing

- to compute mirror reflection color, ask:
    - "*what color is seen from the surface point in the <u>perfect/mirror reflection direction</u>*"

Mirror reflection

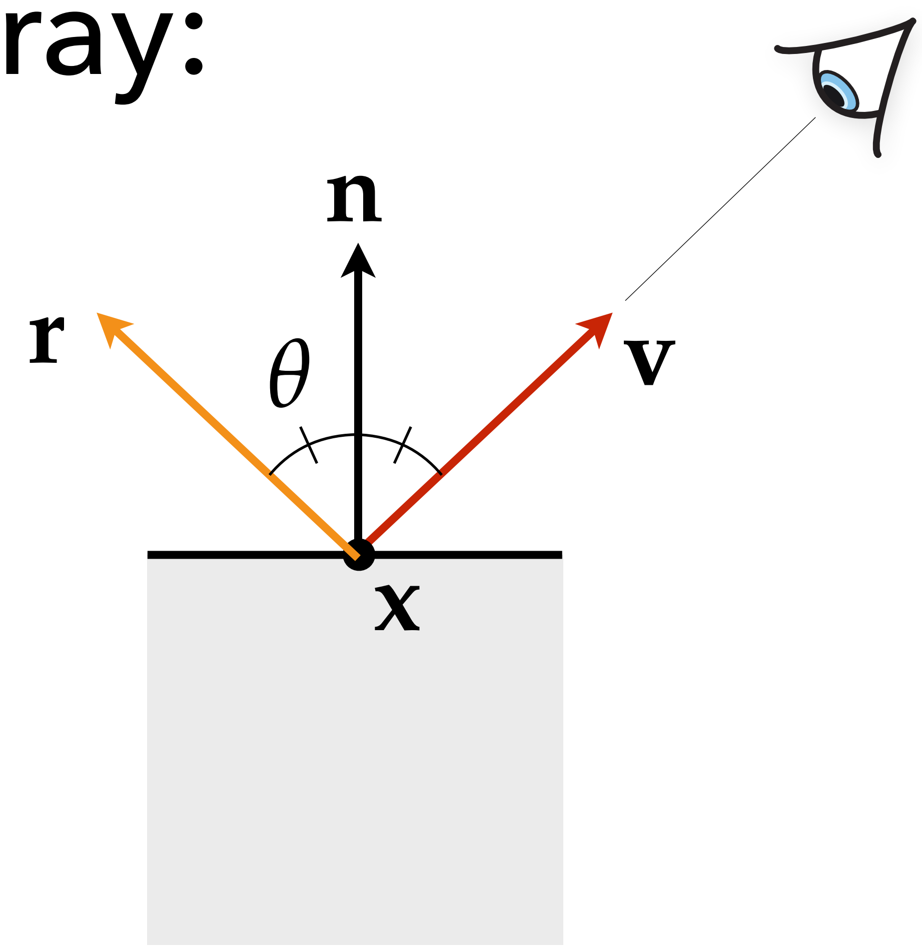
Evaluated by tracing a new ray:

$$L_r = \rho_r \, \mathrm{trace}(\mathbf{x}, \mathbf{r})$$

mirror reflected light

reflection coefficient

recursive ray



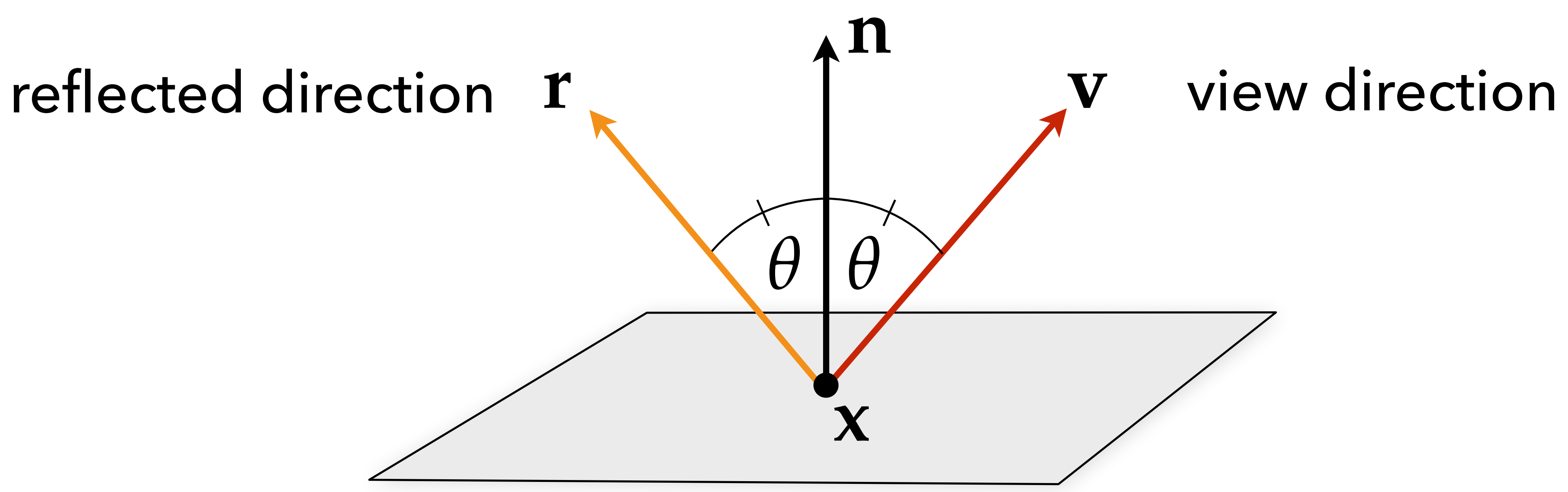
Implementation details:

- don't self-intersect ($t_{\min} > \epsilon$)
- don't recurse indefinitely

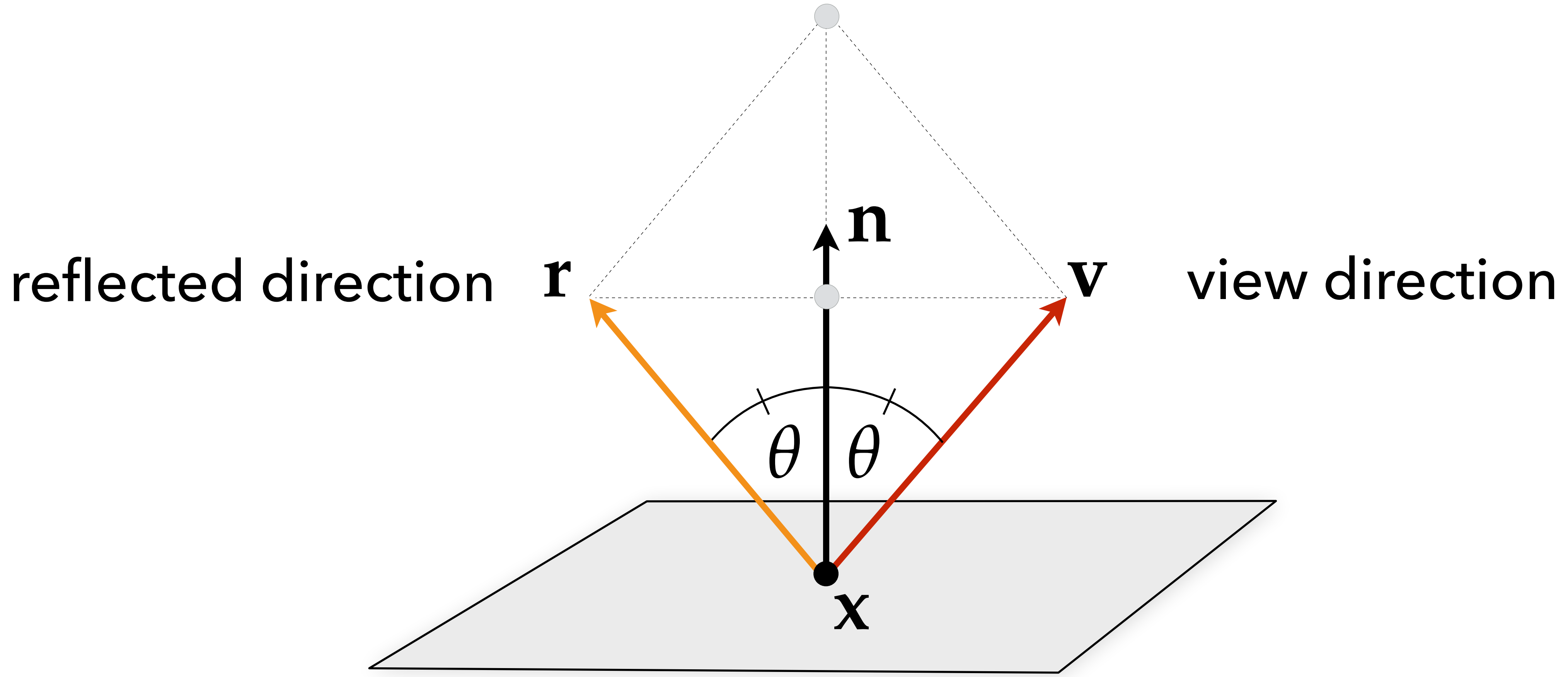
"Glazed" material with mirror and diffuse:

