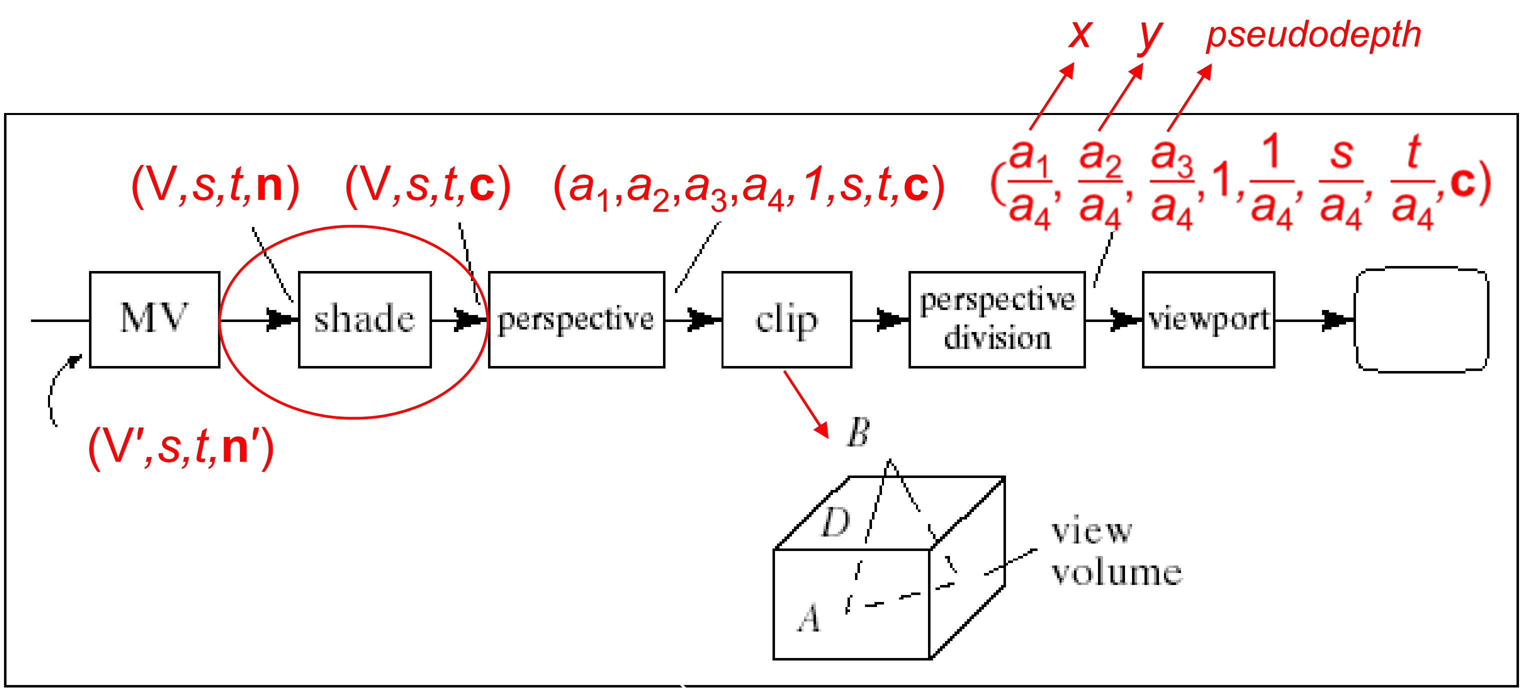
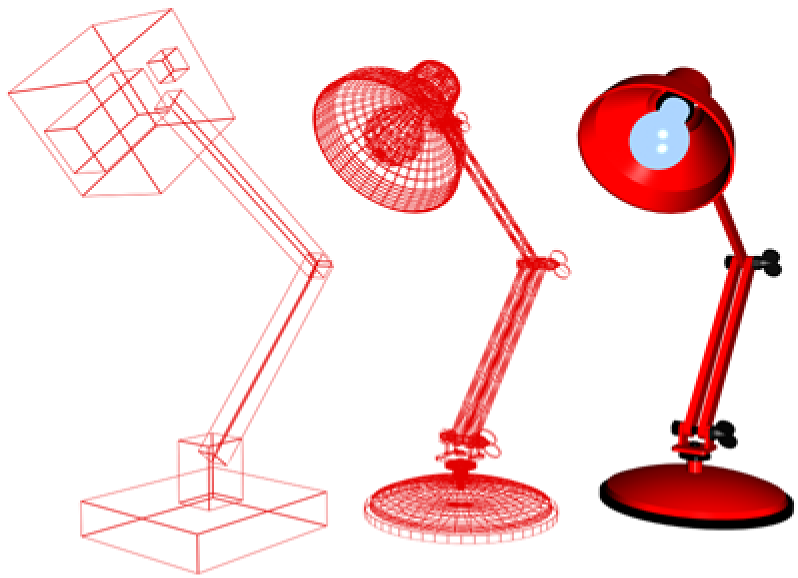
Reminder: The Pipeline



Rendering Styles

- ***Blocked, wireframe, & shaded renderings***



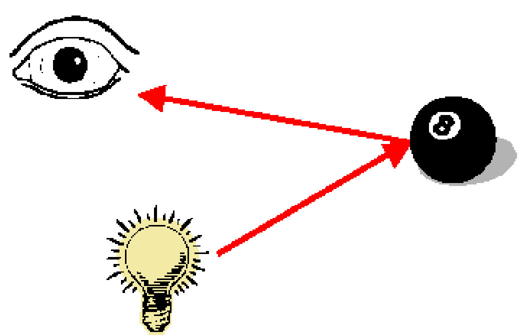

A4
A4 [2h 43m 19,2s]

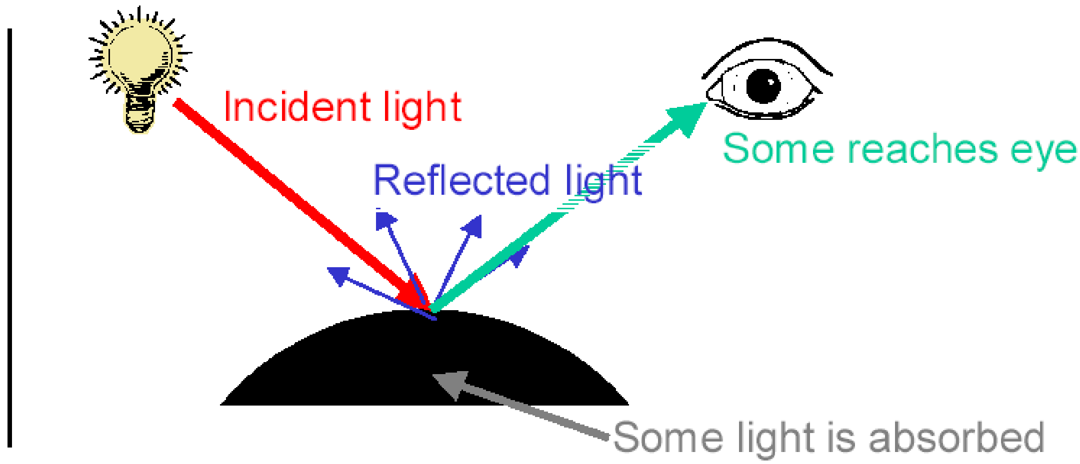
Object Appearance

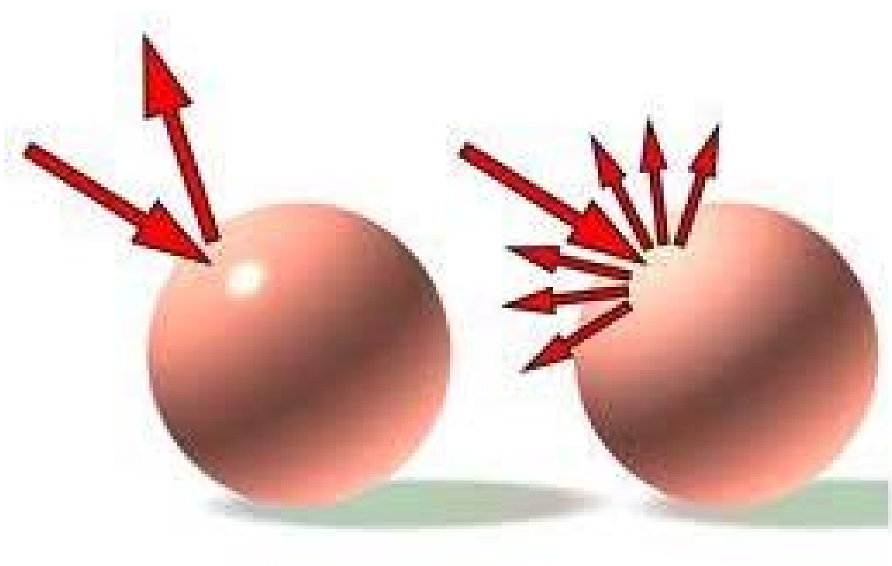
Light transport in a scene

- Light is emitted from light sources
- Light interacts with surfaces
  - *On impact with an object, some light is reflected and some is absorbed*
  - *Distribution of reflected light determines "finish" (matte, glossy, …)*
- Composition of light arriving at camera determines the appearance of the scene