$$L = L_d + L_r$$

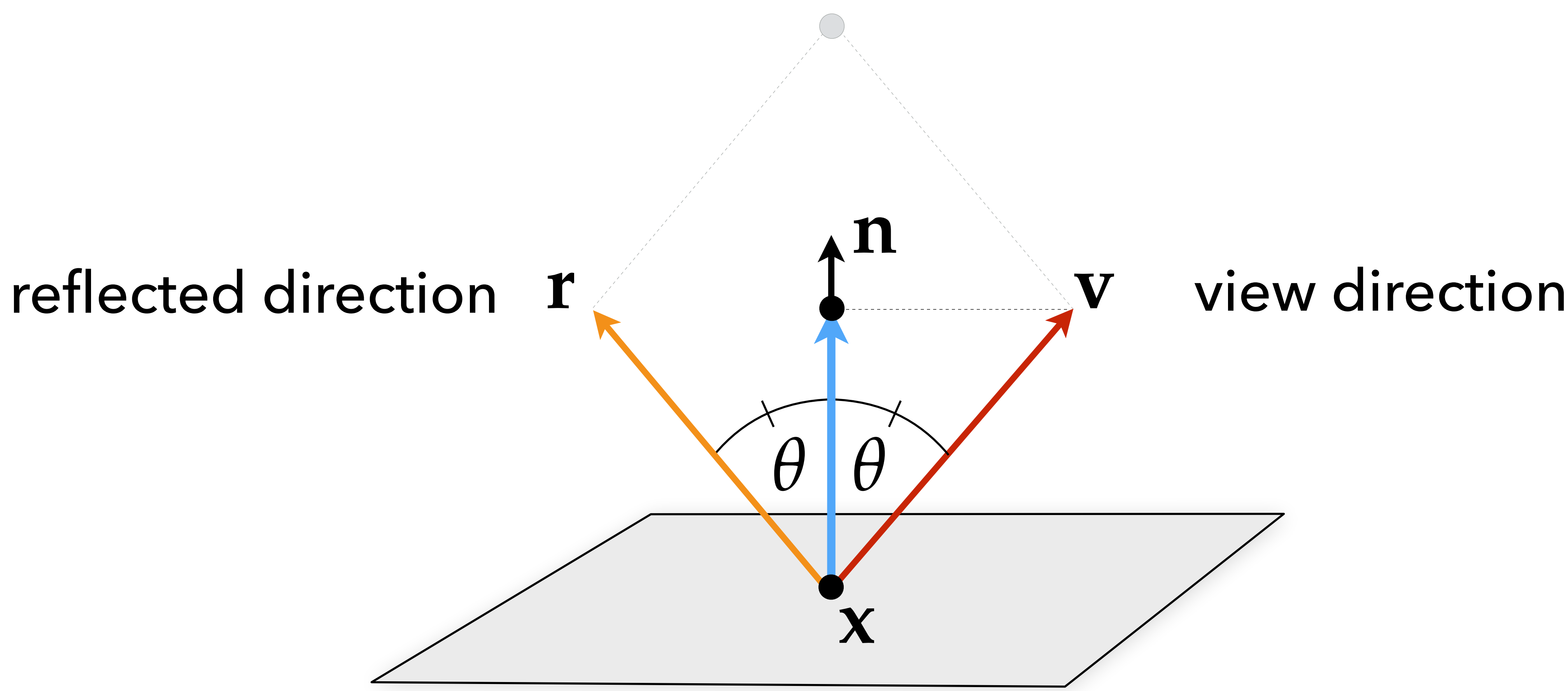
Perfect/Mirror Reflection Direction



Perfect/Mirror Reflection Direction

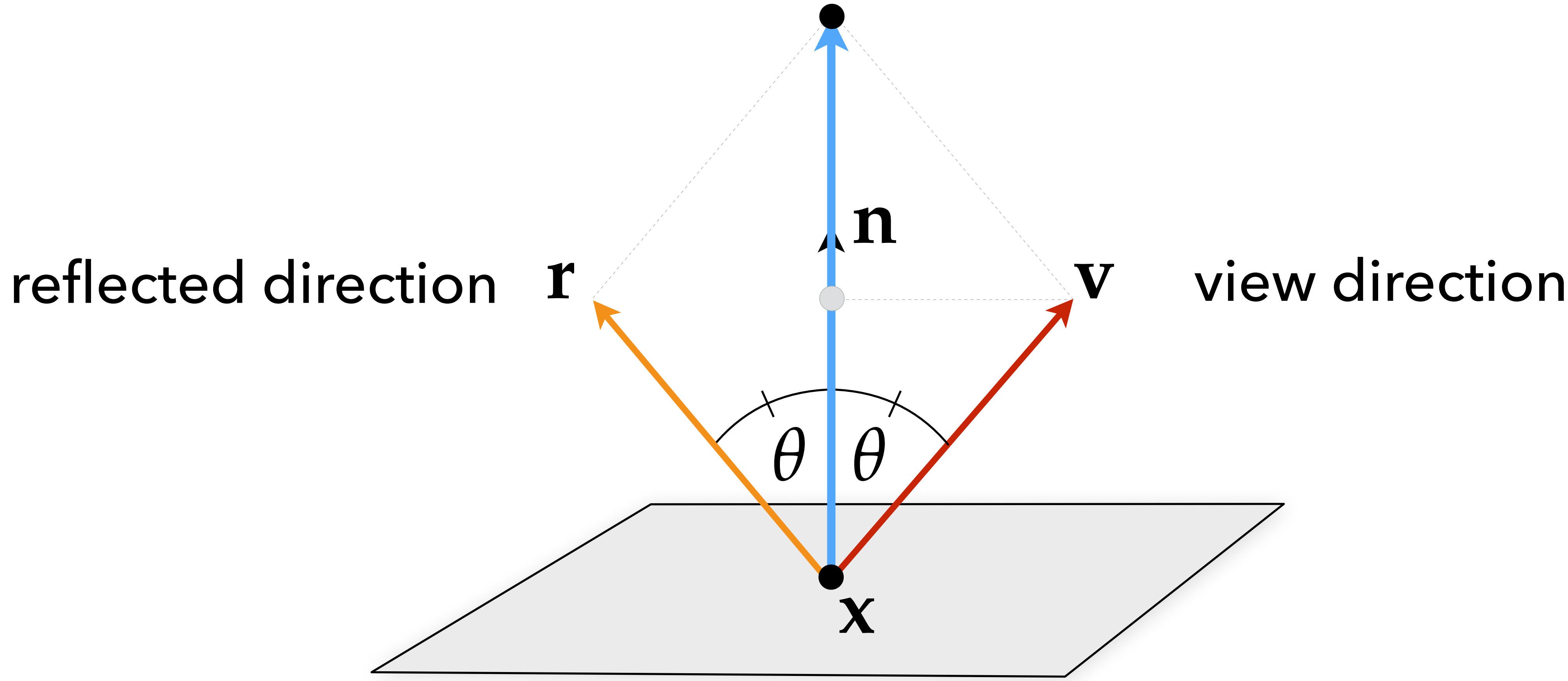


Perfect/Mirror Reflection Direction



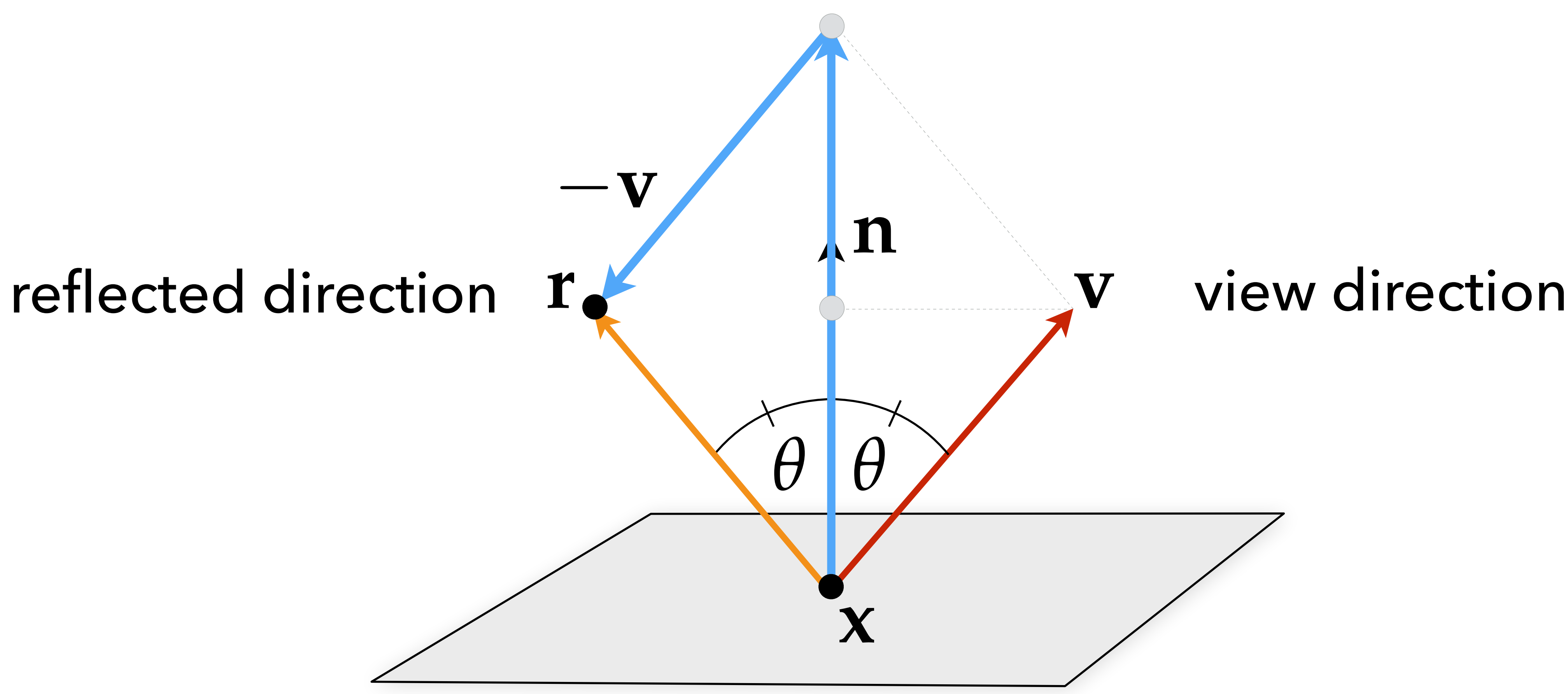
$$\mathbf{n}(\mathbf{n}\cdot\mathbf{v})$$

Perfect/Mirror Reflection Direction



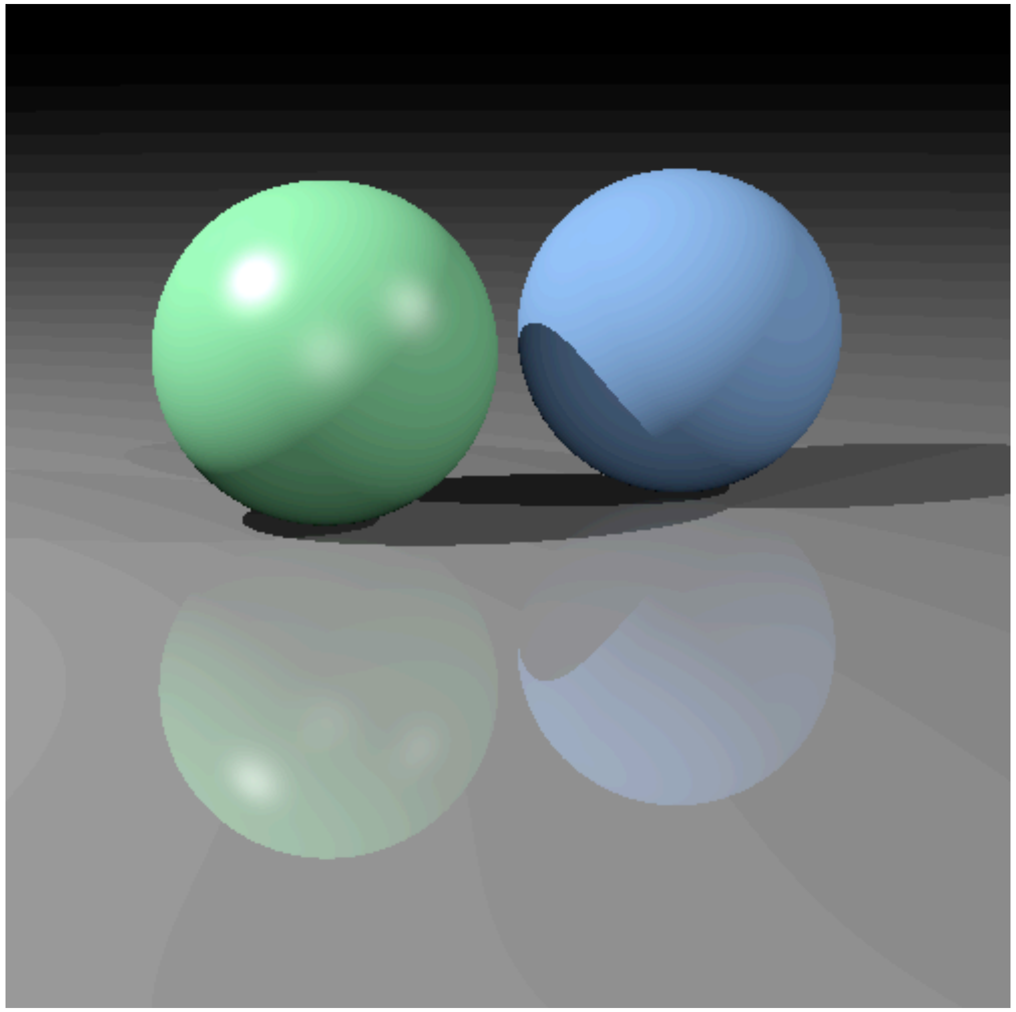
$$2\mathbf{n}(\mathbf{n} \cdot \mathbf{v})$$

Perfect/Mirror Reflection Direction



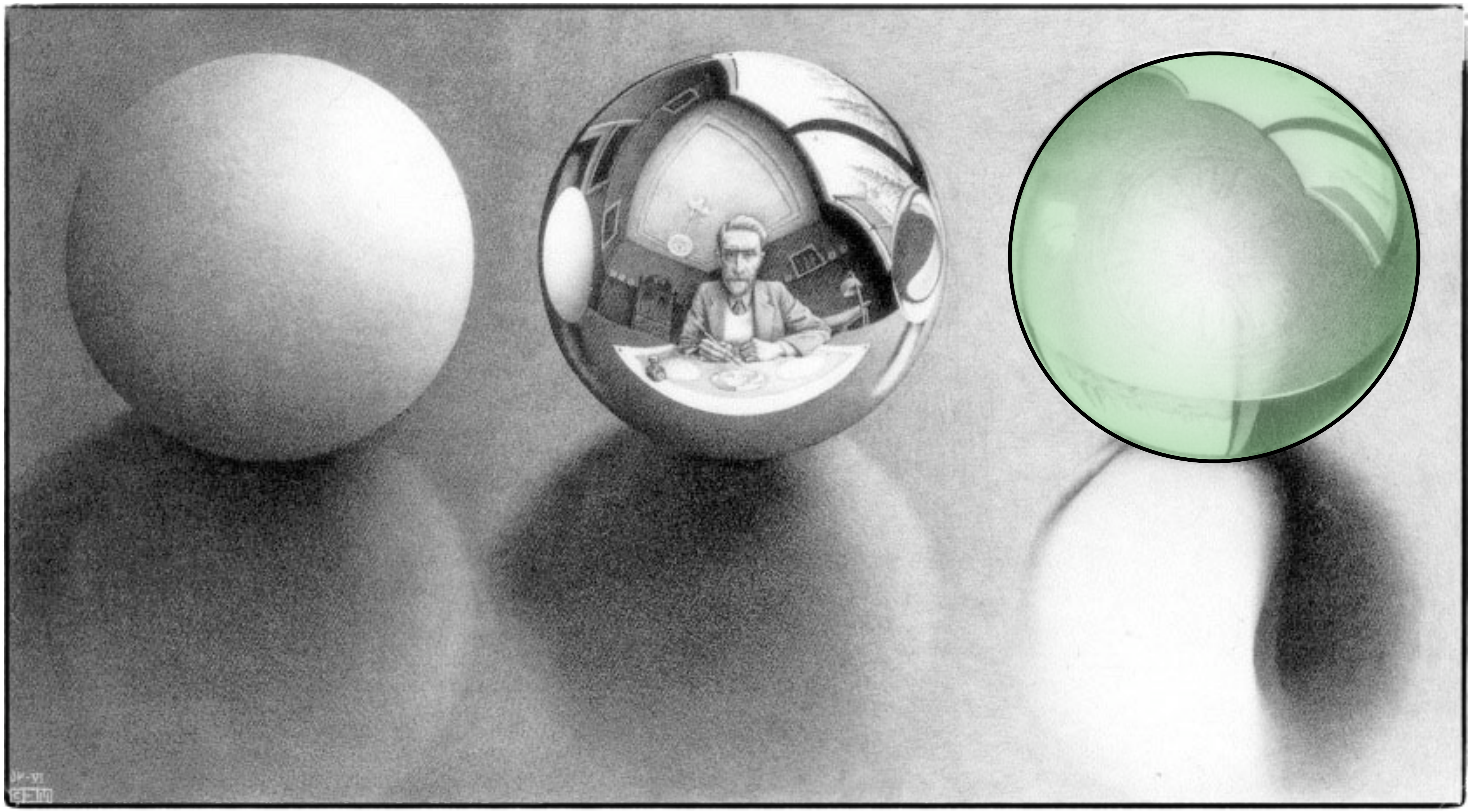
$$\mathbf{r} = 2\mathbf{n}(\mathbf{n}\cdot\mathbf{v}) - \mathbf{v}$$

Diffuse + Mirror Reflection

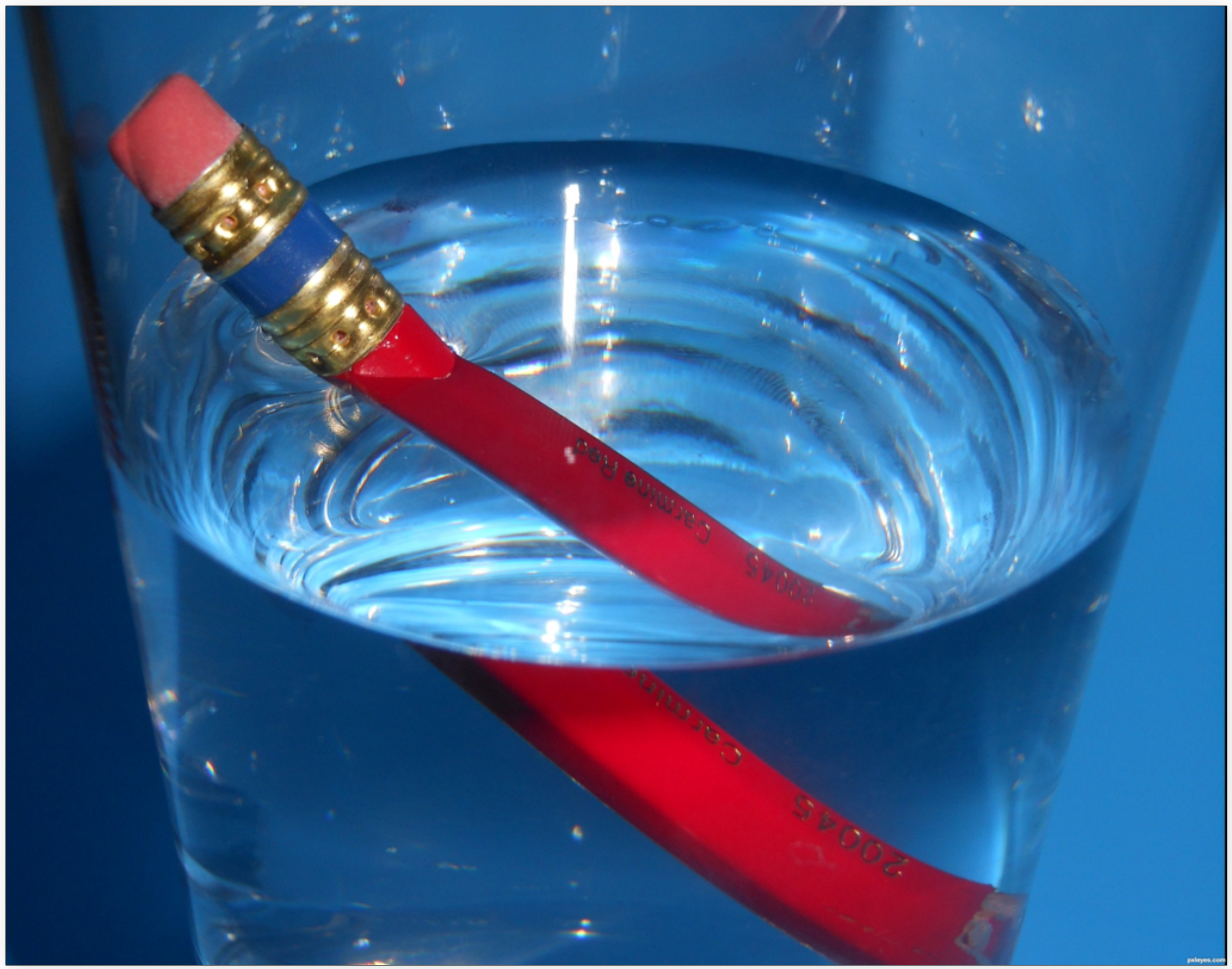


(glazed material on floor)

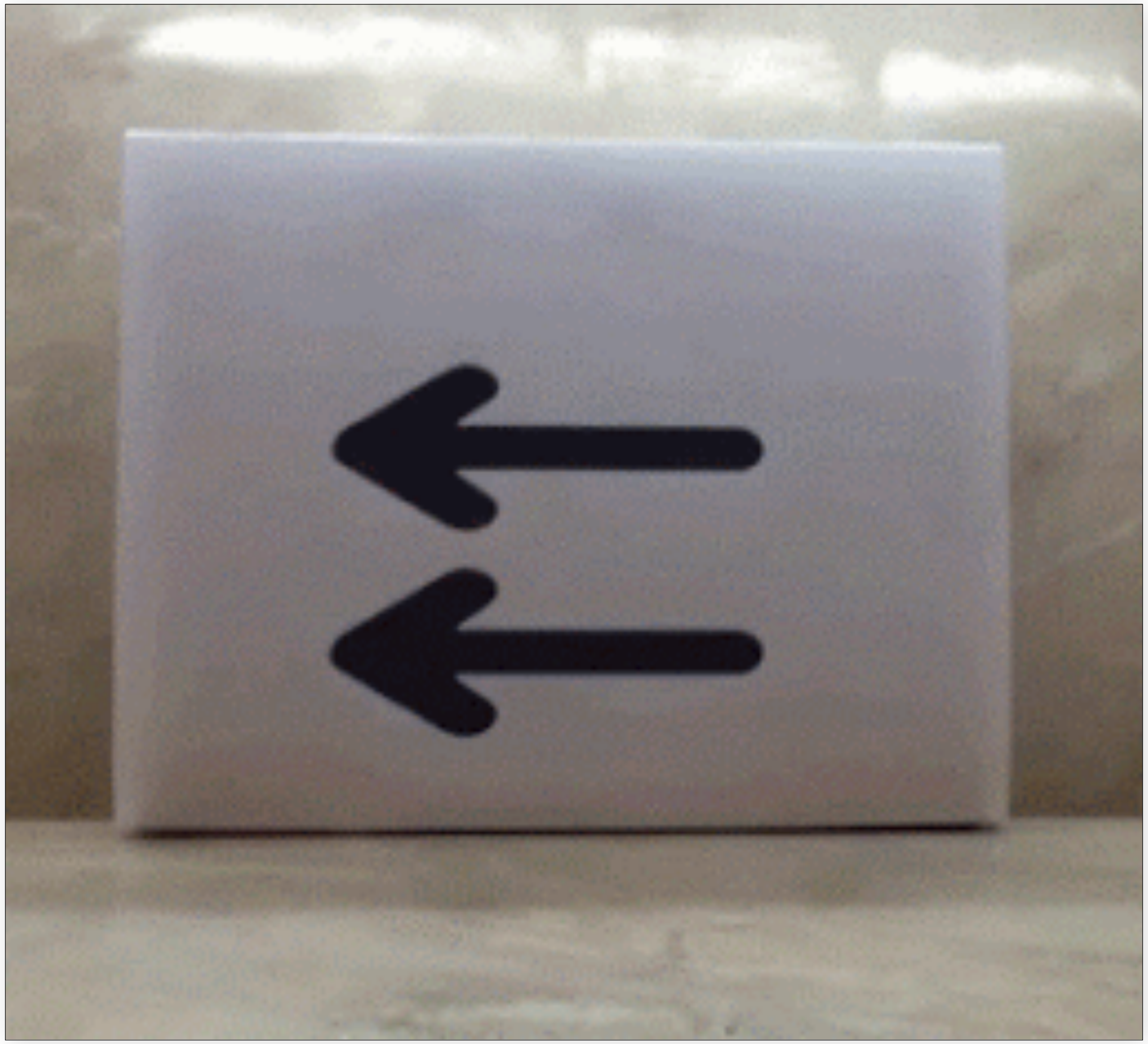
Specular Refraction



Specular Refraction



Specular Refraction



Index of Refraction

Speed of light in vacuum / speed of light in medium

	η
Vacuum	1
Air at STP	1.00029
Ice	1.31
Water	1.33
Crown glass	1.52 – 1.65
Diamond	2.417

Specular Refraction/Transmission

Materials like water, glass, etc. also refract/blend light

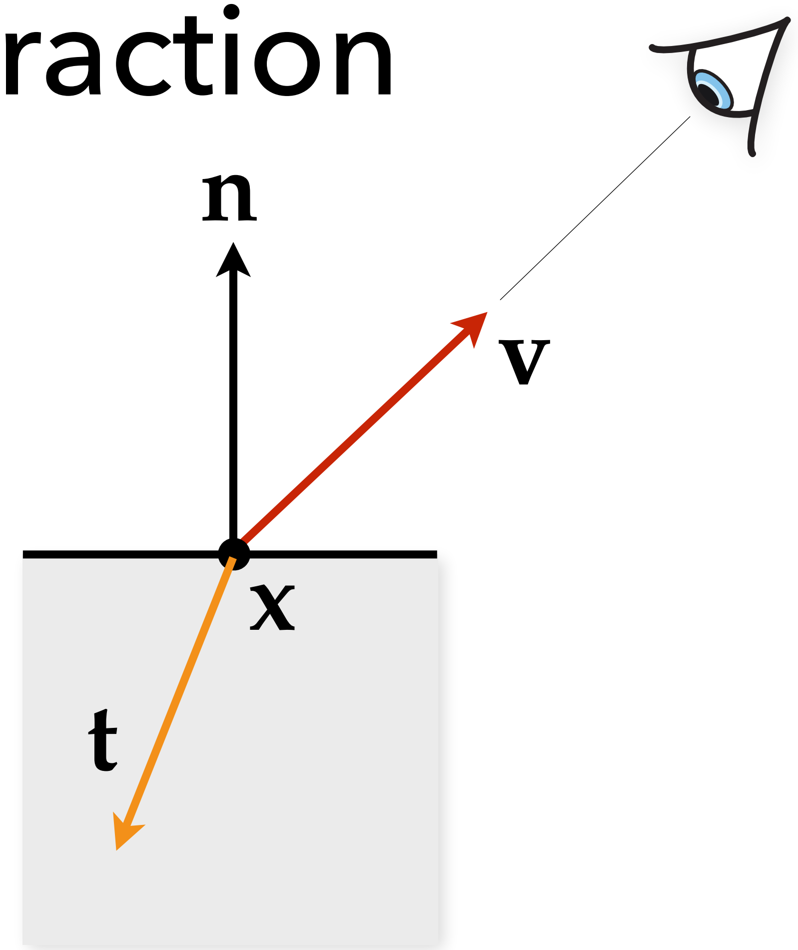
Trace a recursive ray in the refraction direction

$$L_t = \rho_t \, \mathrm{trace}(\mathbf{x}, \mathbf{t})$$

refracted light

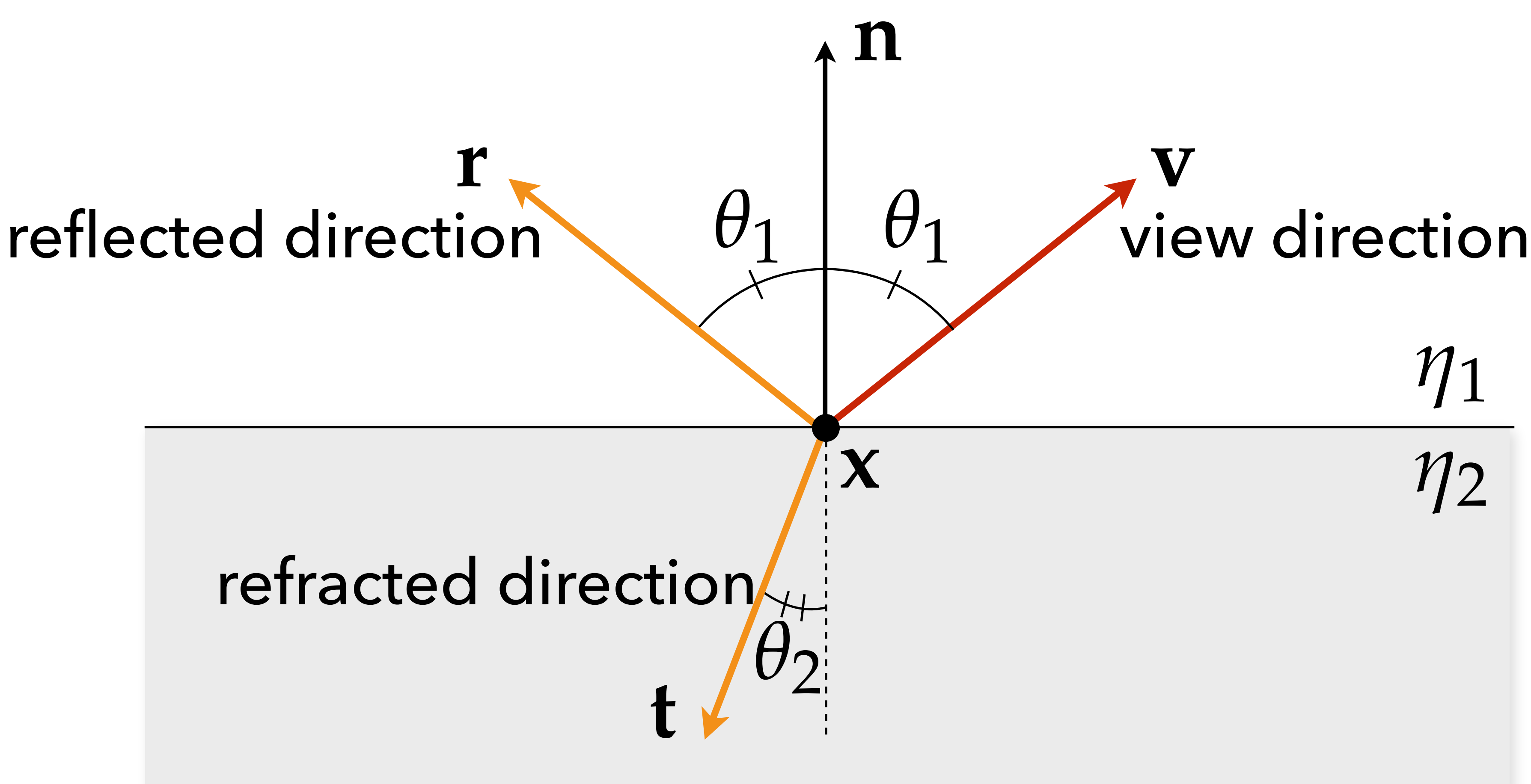
refraction coefficient

recursive ray



Specular Refraction/Transmission

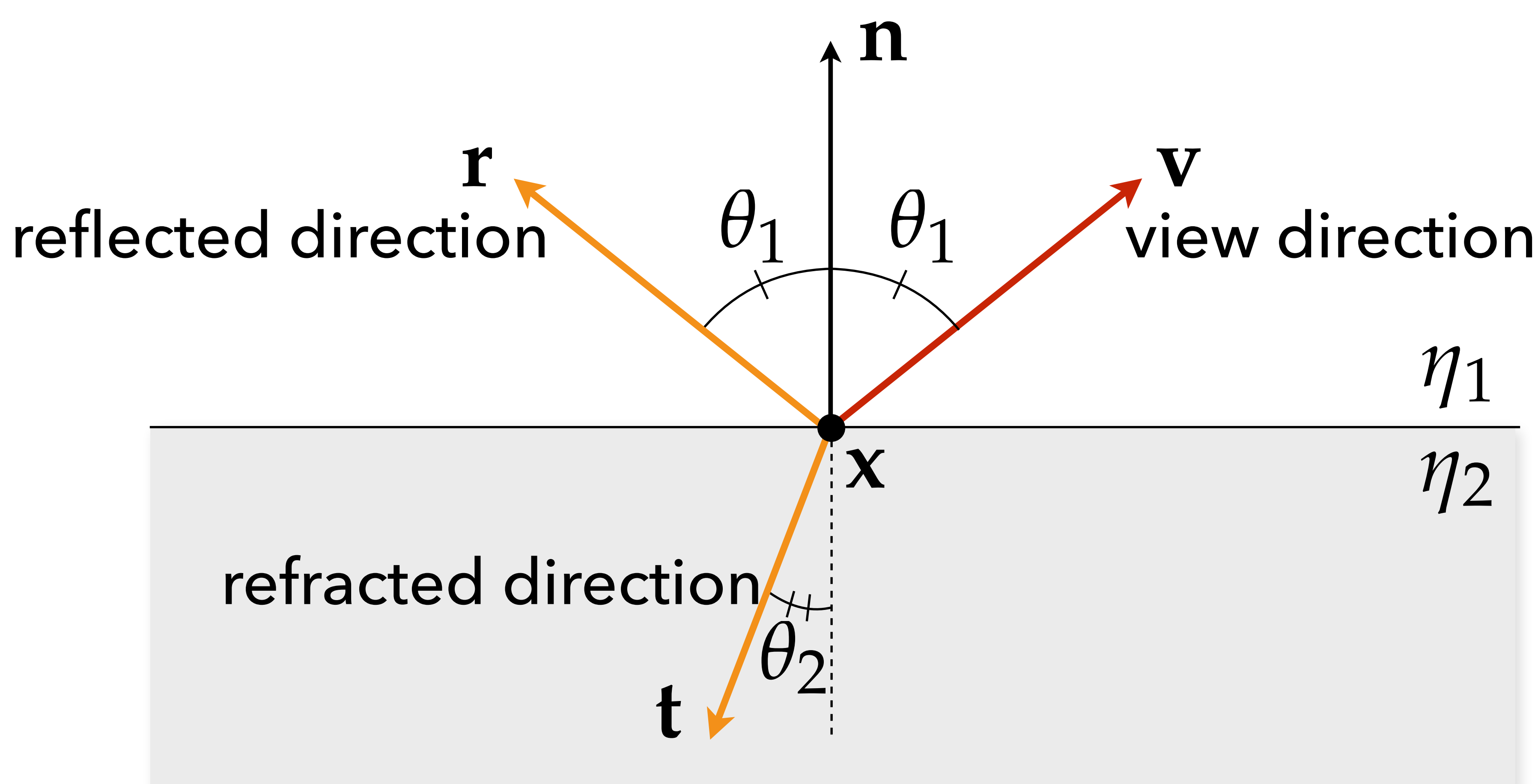
Snell's law



$$\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$$

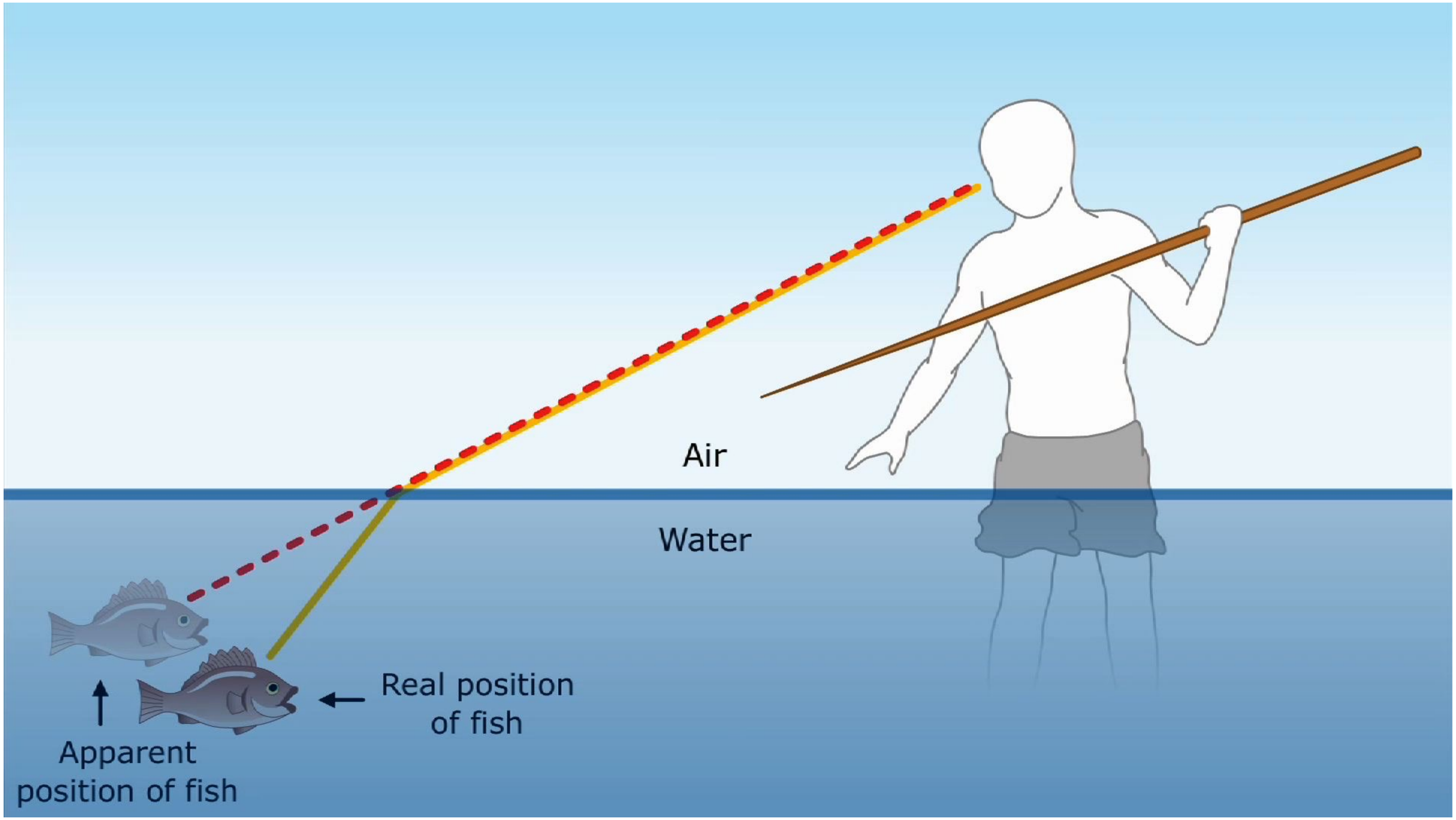
Specular Refraction/Transmission

Snell's law



$$\mathbf{t} = \eta_1/\eta_2\left(\left(\mathbf{v}\cdot\mathbf{n}\right)\mathbf{n} - \mathbf{v}\right) - \mathbf{n}\sqrt{1 - \eta_1^2/\eta_2^2\left(1 - \left(\mathbf{v}\cdot\mathbf{n}\right)^2\right)}$$