Interaction of Light With a Surface at a Single Point







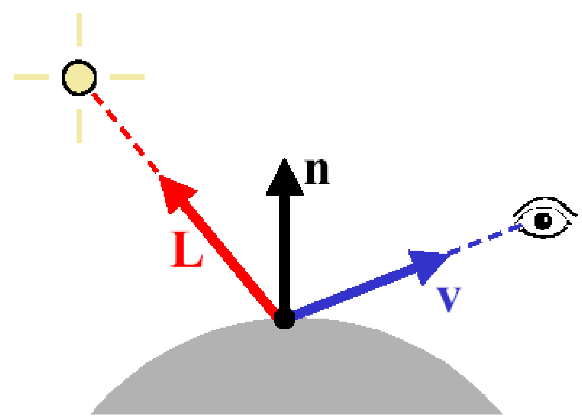
Modeling Light Sources

- Generally, light sources are complex
  - *The sun, light bulbs, fluorescent lights, monitors, …*
- Simple, point light sources
  - *The light source is a single infinitesimal point*
  - *Emits light equally in all directions (isotropic illumination)*
  - *Outgoing light is a set of rays originating at light source*

A Basic Local Illumination Model

We are interested only in the light that finally arrives at the view point

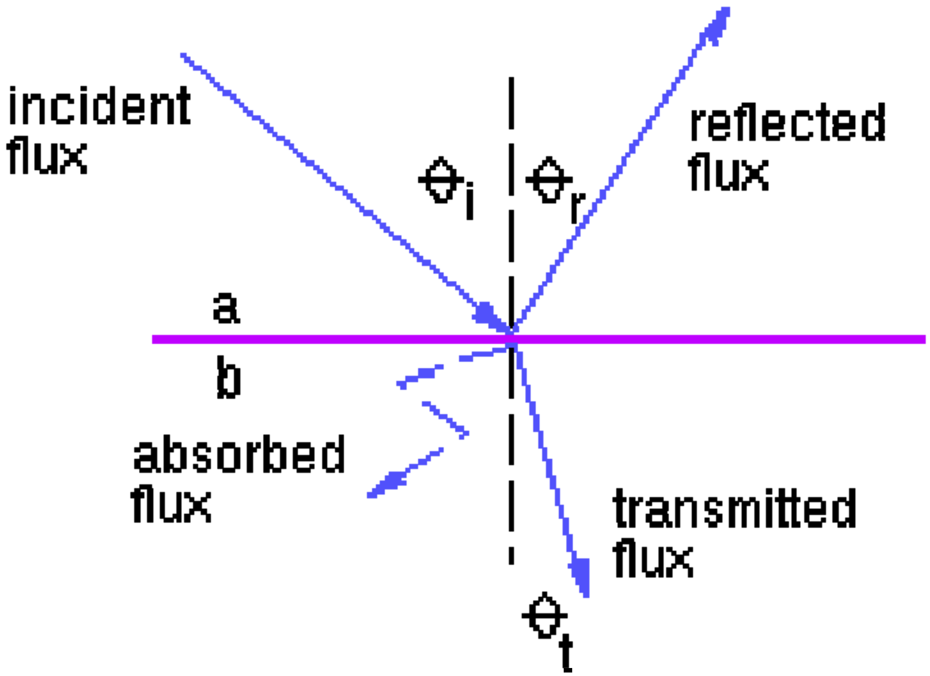
- This is a function of the light and viewing positions, and local surface reflectance



- We characterize light using RGB triples and operate on each channel separately (light superposition)