Refraction – Practical Consequences

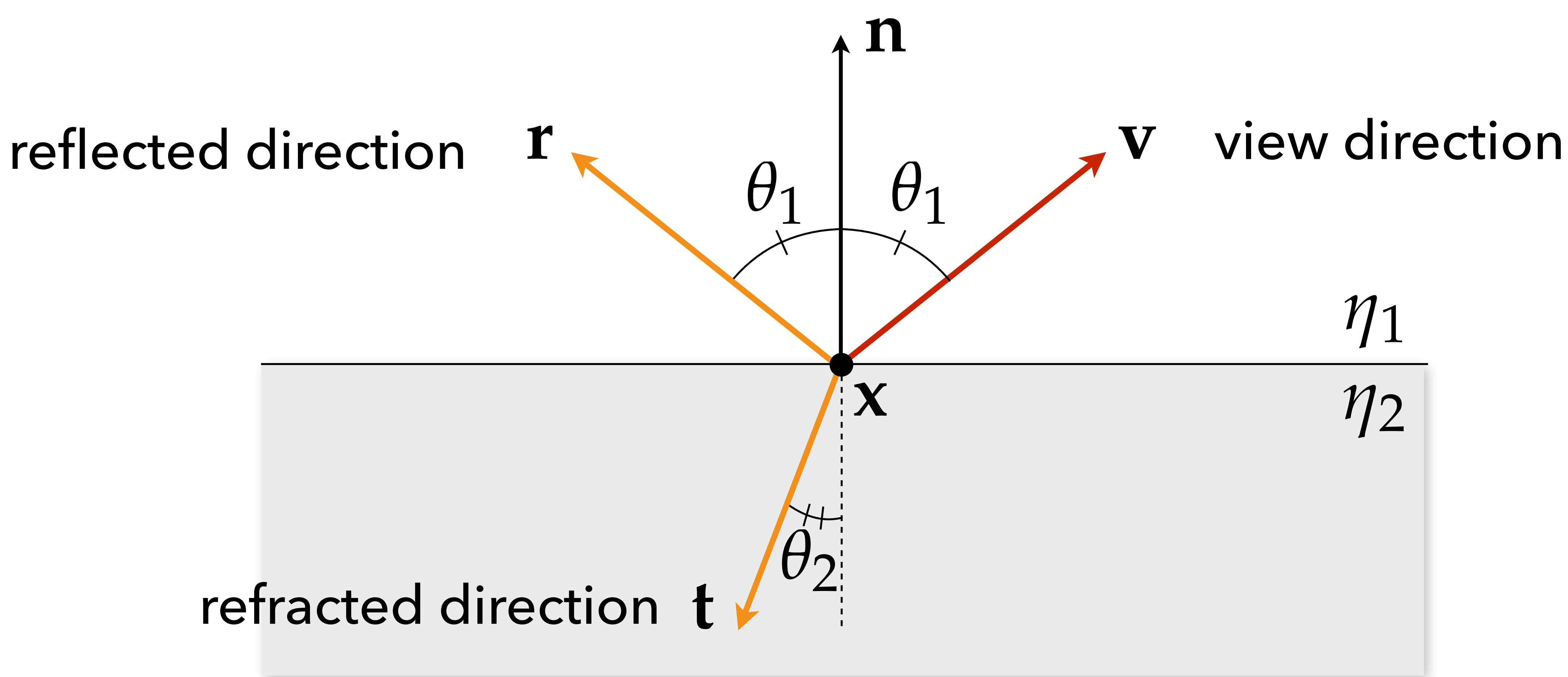


What is This Dark Circle?

source: mrreid.org

Recall…

Snell’s law

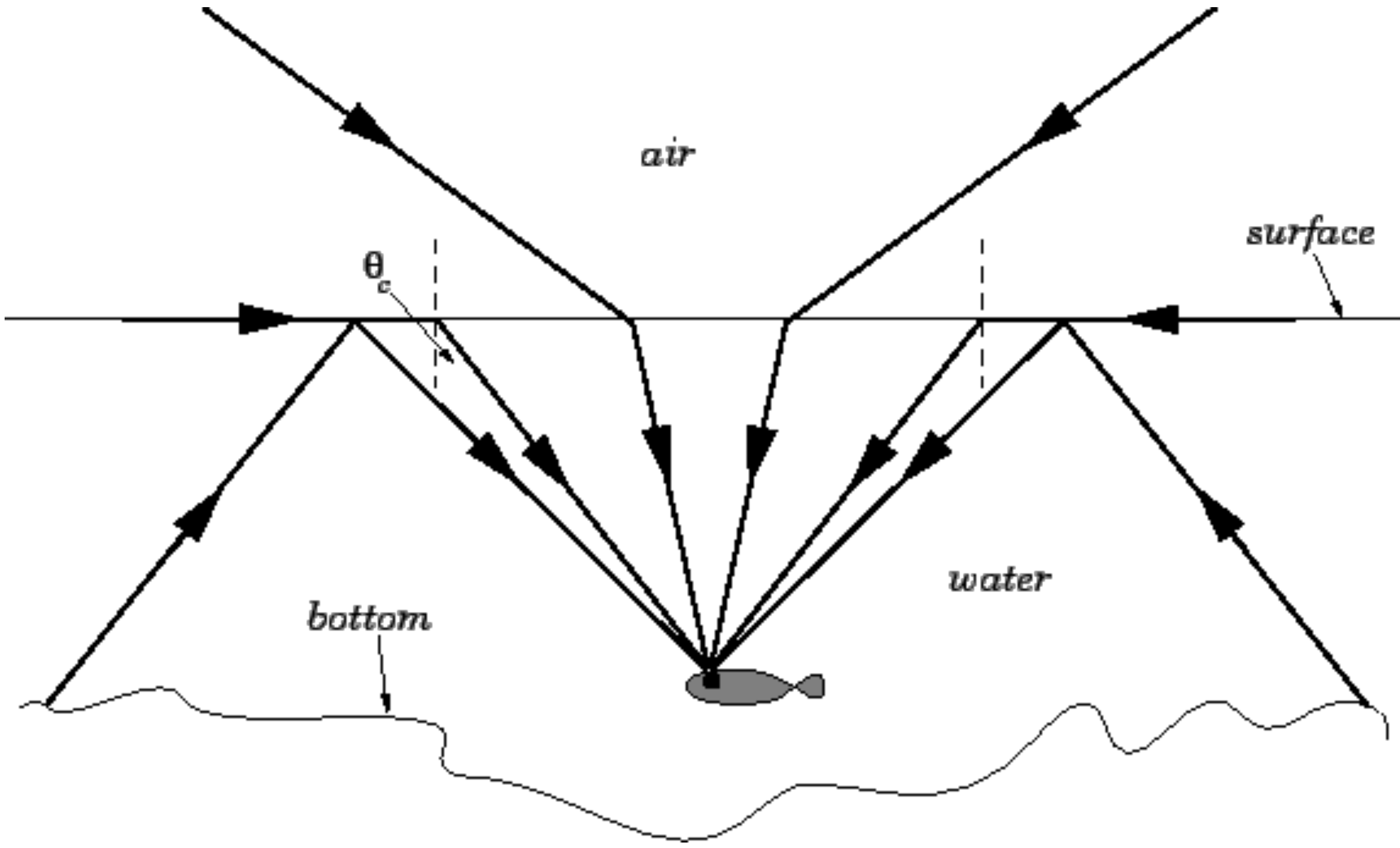


$$\mathbf{t} = \eta_1/\eta_2\left(\left(\mathbf{v}\cdot\mathbf{n}\right)\mathbf{n}-\mathbf{v}\right)-\mathbf{n}\sqrt{1-\eta_1^2/\eta_2^2\left(1-\left(\mathbf{v}\cdot\mathbf{n}\right)^2\right)}$$

What is This Dark Circle?

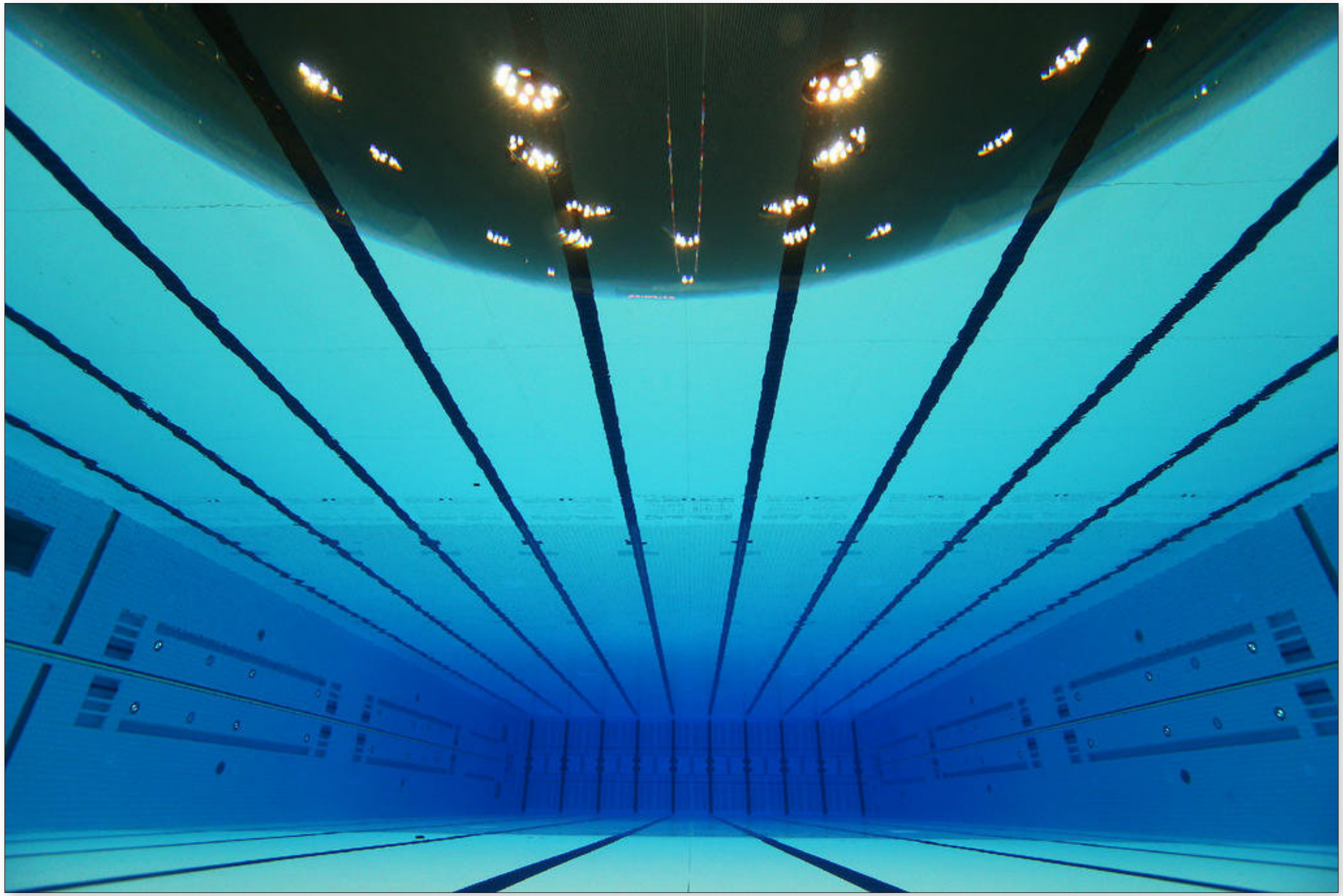
Called
“Snell's window” or
“optical man-hole”

Caused by total
internal reflection



source: mrreid.org

Total Internal Reflection



source: mrreid.org

Total Internal Reflection

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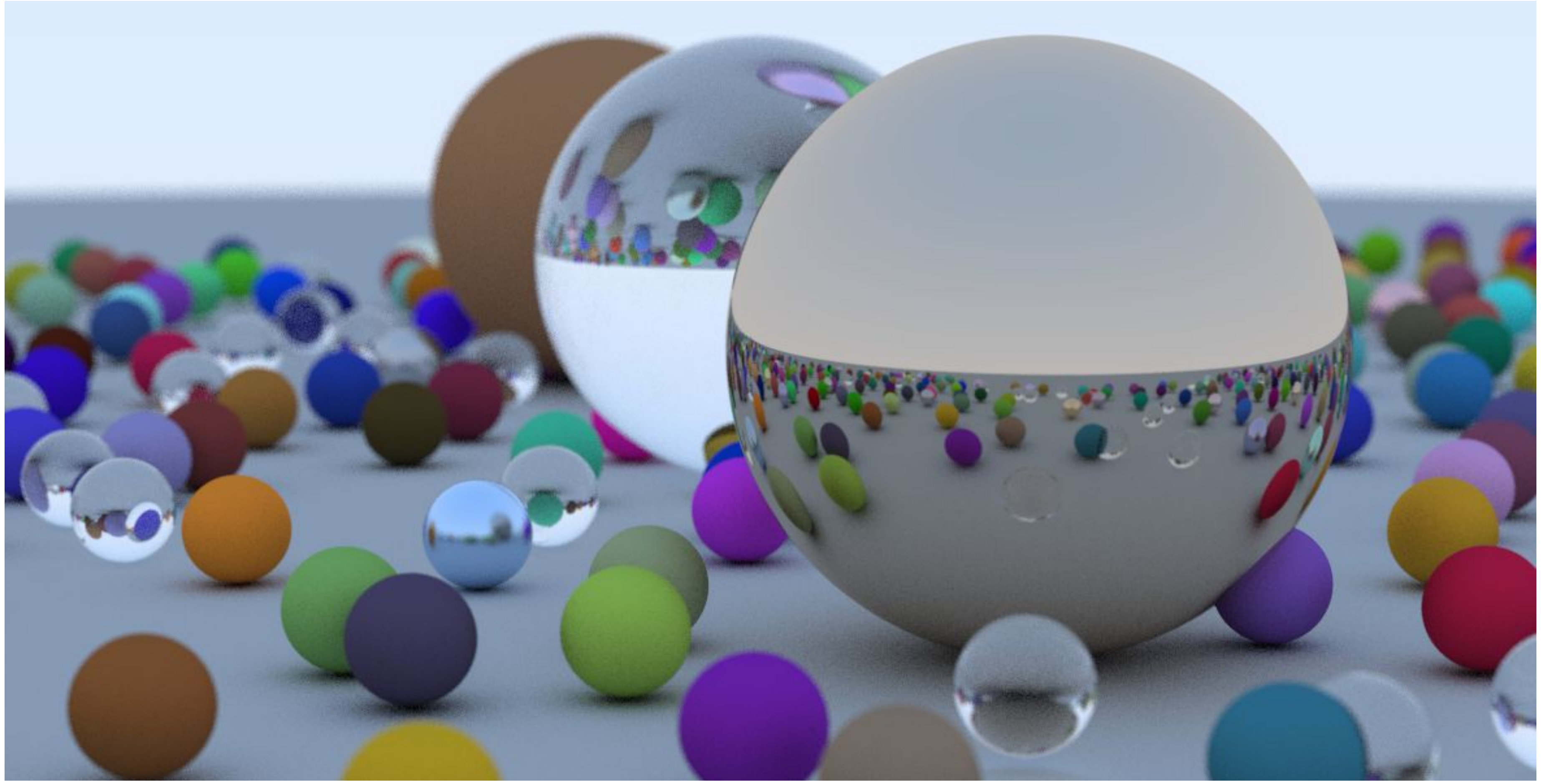
IMAGE SYNTHESIS



PHENOMENOLOGICAL SHADING 2

Prof. Derek Nowrouzezahrai
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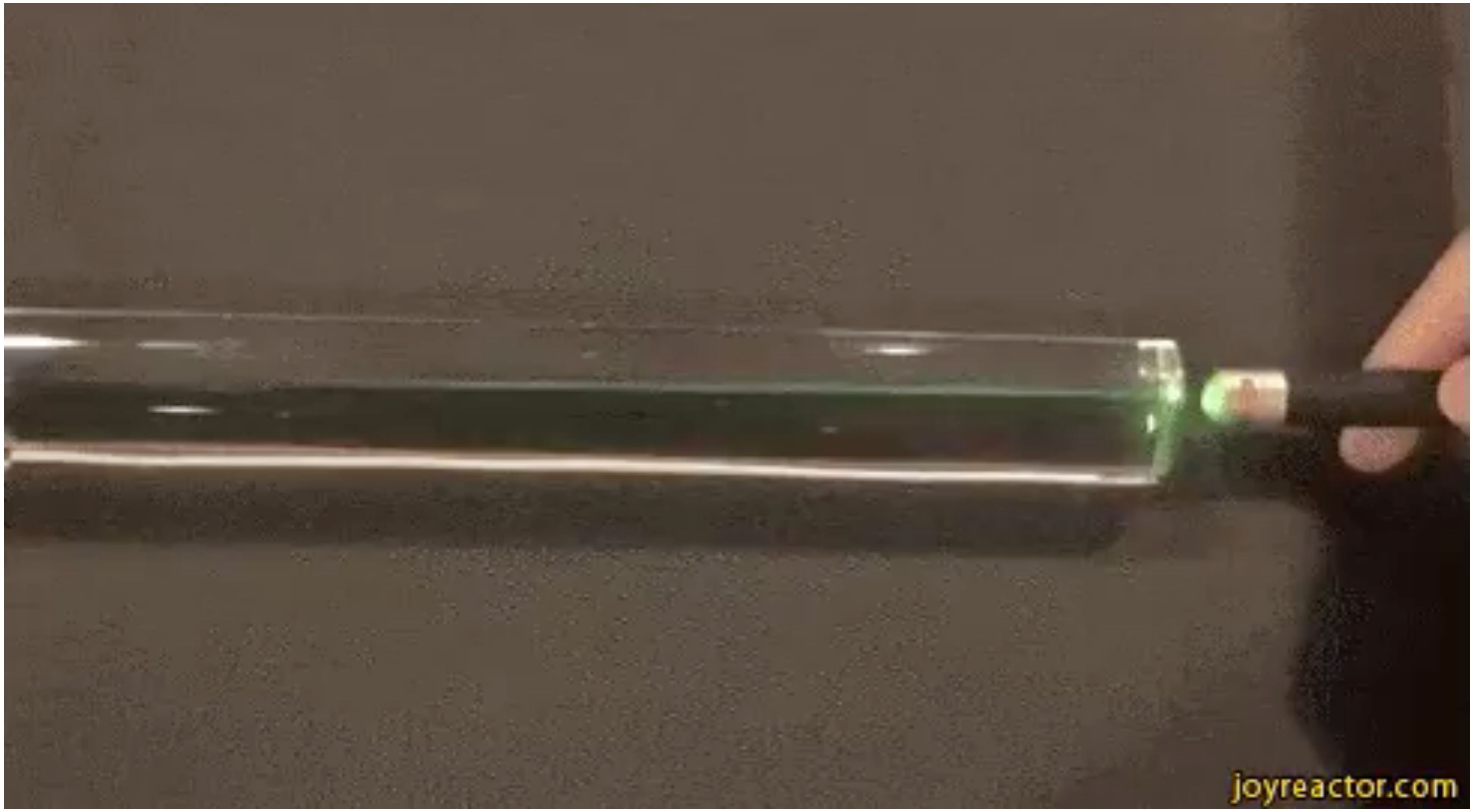
Total Internal Reflection

Can only happen when light passes from a higher index of refraction to lower index of refraction

Total Internal Reflection

Total Internal Reflection

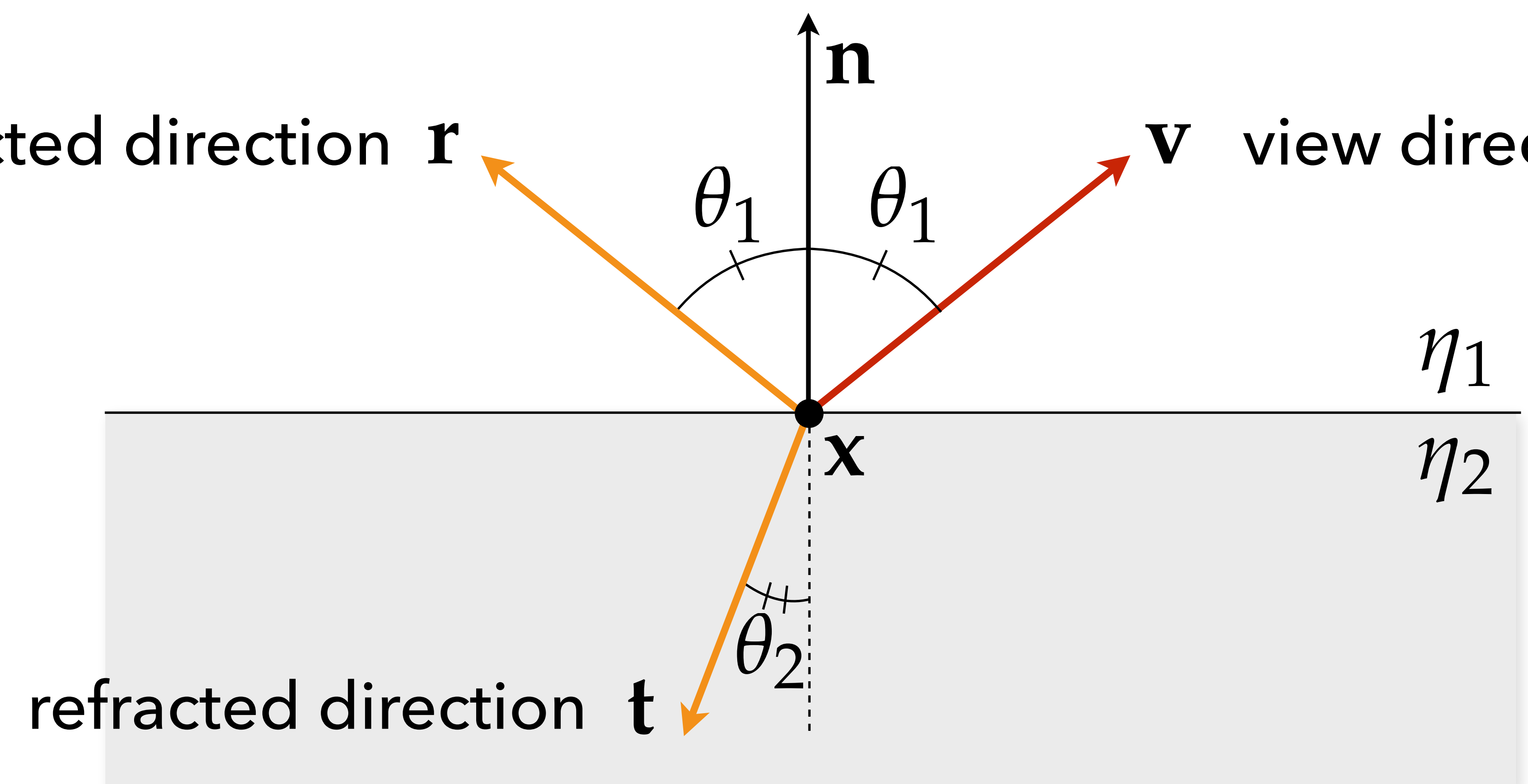


source: imgur.com

Reflection vs. Refraction

How much light is reflected vs. refracted?

- in reality determined by "Fresnel equations"



Fresnel Equations

Reflection and *refraction* from smooth *dielectric* (e.g. glass) surfaces

Reflection from *conducting* (e.g. metal) surfaces

Derived from Maxwell equations

Involves polarization of the wave

Fresnel Equations for Dielectrics

Reflection of light polarized parallel and perpendicular to the plane of refraction

$$\rho_{||} = \frac{\eta_2 \cos\theta_1 - \eta_1 \cos\theta_2}{\eta_2 \cos\theta_1 + \eta_1 \cos\theta_2}$$

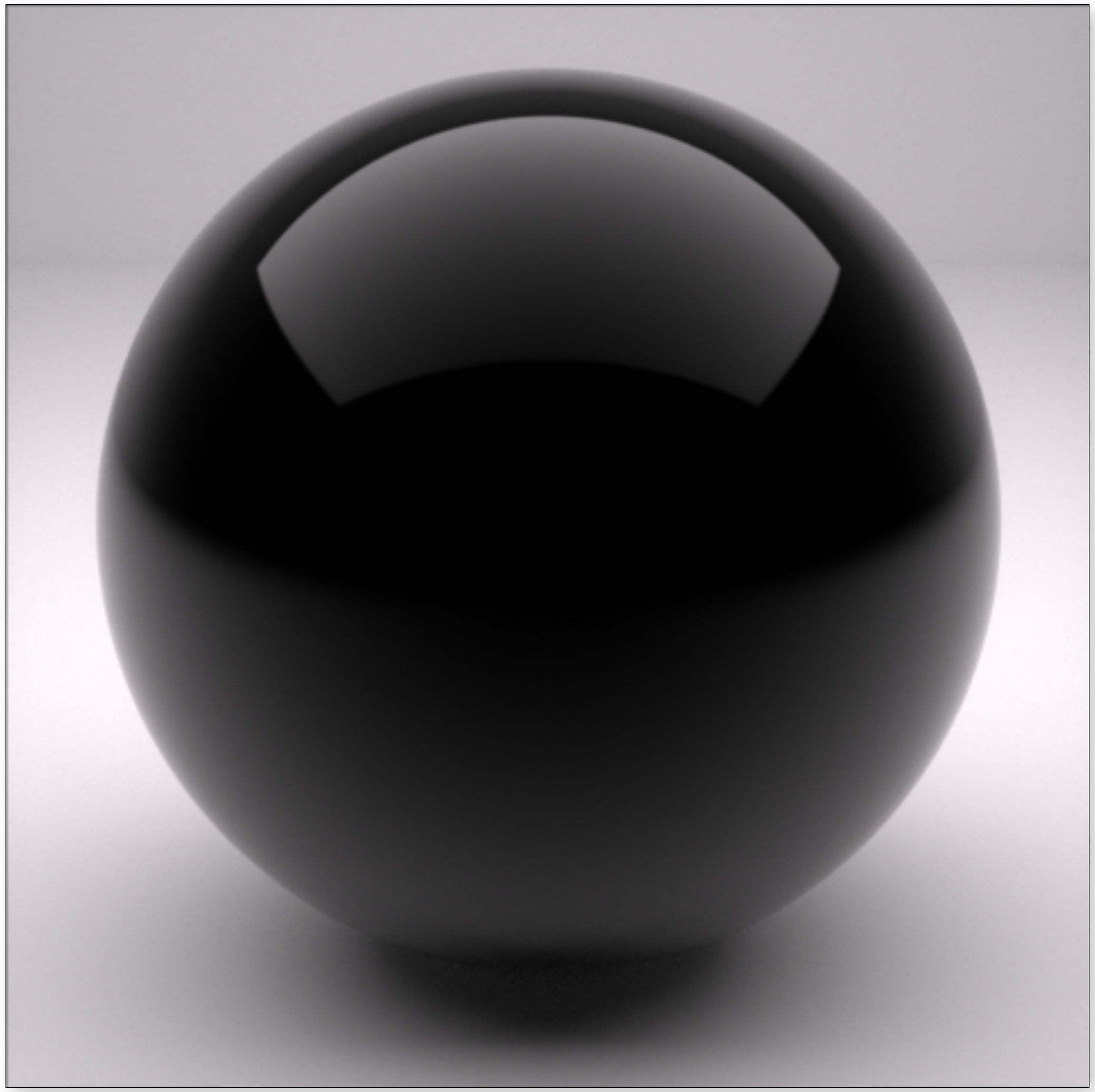
$$\rho_{\perp} = \frac{\eta_1 \cos\theta_1 - \eta_2 \cos\theta_2}{\eta_1 \cos\theta_1 + \eta_2 \cos\theta_2}$$

reflected: $\rho_r = \dfrac{\rho_{||}^2 + \rho_{\perp}^2}{2}$

refracted: $\rho_t = 1 - \rho_r$

- faster approximations possible (Schlick), but sacrifice in accuracy no longer worthwhile

Fresnel Reflection



Fresnel Reflection & Refraction

A Simple Empirical Material Model

Combines several effects:

1. Diffuse Reflection
   - light is reflected equally in every direction
   - shading is weighted by surface "color" property

2. Specular reflection/refraction (e.g., chrome, glass, glaze/varnish)
   - light reflected/refracted only in a single direction

3. Specular "highlights"
   - approximation of blurred reflection, **but only of the light source**

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Rough Materials

In reality, most materials are neither perfectly diffuse nor specular, but somewhere in between

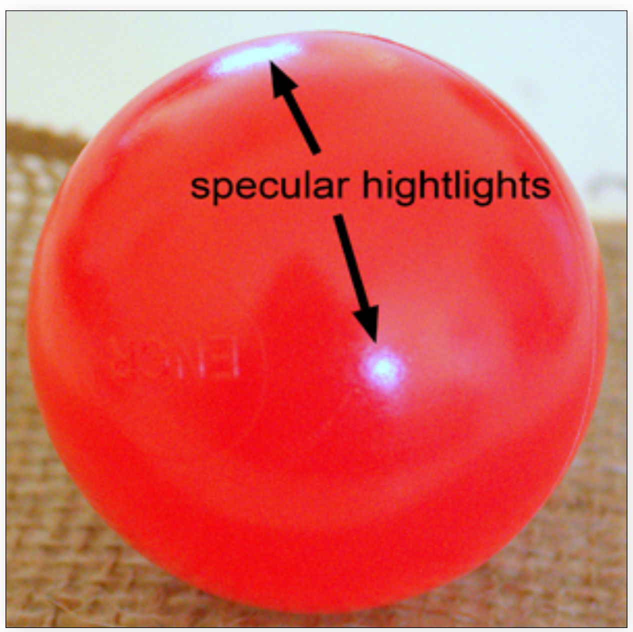
- e.g., a shiny surface scratched up at a microscopic level

Later, we'll look at how to more accurately mathematically model these types of surfaces

- for now, we can easily approximate one of their important characteristics: *glossy specular highlights of light sources*