Local Illumination Physics

Law of reflection and Snell's law of refraction

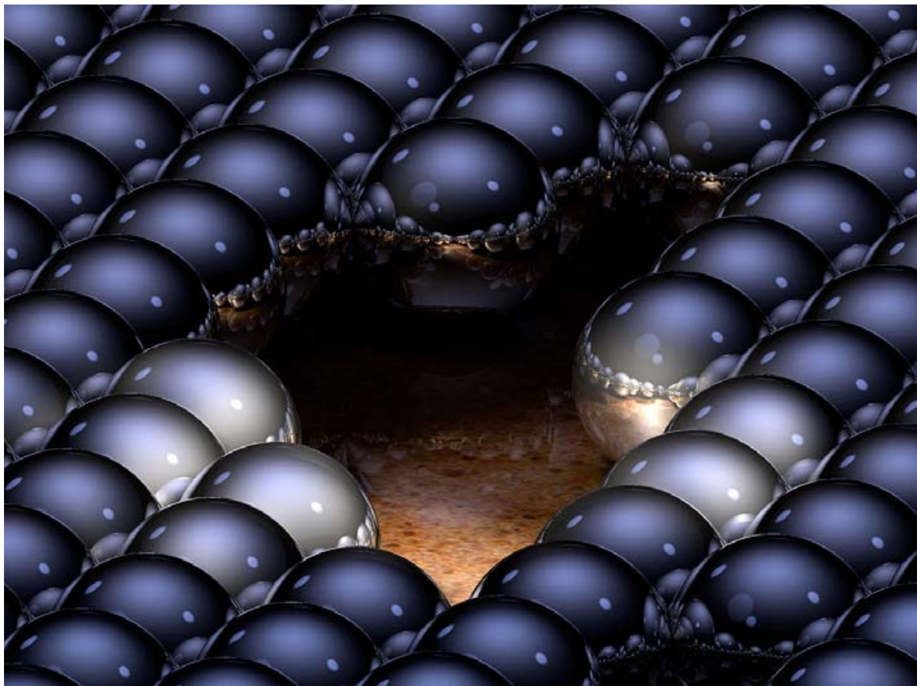


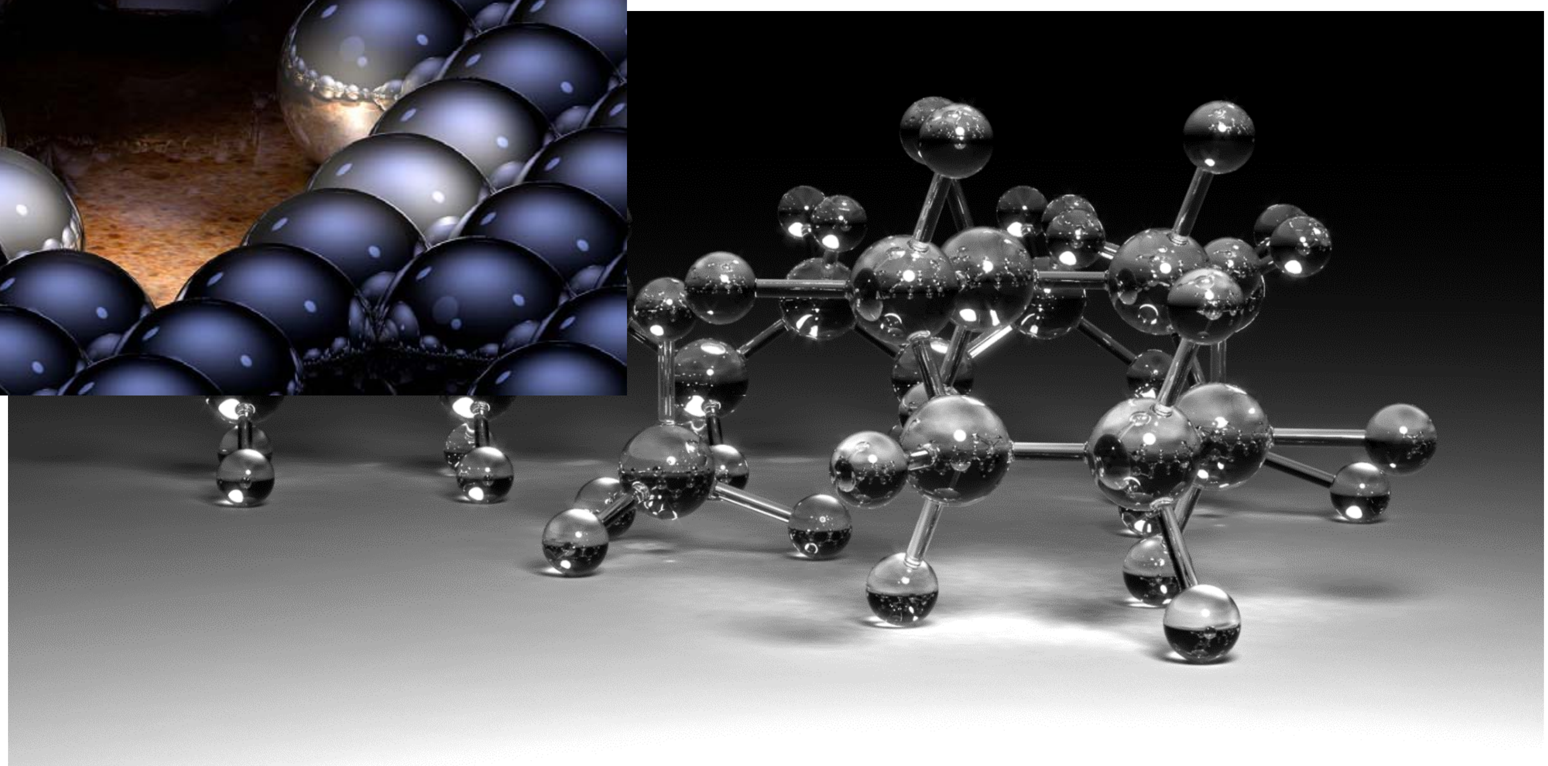
$$\theta_i = \theta_r$$

$$\frac{n_b}{n_a} = \frac{\sin(\theta_i)}{\sin(\theta_t)}$$

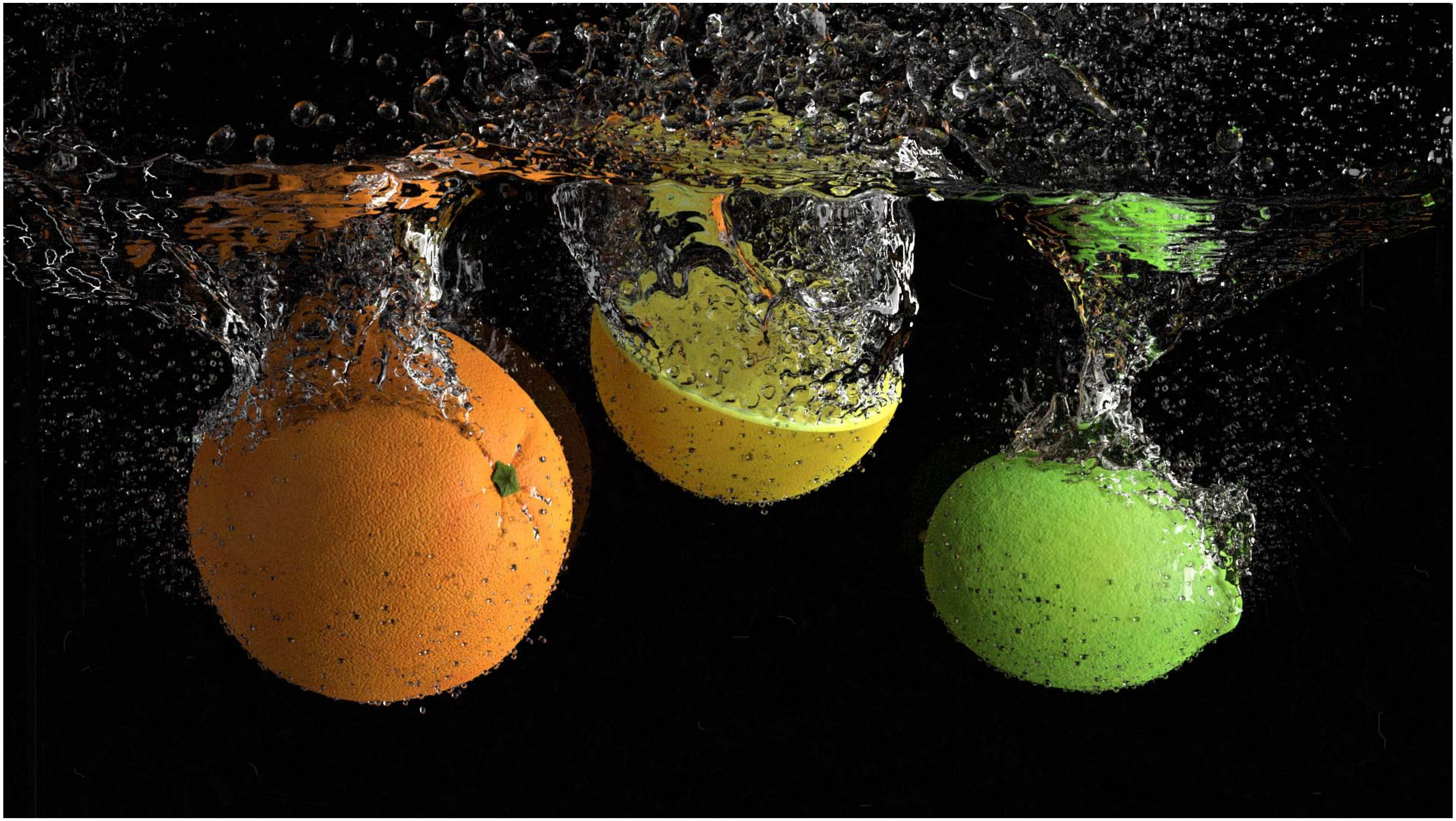
n: Refractive index

Reflection and Refraction
(Ray Tracing Rendering)



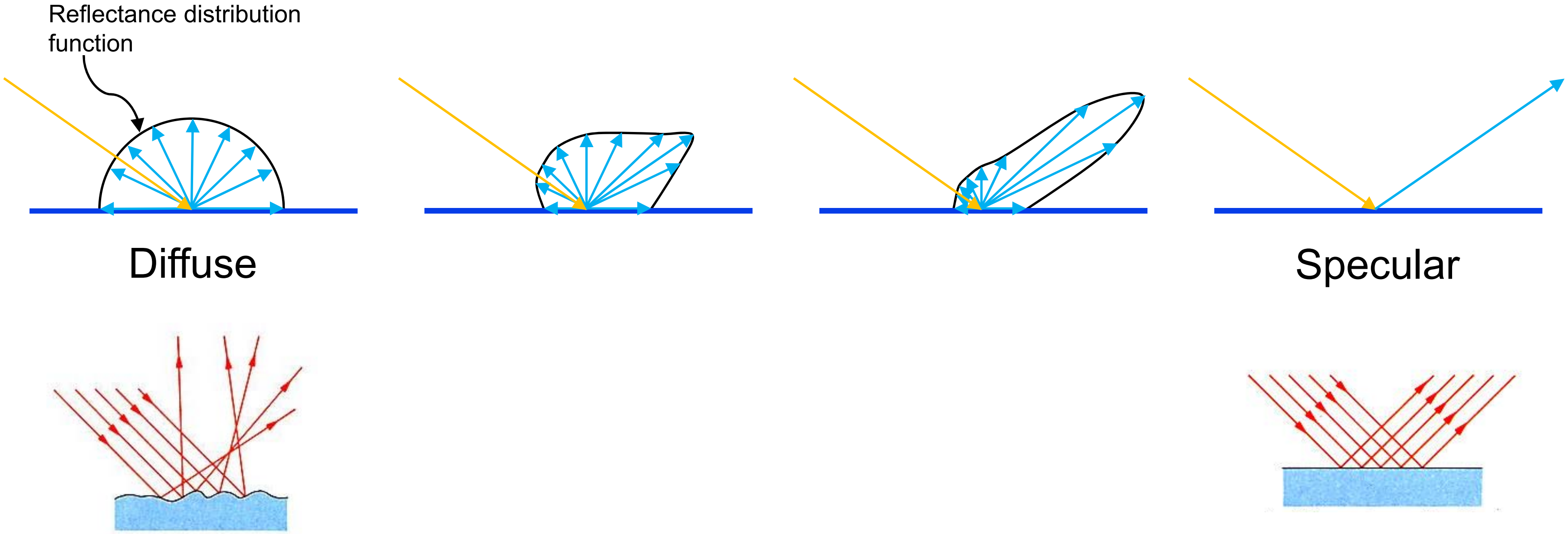


Refraction



What Are We Trying to Model ?

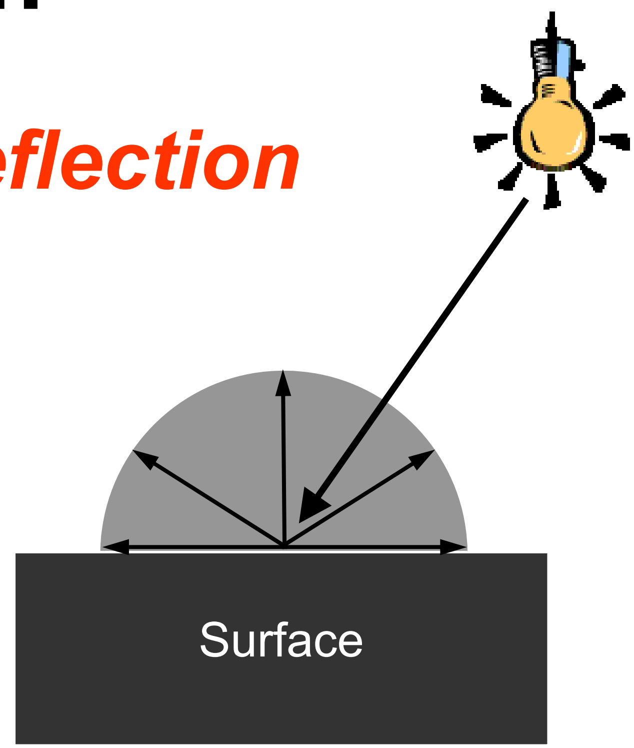
From diffuse to specular reflectance



Diffuse Reflection

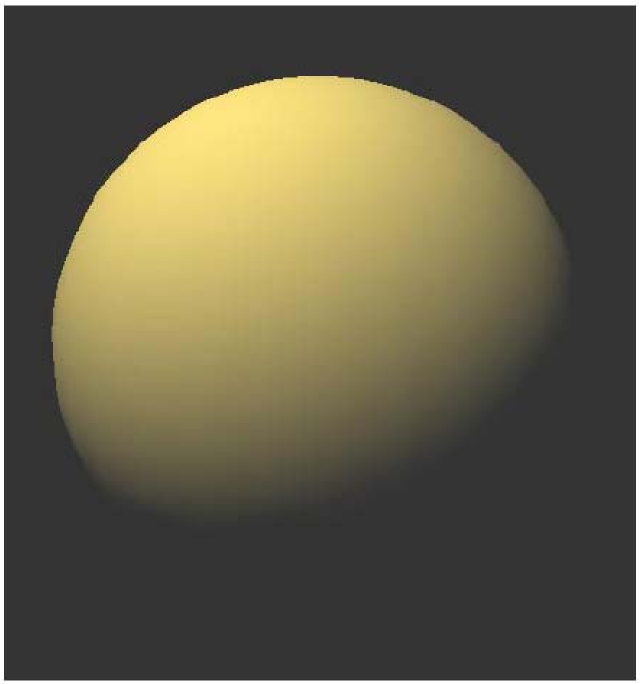
This is the simplest kind of reflection

- Also called “Lambertian reflection” (Lambert’s Law)
- Models dull, matte surfaces – materials like chalk
- Ideal diffuse reflection
  - *Scatters incoming light equally in all directions*
  - *Identical appearance from all viewing directions*
  - *Reflected intensity depends only on the direction of the light source*

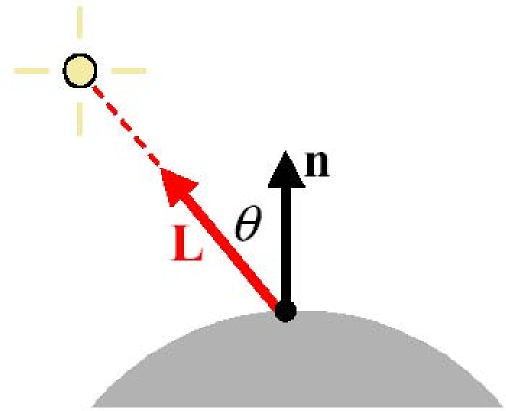


Lambert's Law for Diffuse Reflection

Purely diffuse object



$$I = I_L k_d \cos\theta$$
$$= I_L k_d (\mathbf{n} \cdot \mathbf{L})$$



I : resulting intensity

I_L : light source intensity

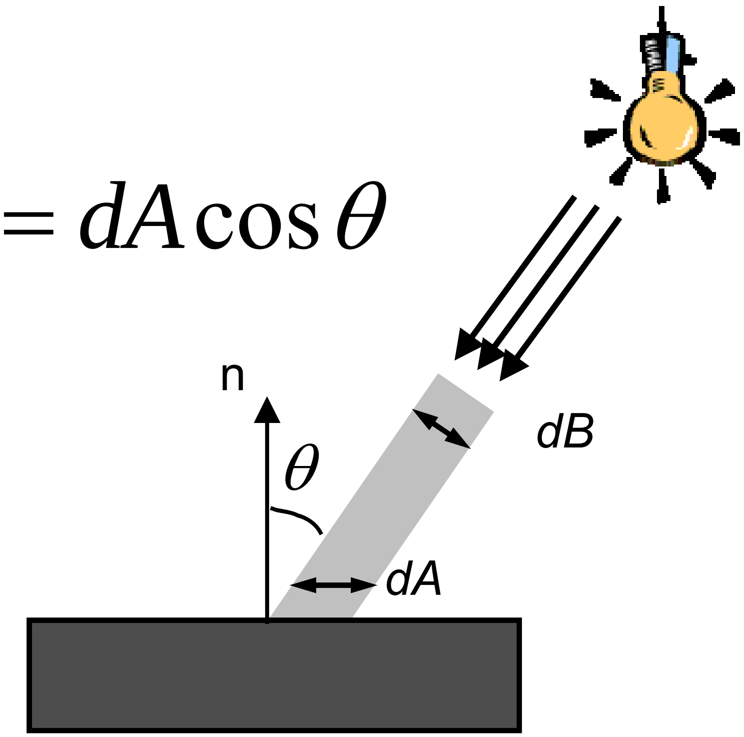
k_d : (diffuse) surface reflectance coefficient

$$k_d \in [0,1]$$

θ : angle between normal & light direction

Proof of Lambert's Cosine Law

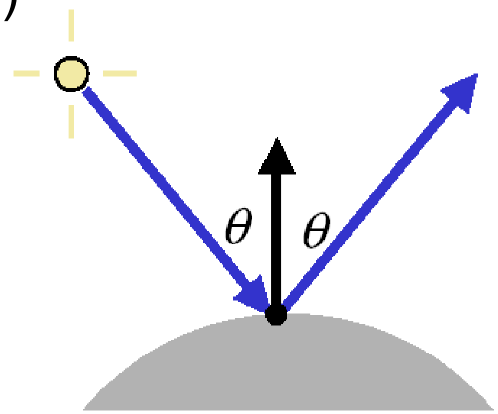
$$dB = dA\cos\theta$$



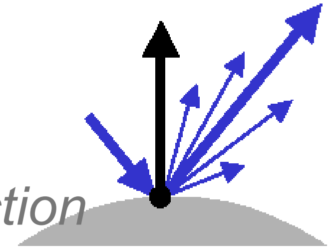
Specular Reflection

Shiny surfaces

- Their appearance changes as the viewpoint moves
- They have glossy "specular highlights" (specularities)
- A mirror is a perfect specular reflector
  - *Incoming light is reflected about normal direction*
  - *Nothing reflected in other directions*



- Most surfaces are imperfect specular reflectors
  - *Reflect light rays in cone about perfect reflection direction*