Specular Emitter Highlights

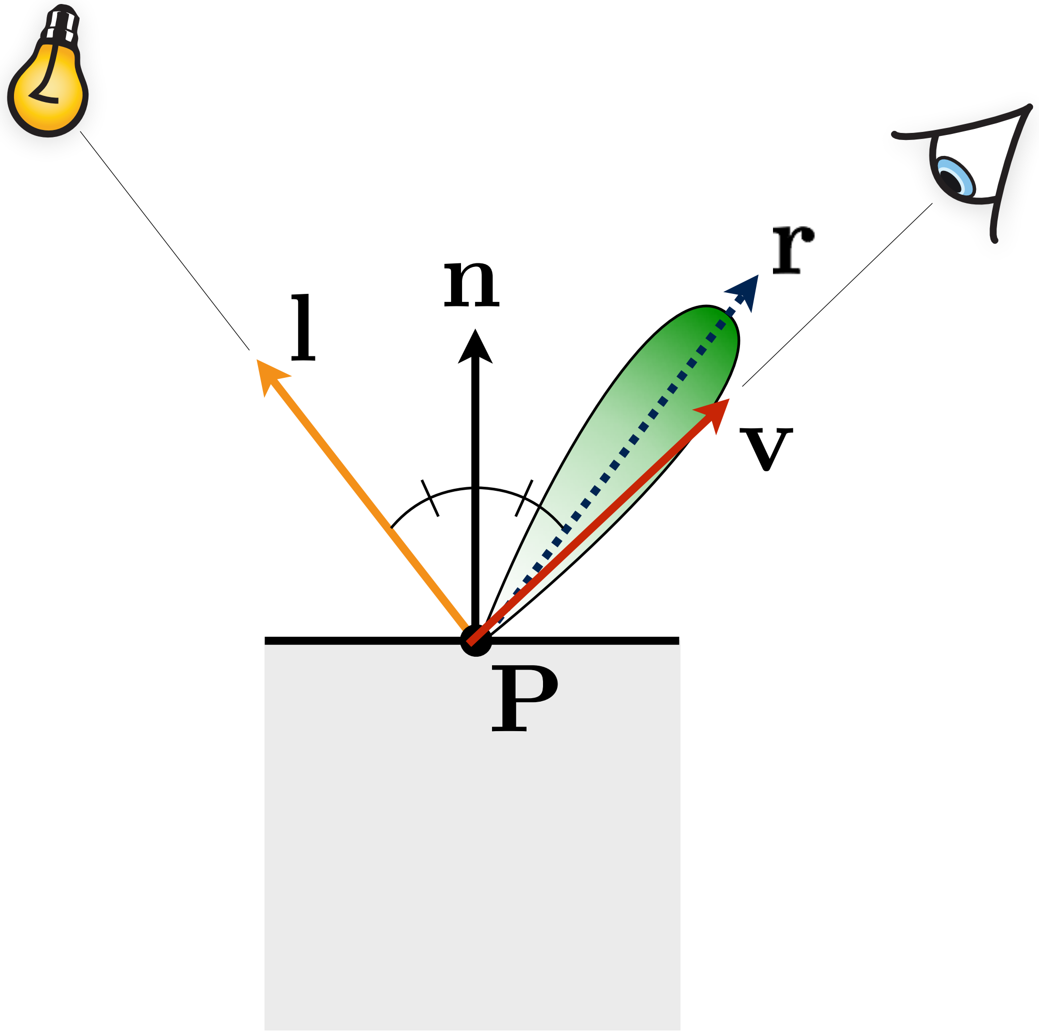
These are effectively just "blurry" reflections of the light source



Specular Emitter Highlights – Phong

Intensity depends on view direction

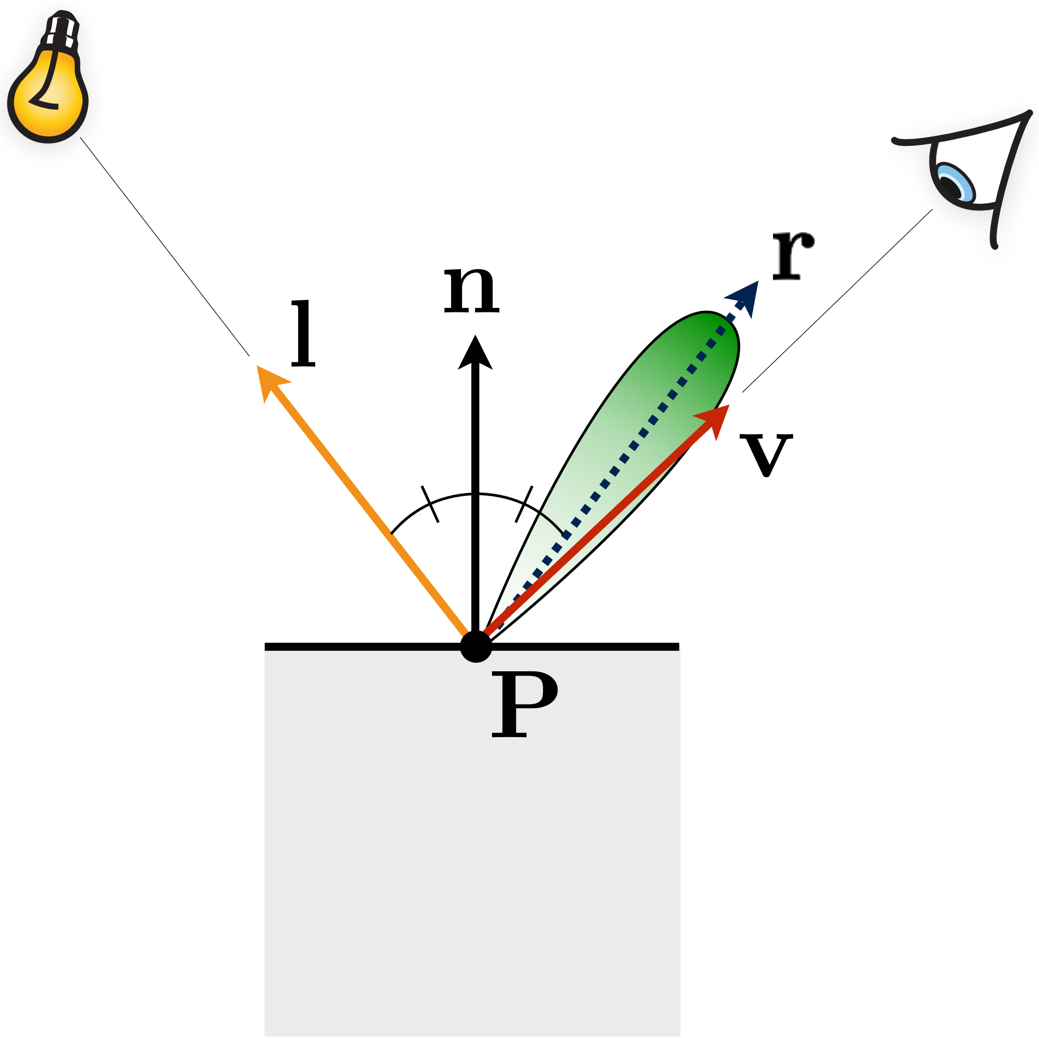
- brightest at the mirror direction,
  bright around the mirror direction



Specular Emitter Highlights – Phong

Intensity depends on view direction

- brightest at the mirror direction, bright around the mirror direction
- mirror reflect **light direction**
- dot product with view ray
    - measures similarity



Specular Emitter Highlights – Phong

Intensity depends on view direction

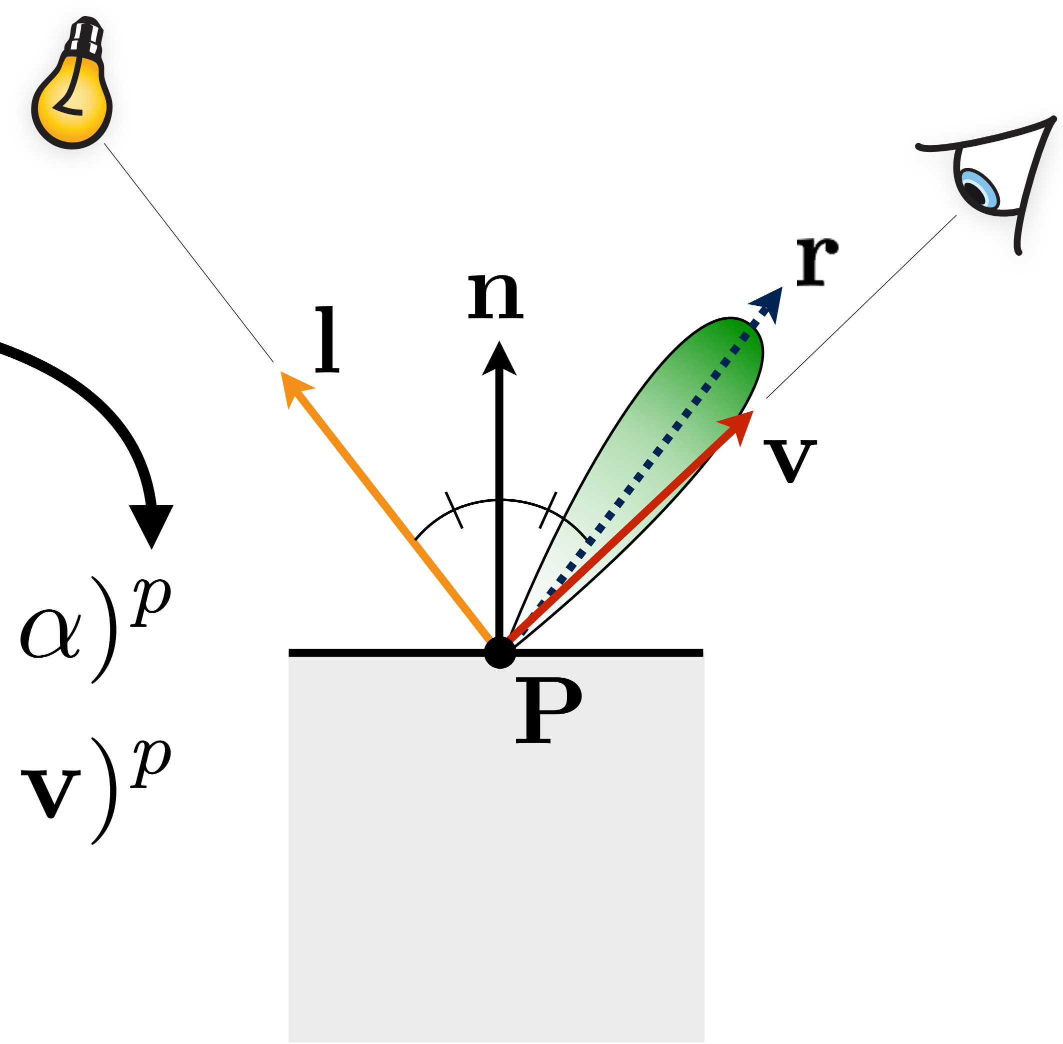
- brightest at the mirror direction, bright around the mirror direction

- mirror reflect **light direction**

specular coefficient

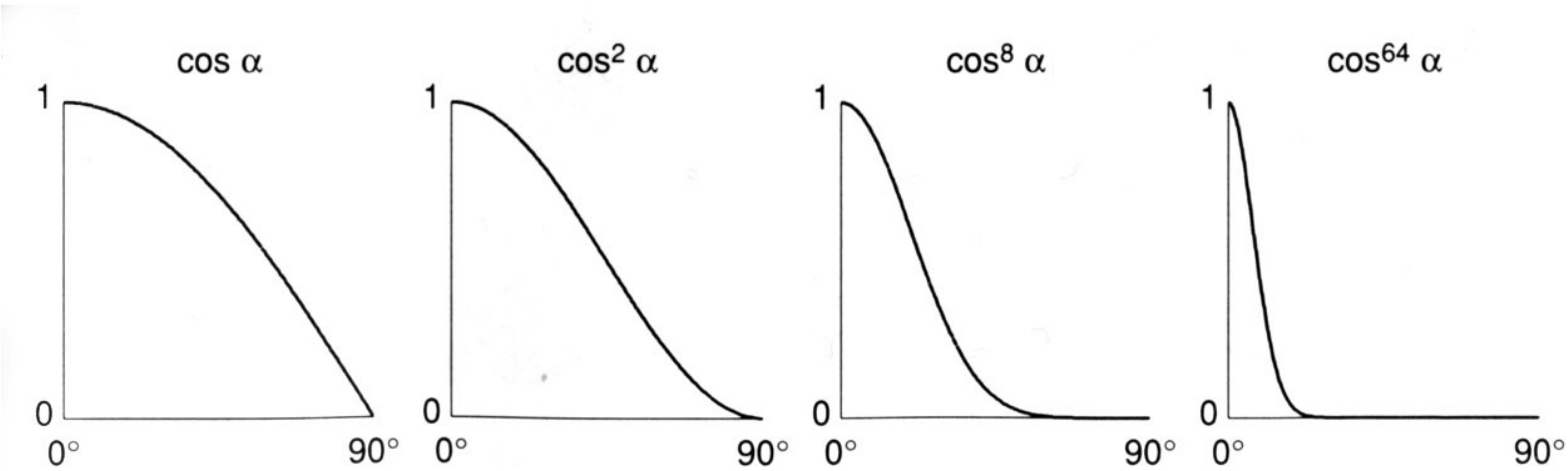
specularly reflected light intensity

$$L_s = \rho_s L_i \max(0, \cos\alpha)^p$$
$$= \rho_s L_i \max(0, \mathbf{r} \cdot \mathbf{v})^p$$