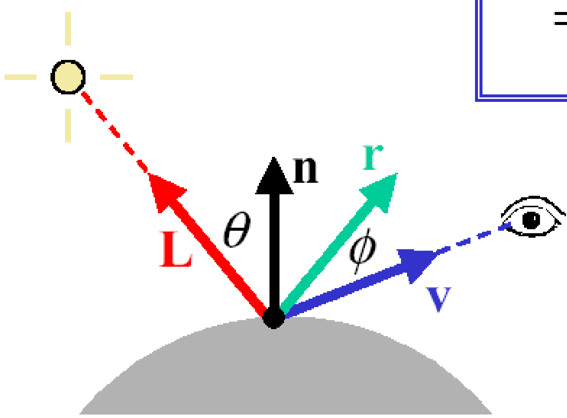


The Phong Model

A common specular reflection term is added

- It is purely empirical – there is no physical basis for it

$$I = I_L k_d \cos\theta + I_L k_s \cos^n \phi$$
$$= I_L k_d (\mathbf{n} \cdot \mathbf{L}) + I_L k_s (\mathbf{r} \cdot \mathbf{v})^n$$



I : resulting intensity

I_L : light source intensity

k_s : (specular) surface reflectance coefficient

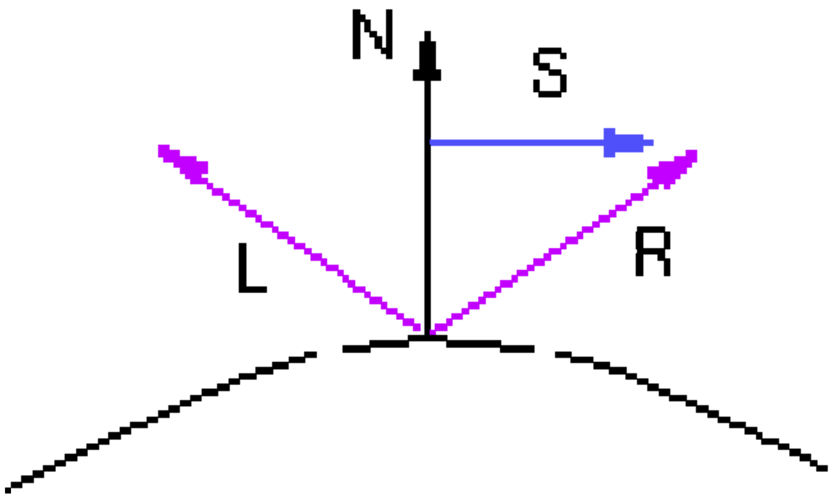
$k_s \in [0,1]$

ϕ : angle between viewing & reflection direction

n : "shininess" factor

Computing R

All vectors are unit length!

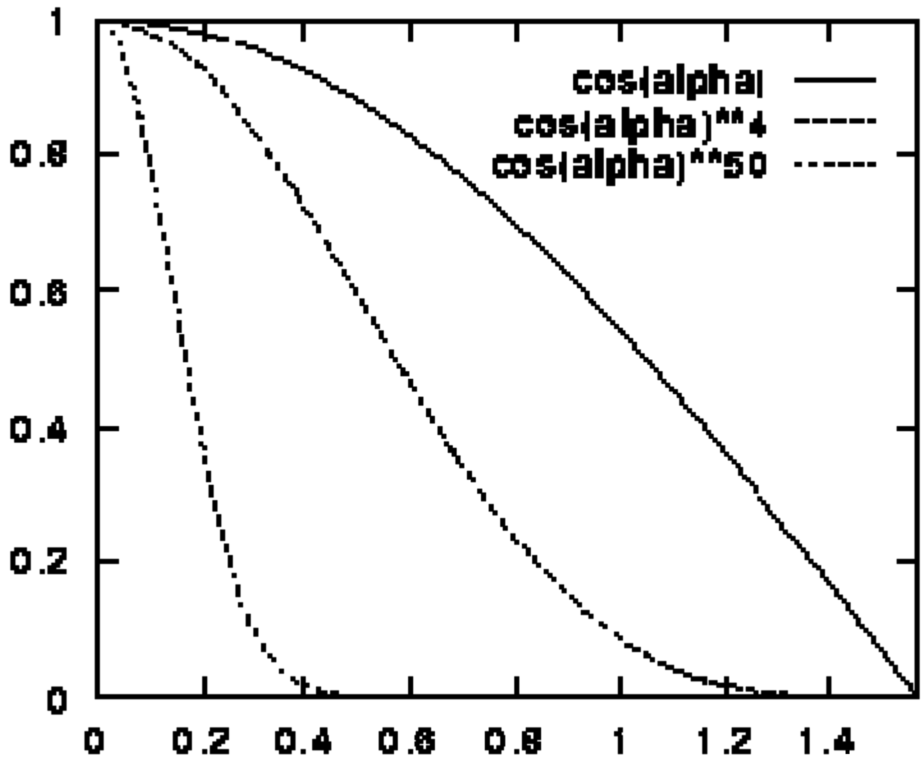


$$R = (N \bullet L)\, N + S$$

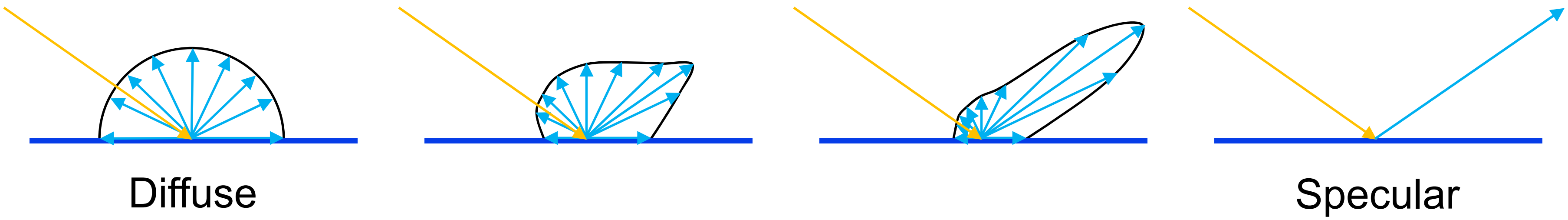
$$S = (N \bullet L)\, N - L$$

$$R = 2N\, (N \bullet L) - L$$

The Effect of the Exponent *n*



Comparison



Phong Model Examples

Diffuse only

Diffuse + Specular (shininess 5)

Diffuse + Specular (shininess 50)

The Ambient Glow

So far, areas not directly illuminated by any light sources appear black

- Looks unnatural
- Lots of ambient light in the real world
- Invent a new light source – a constant ambient "glow"
- Add another term to our illumination equation

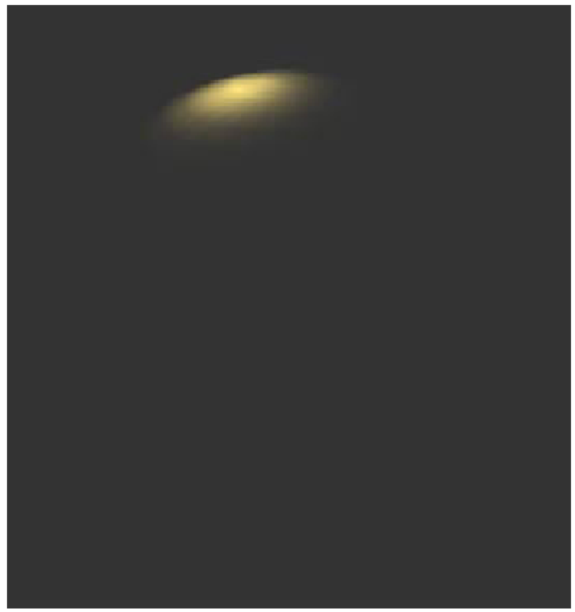
$$I = I_L k_d \cos\theta + I_L k_s \cos^n \phi + I_a k_a$$

I_a : ambient light intensity

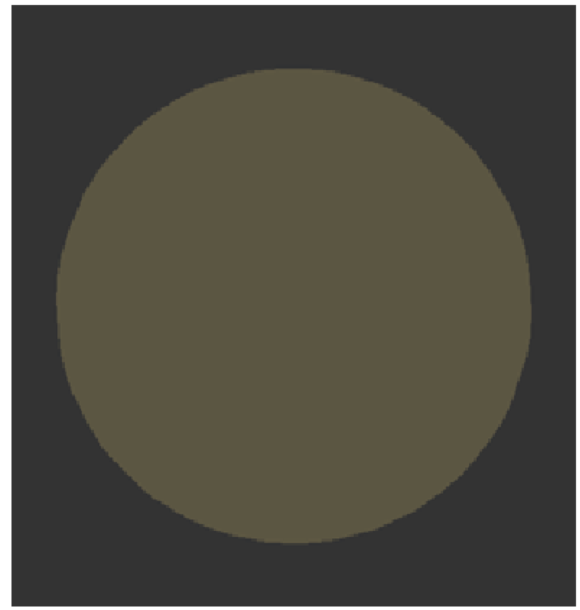
k_a : (ambient) surface reflectance coefficient