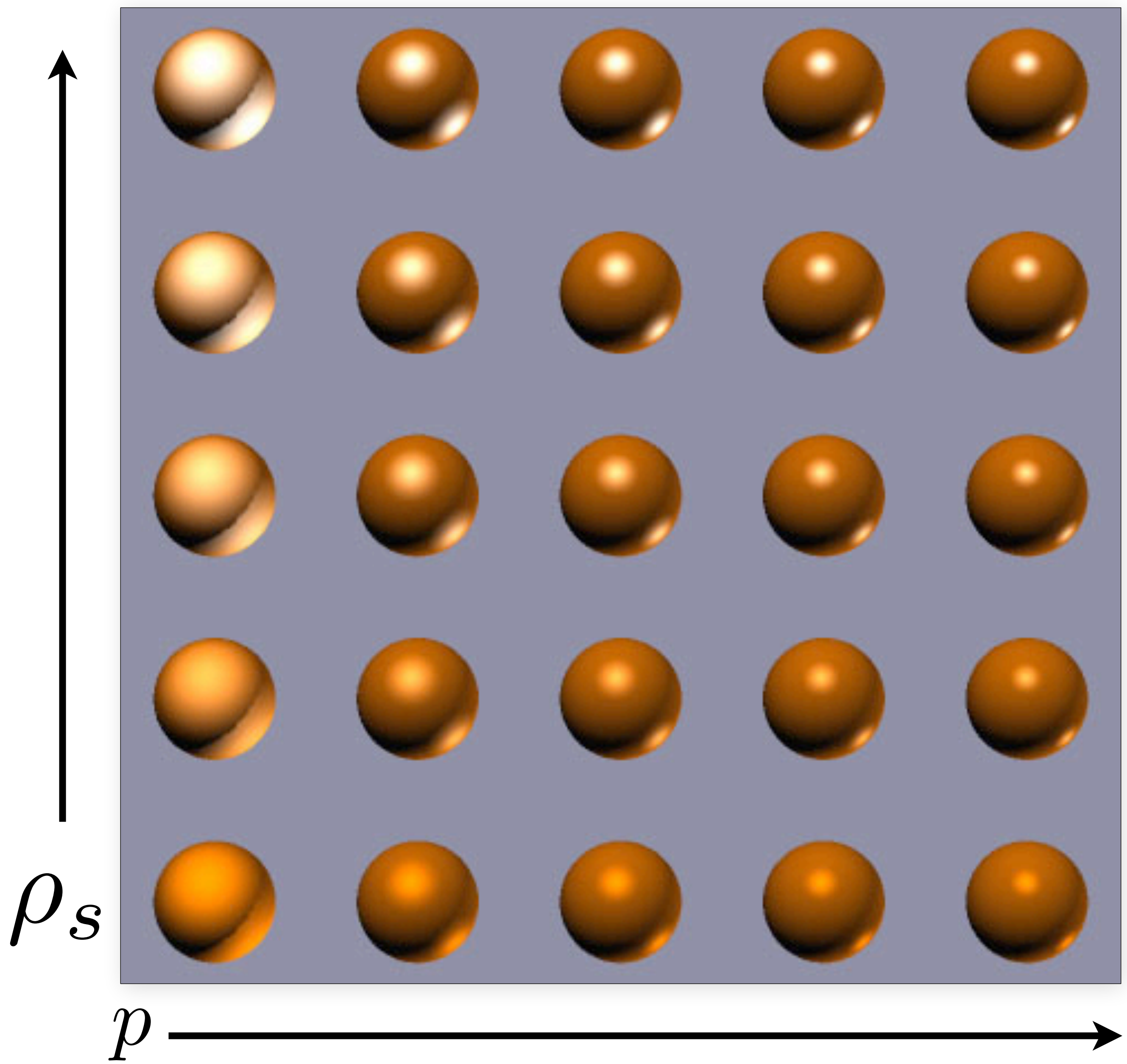
Phong Material Model – Plots

Increasing p narrows the lobe

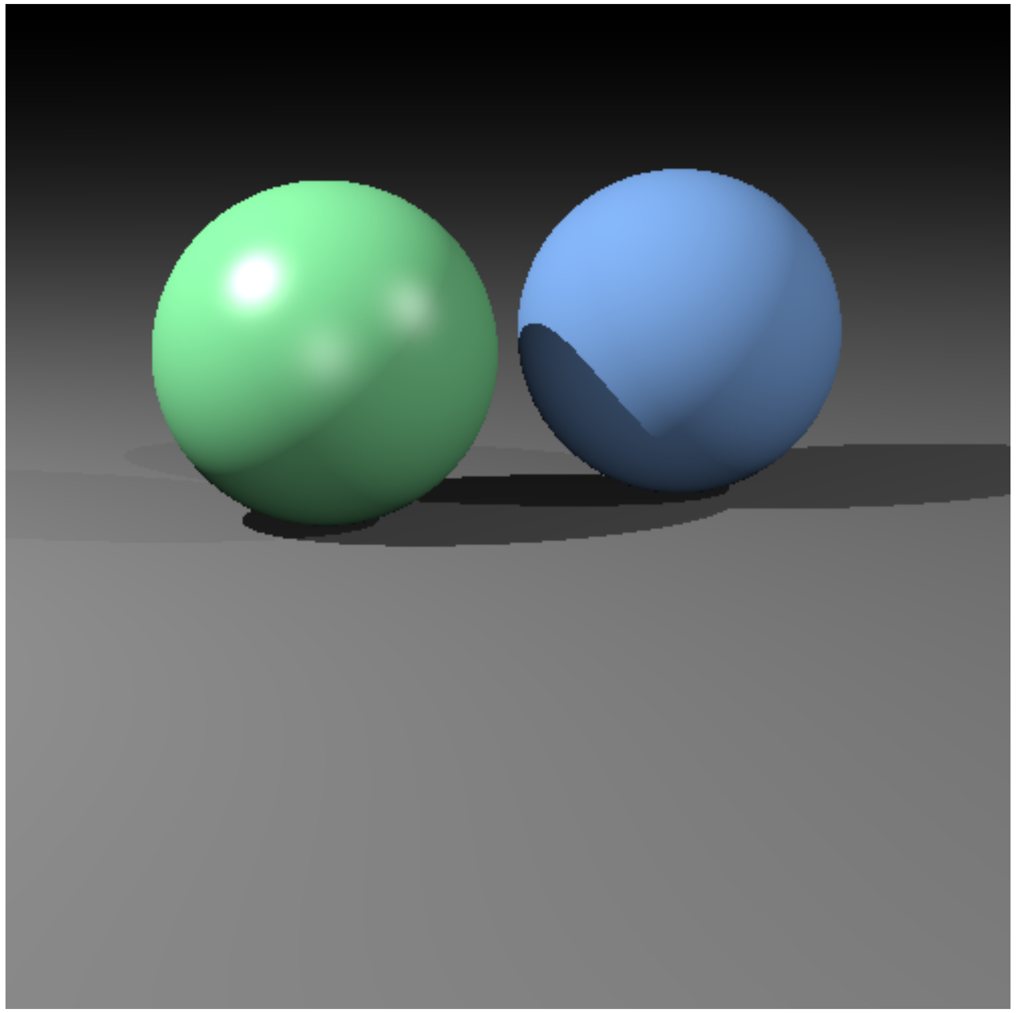


[Foley et al.]

Phong Material Model



Diffuse + Phong (Light) Highlights



Ambient Term Hack

Every reflective surface acts as an indirect source of light

- ceilings are not black
    - illuminated indirectly by walls
- shadows are not perfectly black
    - surroundings provide fill light

Ambient Term Hack

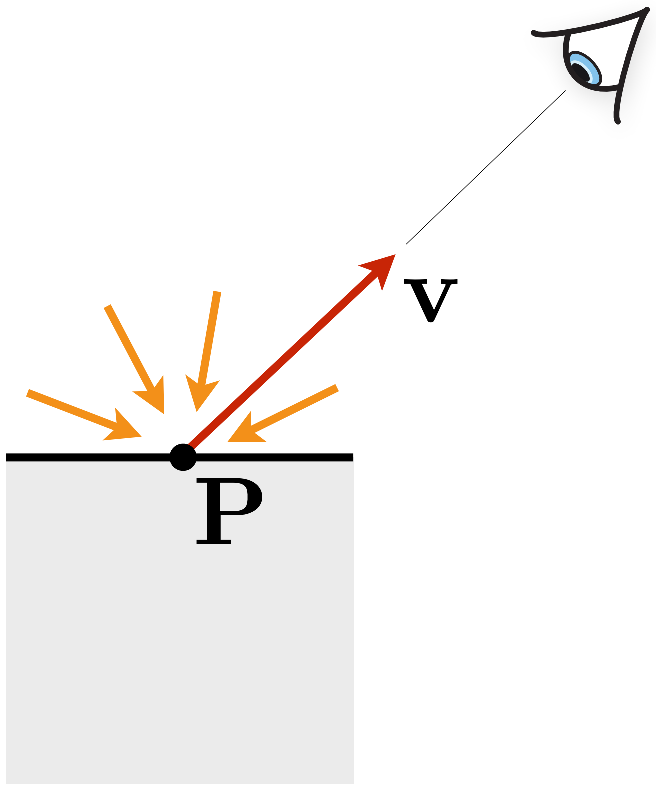
Expensive to compute accurately

- requires a global illumination solution
- we can easily (and poorly) approximate this with a simple constant term

$$L_a = \left(\frac{\rho_d}{\pi}\right) k_a$$

reflected ambient light

global ambient coefficient



Final Empirical Shading Model

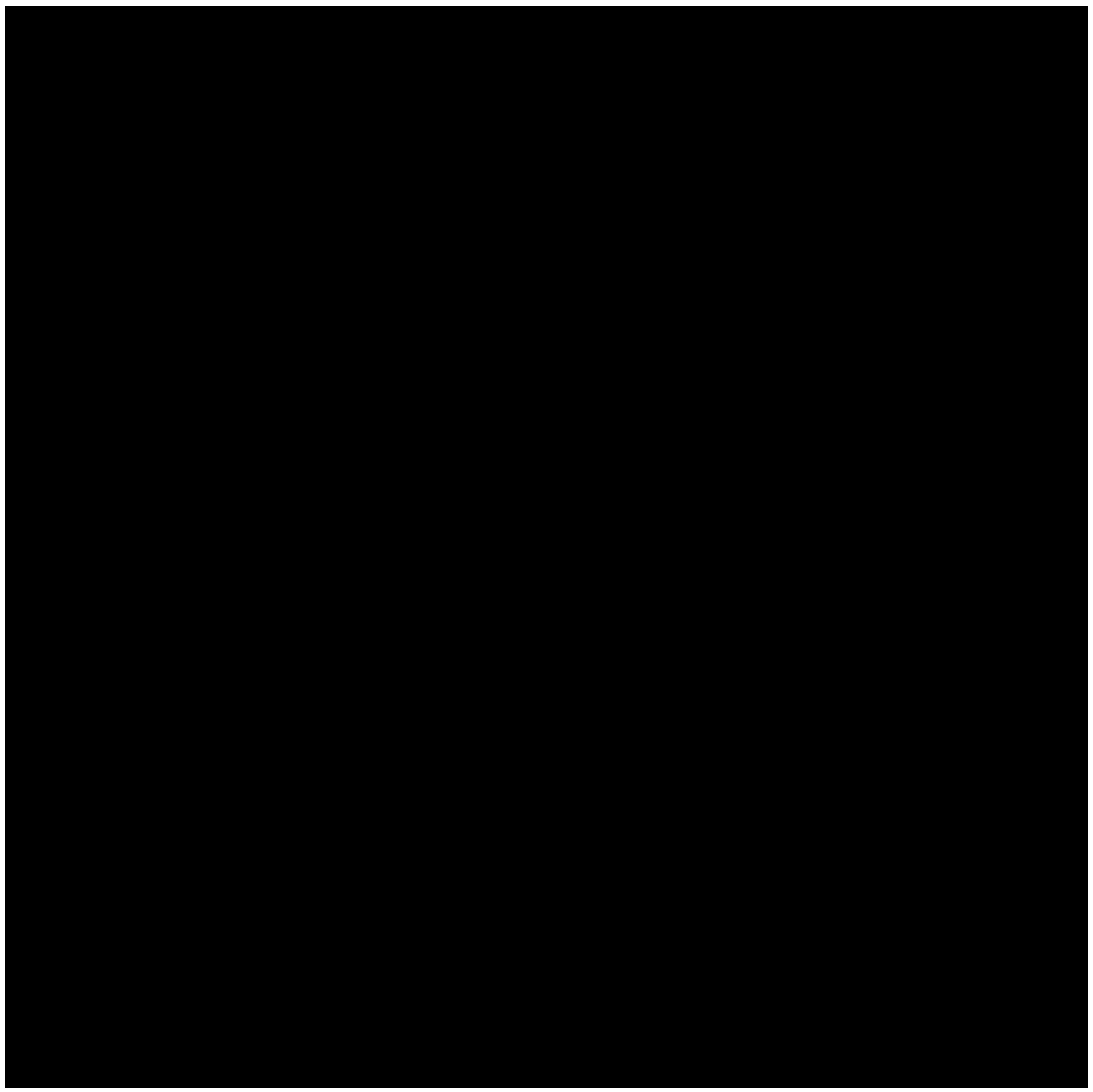
Combine ambient + mirror + refraction + diffuse + highlights in one übermodel:

$$
\begin{aligned}
L &= L_a + L_d + L_r + L_t + L_s \\
&= \frac{\rho}{\pi}\,(k_a + L_i\, V(\mathbf{x}, \mathbf{l})\, \max(0, \mathbf{n} \cdot \mathbf{l})) + \\
&\quad \rho_r\, \mathrm{trace}(\mathbf{x}, \mathbf{r}_e) + \rho_t\, \mathrm{trace}(\mathbf{x}, \mathbf{t}) + \rho_s\, L_i\, V(\mathbf{x}, \mathbf{l})\, \max(0, \mathbf{v} \cdot \mathbf{r}_l)^p
\end{aligned}
$$

The final result is the sum over many lights

$$
L = L_a + L_r + L_t + \sum_{i=1}^{N} [(L_d)_i + (L_s)_i]
$$

Final Empirical Shading Model



1. Initial blank image
2. Intersections
3. Diffuse term
4. Specular term
5. Reflections
6. Ambient term

Empirical Light Sources

Light Sources

Diffuse & Phong reflection depend on L_i

- amount of "incident" light reaching a shade point

Depends on:

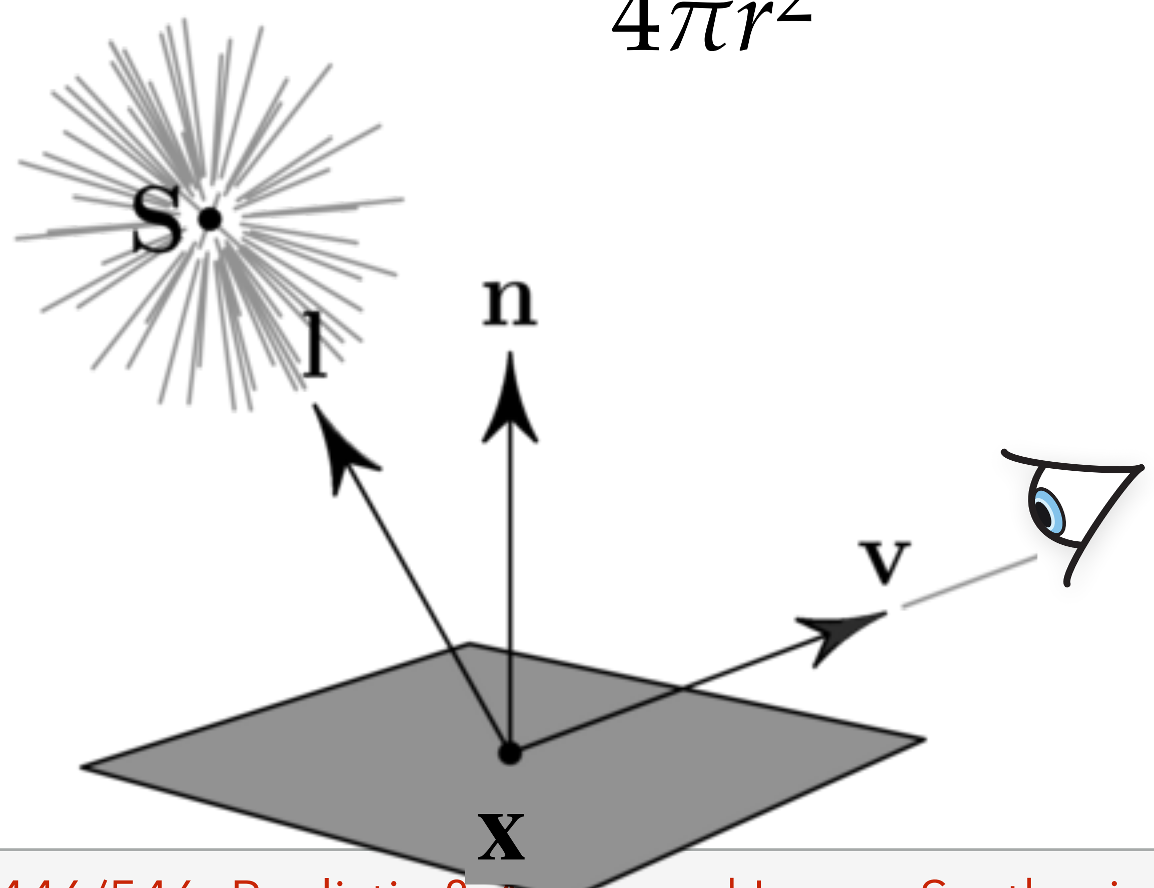
- light geometry,
- light emission, and
- scene geometry

Empirical Emitters — Point Lights

Light emitted evenly from $\mathbf{S}$ in all directions

Incident light differs at each shade point $\mathbf{x}$

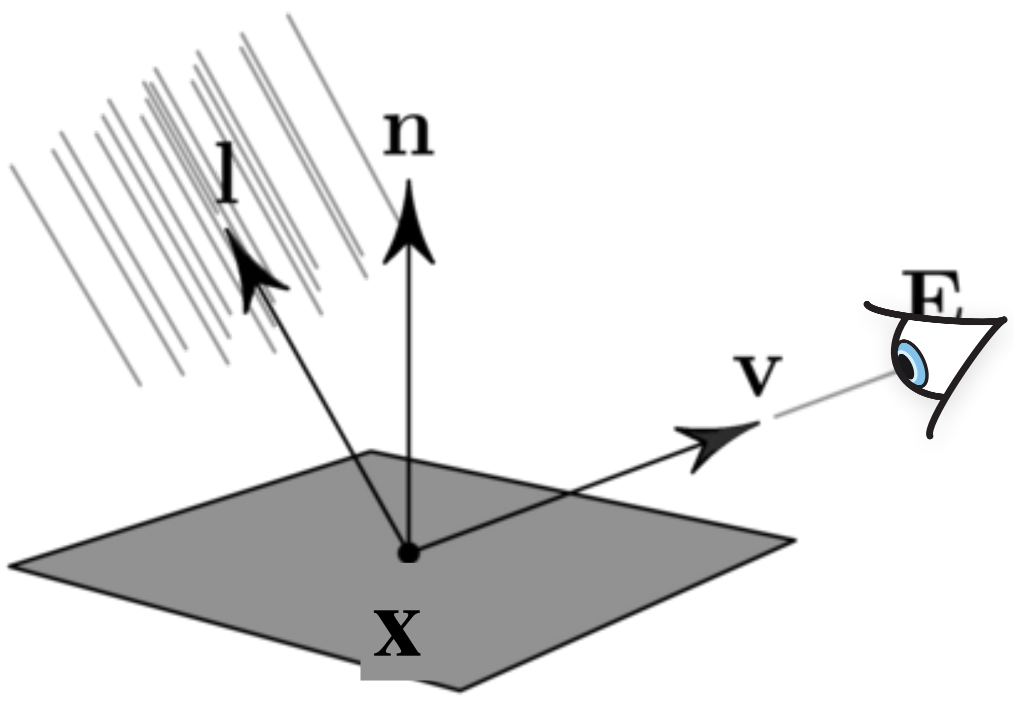
- light direction: $\mathbf{l} = (\mathbf{S} - \mathbf{x}) / |\mathbf{S} - \mathbf{x}|$
- incident light at $\mathbf{x}$: $L_i = \dfrac{\Phi}{4\pi r^2}$