Our Three Basic Components of Illumination

Diffuse

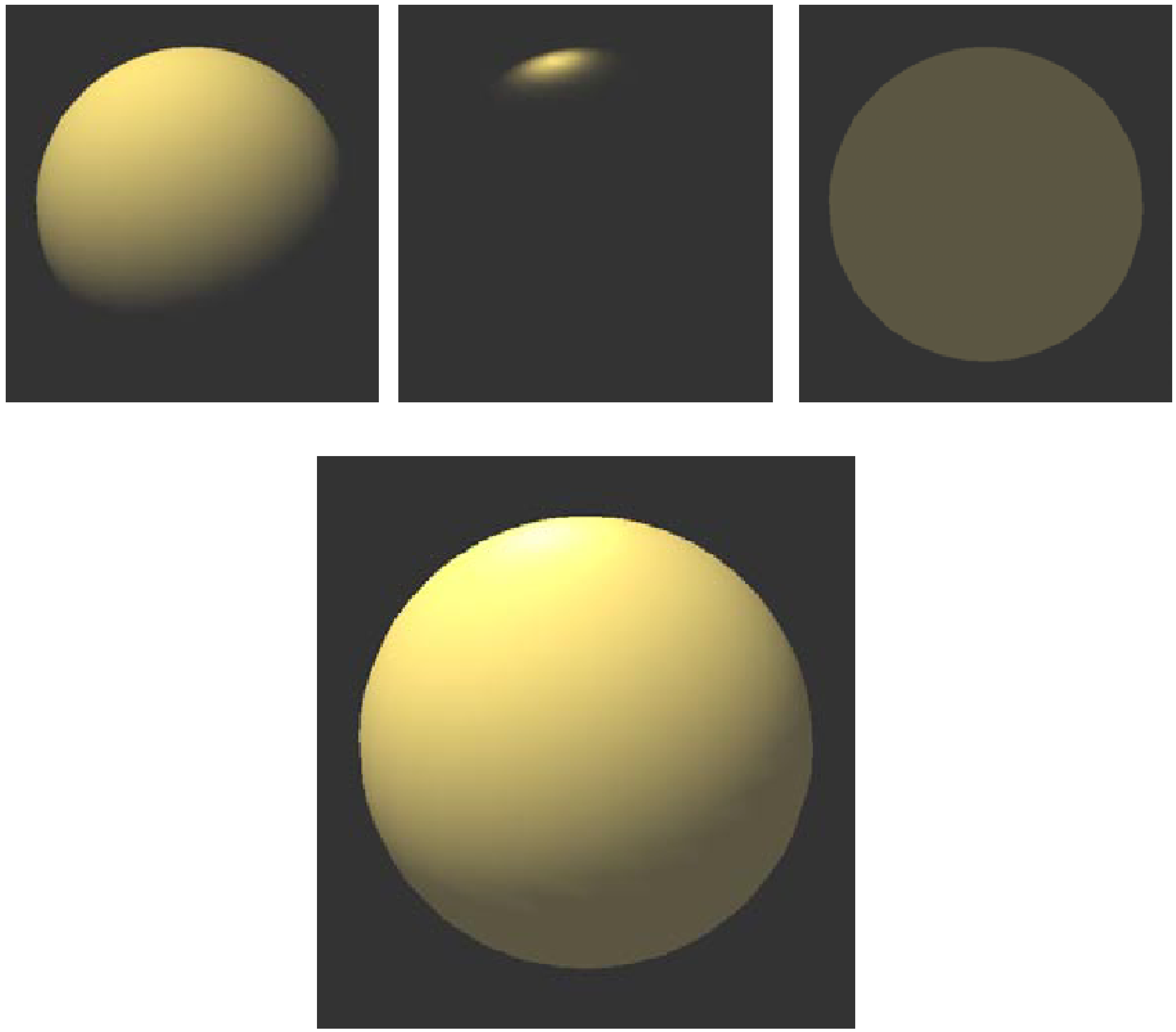


Specular



Ambient

Combined for the Final Result



Lights and Materials

Light properties

$$\underbrace{I_{d(iffuse)},\ I_{s(pecular)}}_{\text{Add Specular Light}},\ I_{a(mbient)}$$

Material properties:

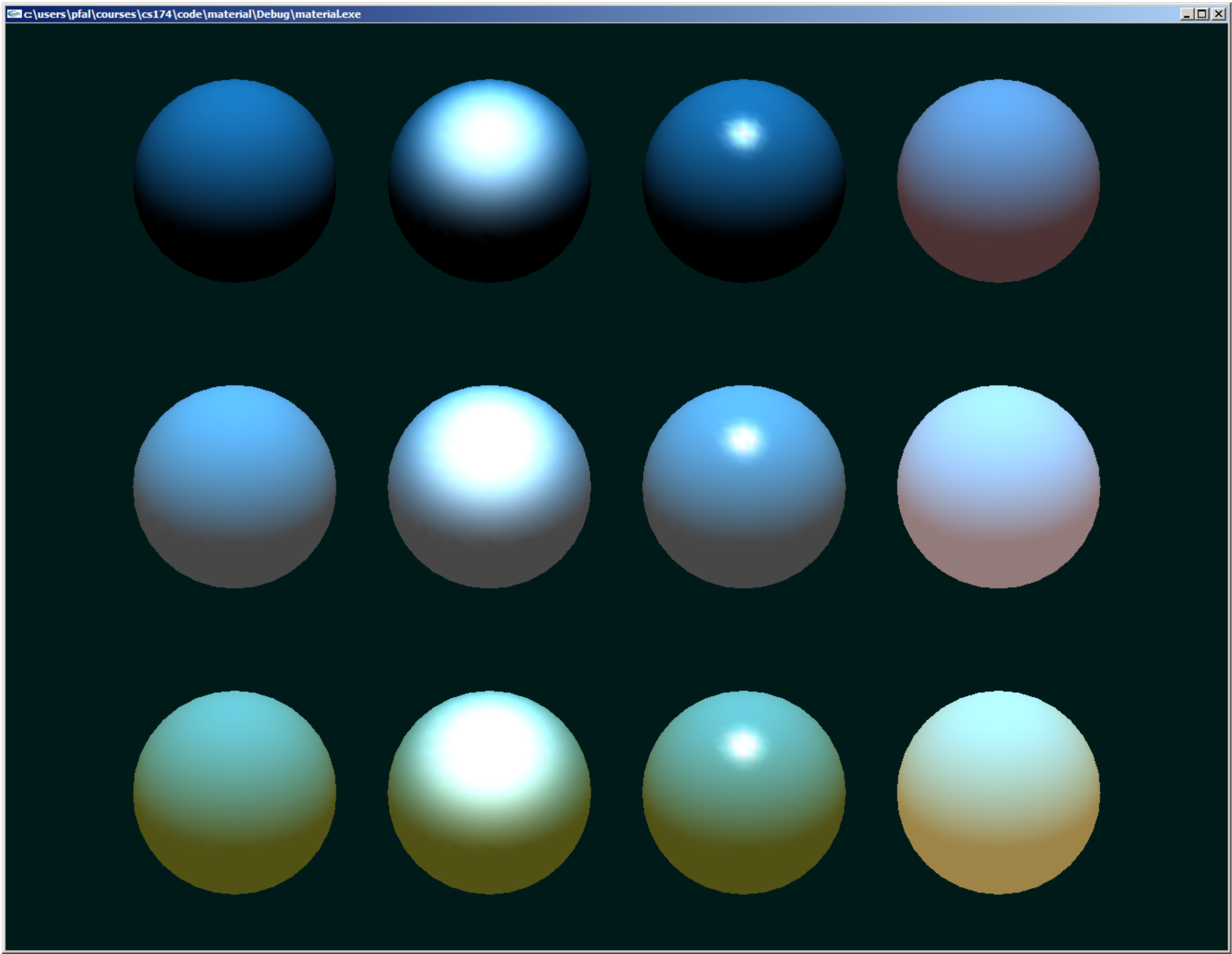
$$k_{d(iffuse)},\ k_{s(pecular)},\ k_{a(mbient)}$$

$$I_r = I_{d\_r} k_{d\_r} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_r} k_{s\_r} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_r} k_{a\_r}$$