Empirical Emitters – Directional Lights

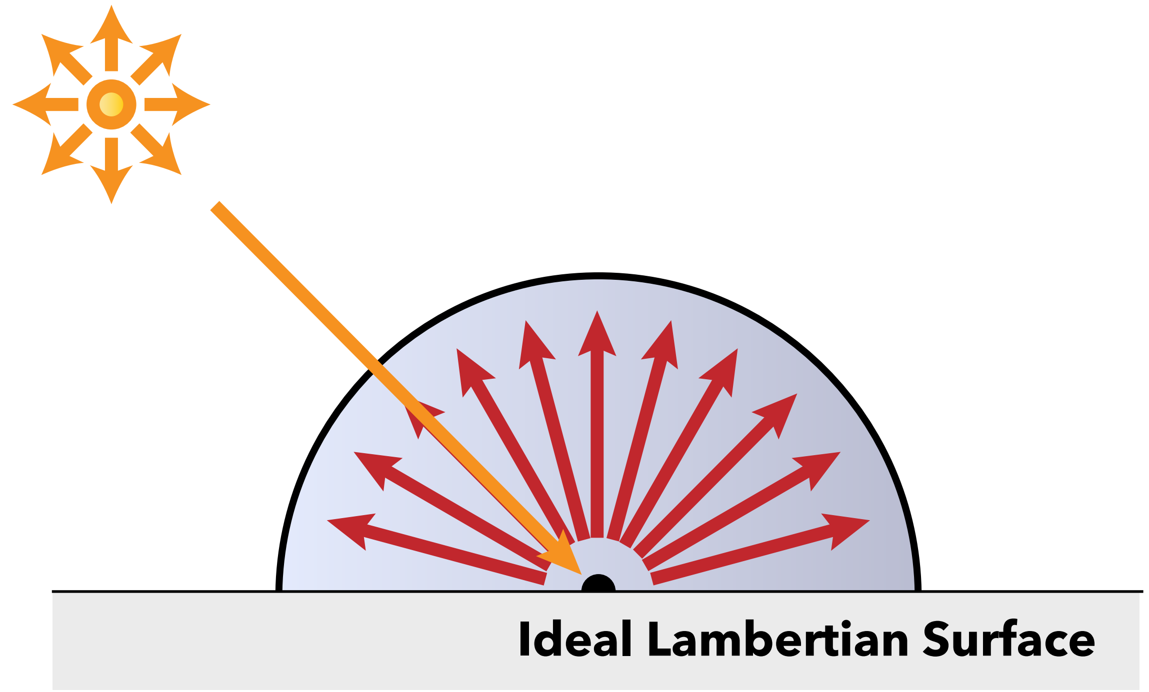
Light emitted from infinity, in direction $\mathbf{d}$

- simulates distant lighting, e.g., sun
    - same at all surface points $\mathbf{x}$
- light direction: $\mathbf{l} = \mathbf{d}$
- incident light at $\mathbf{x}$: $L_i = \Phi$

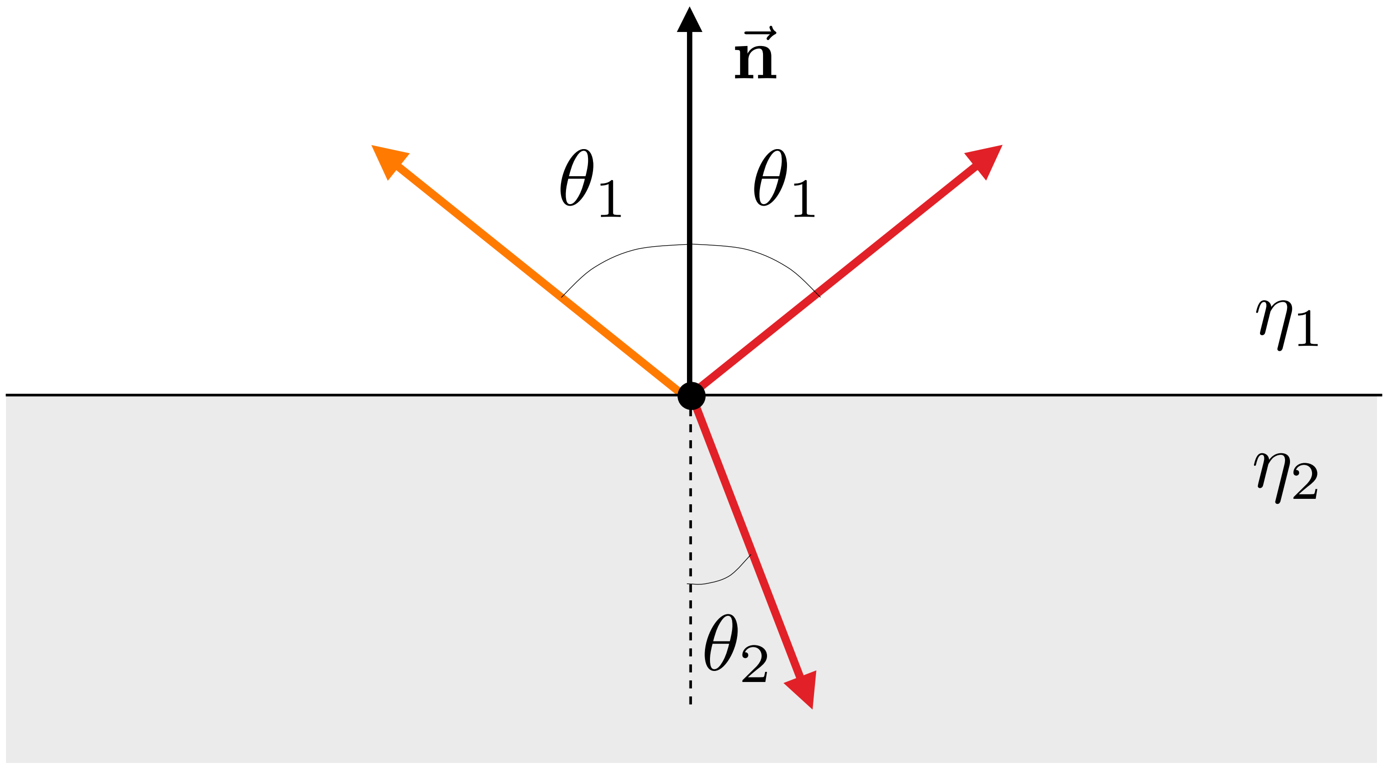


So Far – Idealized Material Models

Diffuse

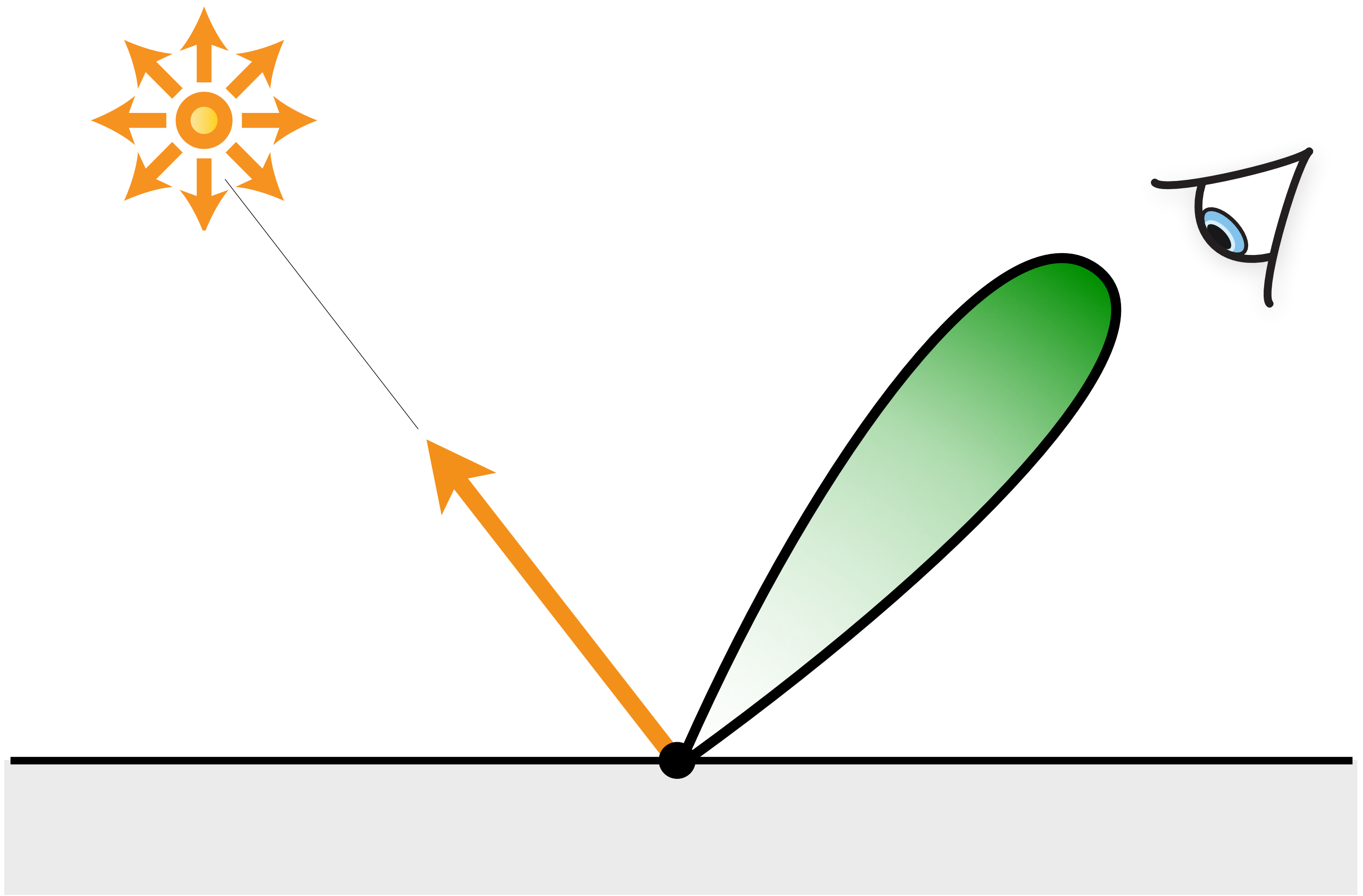


Specular Reflection and Refraction



So Far – Idealized Material Models

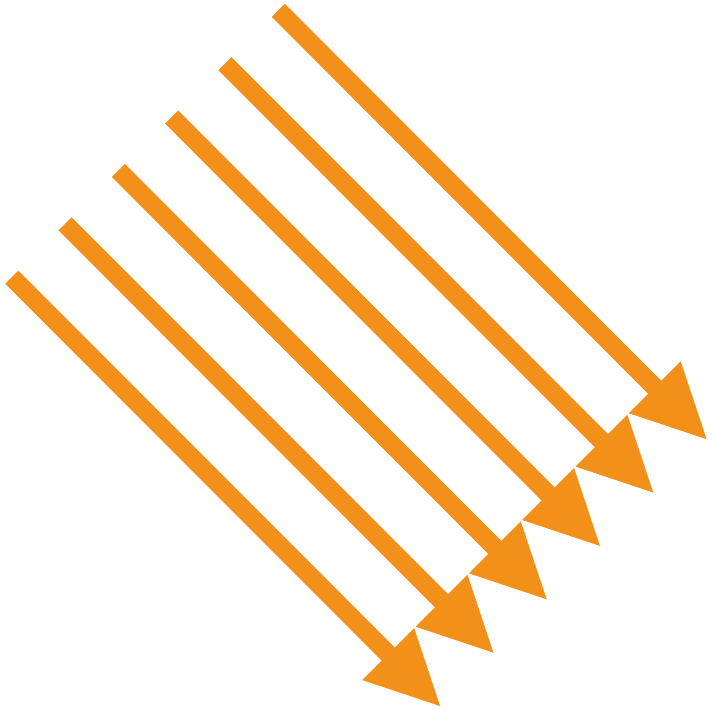
Glossy reflection (of only the light sources)

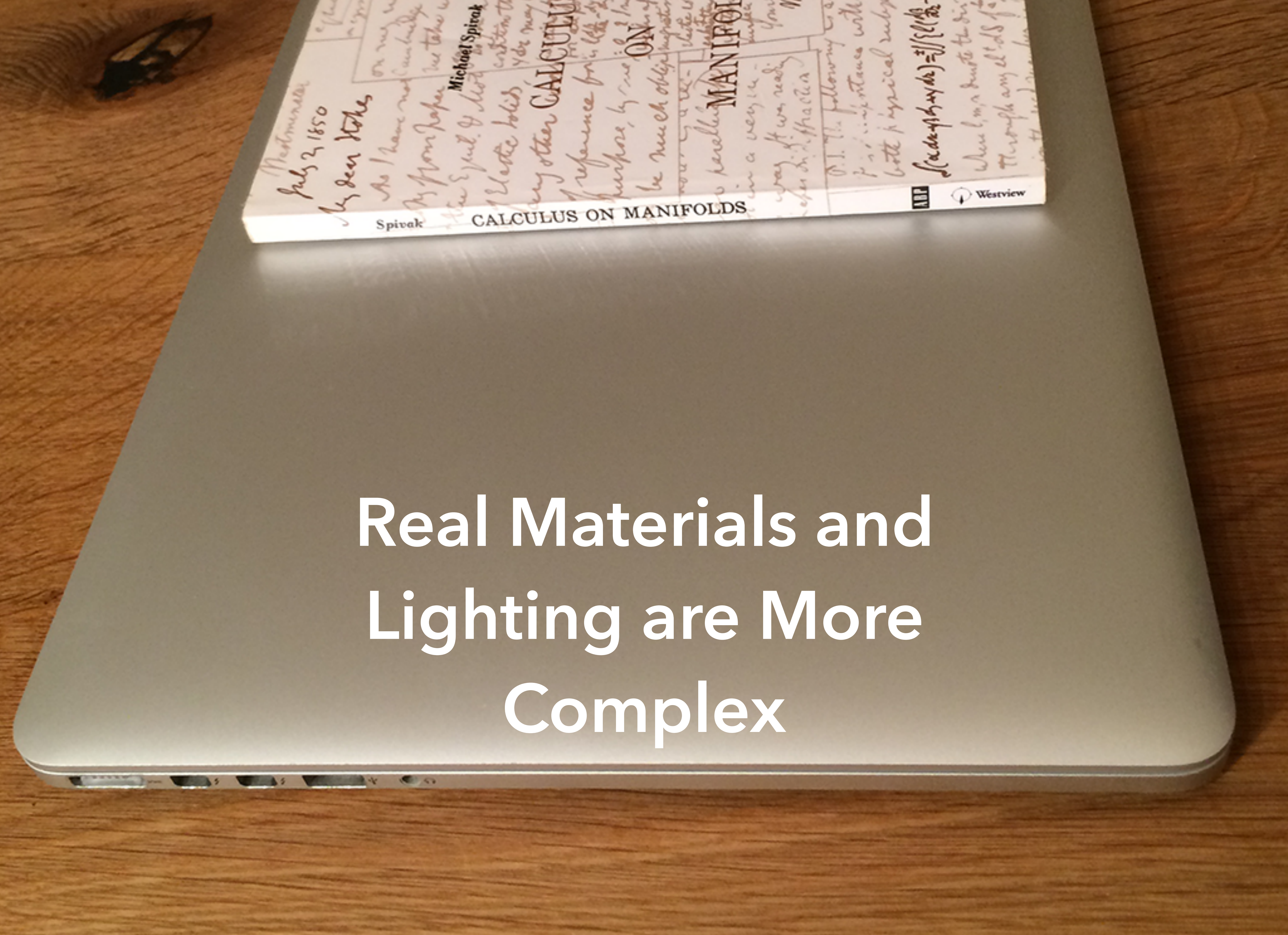


So Far: Idealized Lights/Emitters

Point source:

Directional source:





Real Materials and Lighting are More Complex

Physically-based Shading Models

In reality, most materials are neither perfectly diffuse nor specular, but somewhere in between

- imagine a shiny surface scratched up at a microscopic level

Also, real light sources are not infinitesimal points, but have finite area

Next up (~2 weeks):

- Radiometry: more formal mathematical language
- Monte Carlo: how to solve integrals with compute

Questions?