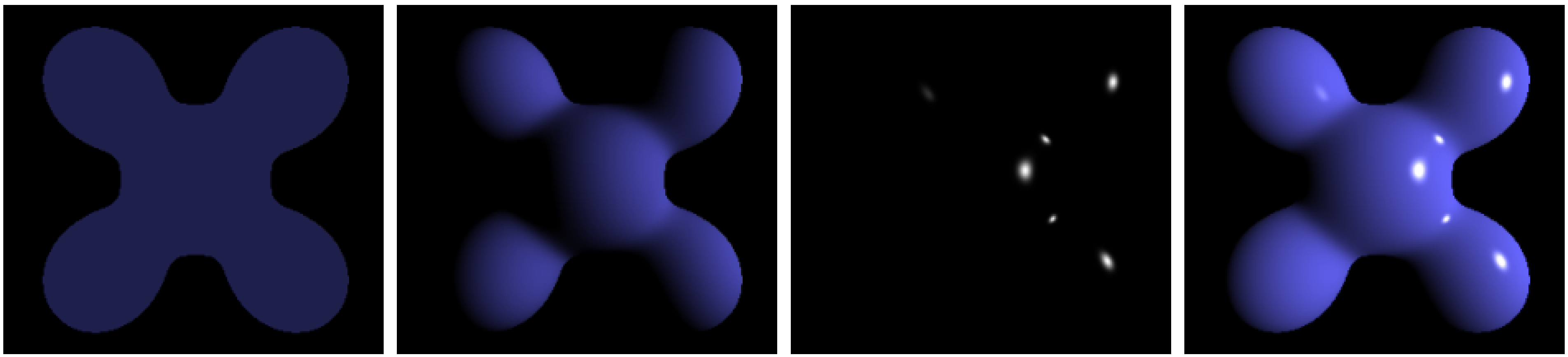
$$I_g = I_{d\_g} k_{d\_g} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_g} k_{s\_g} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_g} k_{a\_g}$$

$$I_b = I_{d\_b} k_{d\_b} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_b} k_{s\_b} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_b} k_{a\_b}$$

Other Examples



Another Example



Ambient + Diffuse + Specular = Phong Reflection

Questions

If you shine red light (1,0,0) on a diffuse white object (1,1,1) what color does the object appear to have?

What if you shine red light (1,0,0) on a diffuse green object (0,1,0) ?

If the object is shiny, what is the color of the highlight?

What color is a mirror?

What Color is a Mirror?

Additional Details

$$I_r = I_{d\_r} k_{d\_r} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_r} k_{s\_r} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_r} k_{a\_r}$$

$$I_g = I_{d\_g} k_{d\_g} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_g} k_{s\_g} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_g} k_{a\_g}$$

$$I_b = I_{d\_b} k_{d\_b} (\mathbf{n} \cdot \mathbf{L}) + I_{s\_b} k_{s\_b} (\mathbf{r} \cdot \mathbf{v})^n + I_{a\_b} k_{a\_b}$$

- How can we handle multiple light sources?
  - *Sum the intensity of the individual contributions*
- What should be done if $I > 1$?
  - *Clamp the value of I to 1*
- What should be done if $\mathbf{n} \cdot \mathbf{L} < 0$
  - *Clamp the value of I to 0 or flip the normal*

Shading Polygons

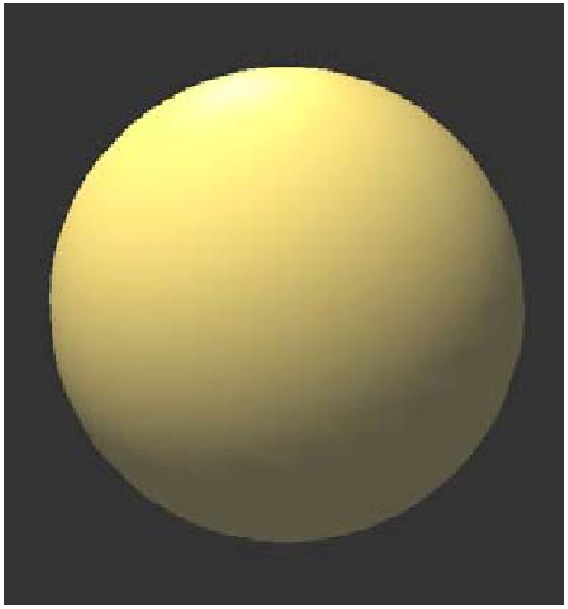
Flat shading

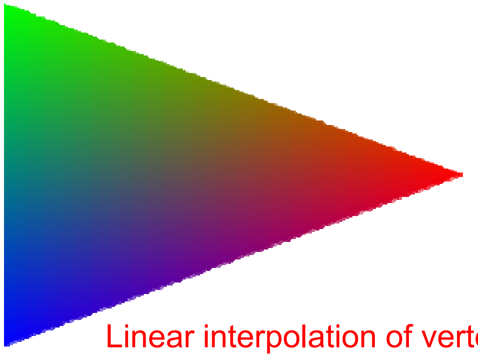
- The model equations are evaluated at surface locations
  - *So where do we apply them?*
- We can evaluate them just once per polygon
  - *Use the resulting color to shade every pixel covered by the polygon*

Shading Polygons

Gouraud shading

- Alternatively, we can evaluate the model equations at every vertex
  - *Linearly interpolate the vertex colors to shade covered pixels*
- Problem: misses details away from the vertices
  - *e.g., specular highlights*



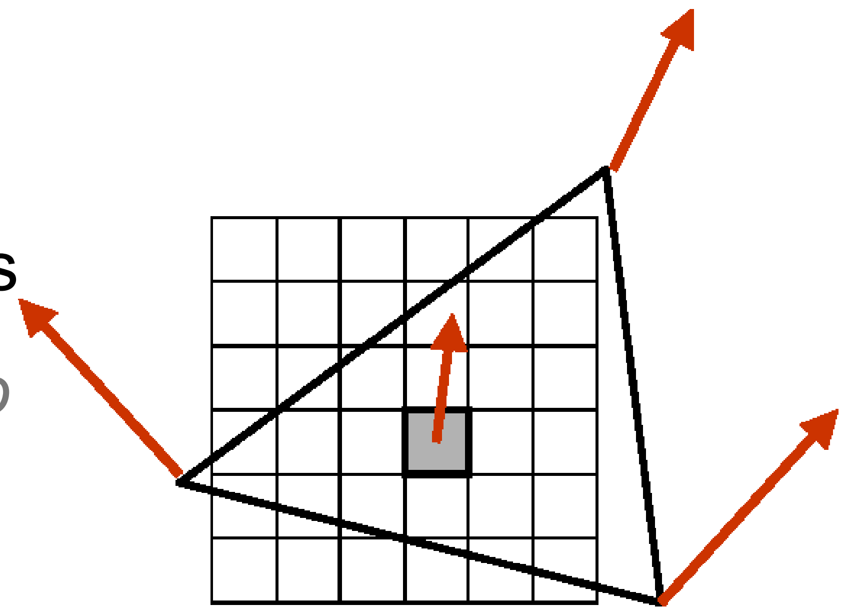


Linear interpolation of vertex colors over a triangle

Shading Polygons

Phong shading

- For every pixel covered by the polygon, interpolate a normal vector from the normal vectors at the vertices
  - *Use interpolated normal to evaluate the model equations at every pixel*
  - *Captures details within polygons*



Summary of the Local Model

The Phong local illumination model

- A sum of diffuse, specular, and ambient terms
- Treat each RGB color channel independently
  - *Light is additive*

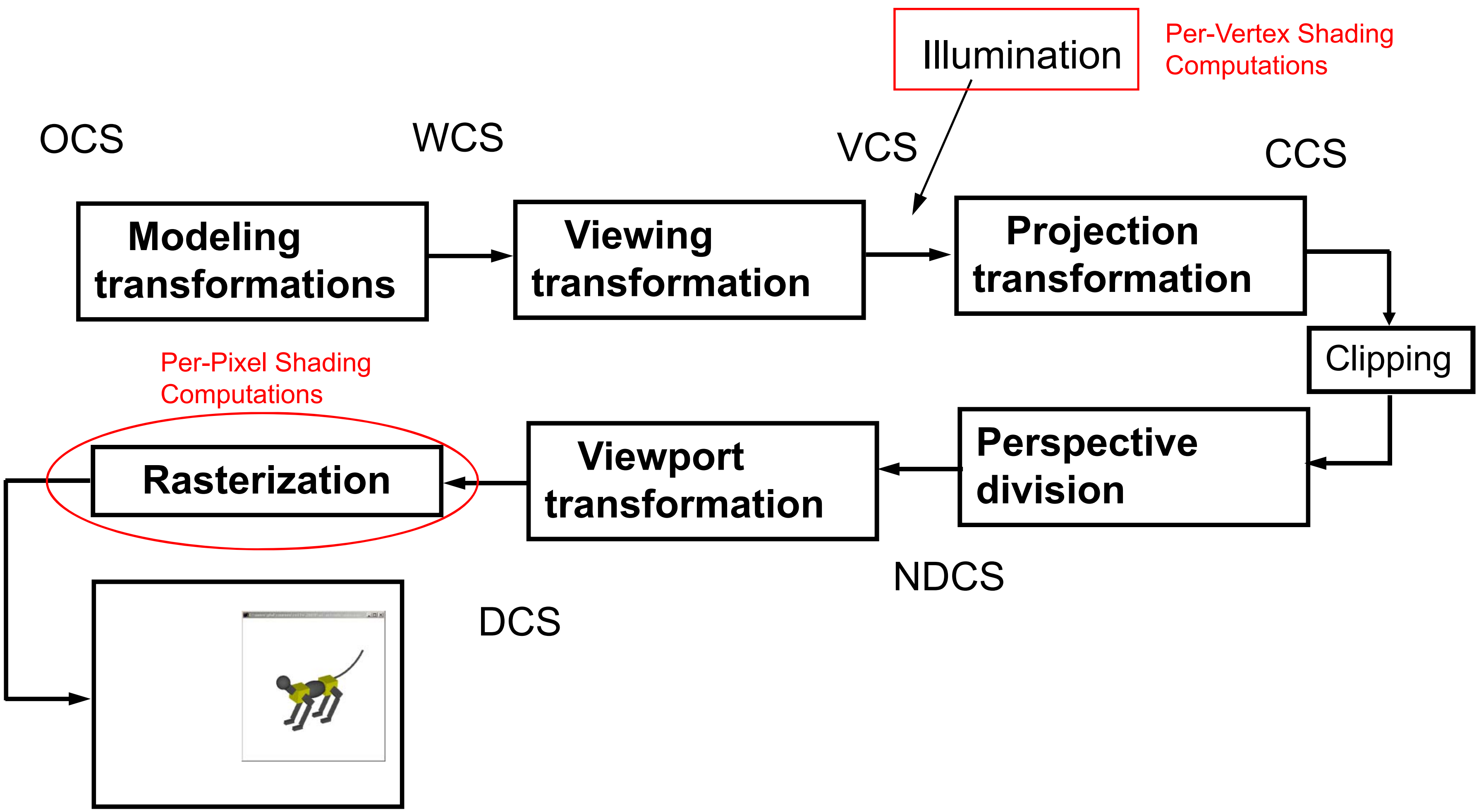
Shading every pixel covered by a polygon

- Flat shading: Constant color
- Gouraud shading: Interpolate vertex colors
- Phong shading: Interpolate vertex normals → pixel color

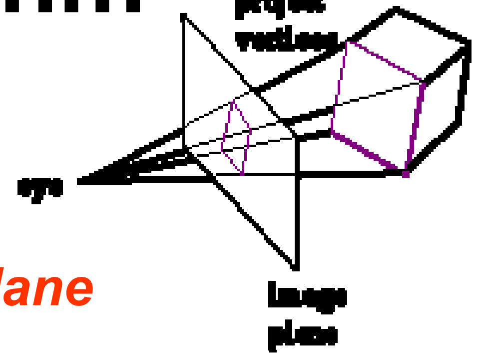
Guerrilla CG Tutorial 03: Smooth Shading

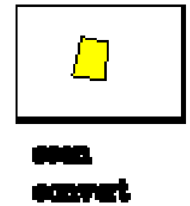
Guerrilla CG Tutorial 04:
Smooth Shading Examples

Illumination in the Graphics Pipeline



Z-Buffer Algorithm





for each polygon in model

  project vertices of polygon onto image plane

  for each pixel inside projected polygon

    calculate pixel z-value

    if z-value is smaller than pixel's z-value currently in z-buffer

        calculate pixel color

        draw pixel

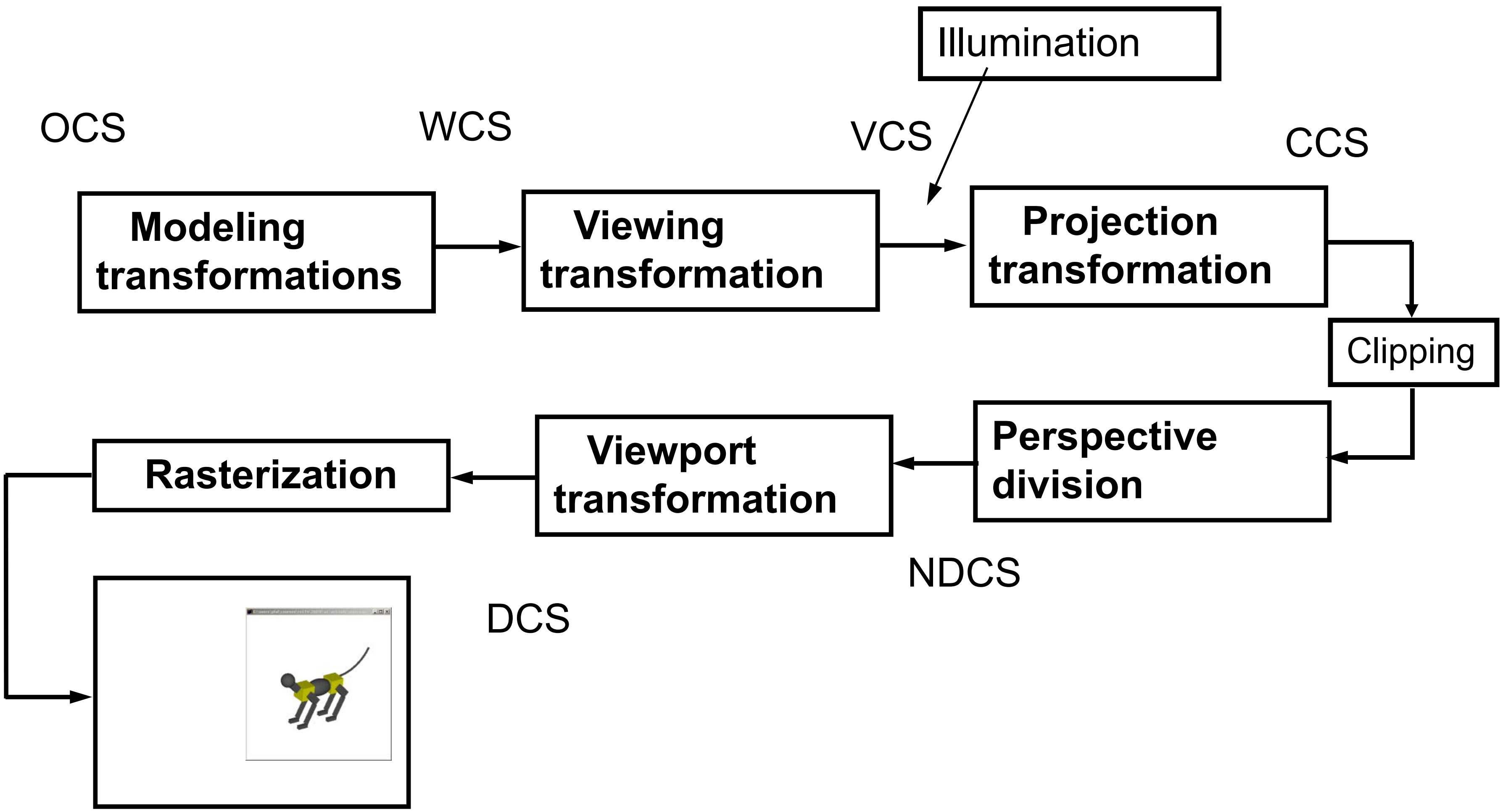
        update pixel z-value in z-buffer

    end

  end

end

Completion of the Z-Buffer Graphics Pipeline



What Have We Ignored?

Some local phenomena

- *Shadows – every point is illuminated by every light source*
- *Attenuation – intensity falls off with square of distance to light source*
- *Transparent objects – light can be transmitted through surfaces*

Global illumination

- *Reflections of objects in other objects*
- *Indirect diffuse light – ambient term is just a hack*

Realistic surface detail

- *An orange sphere doesn’t have the texture of an orange fruit*

Realistic light sources

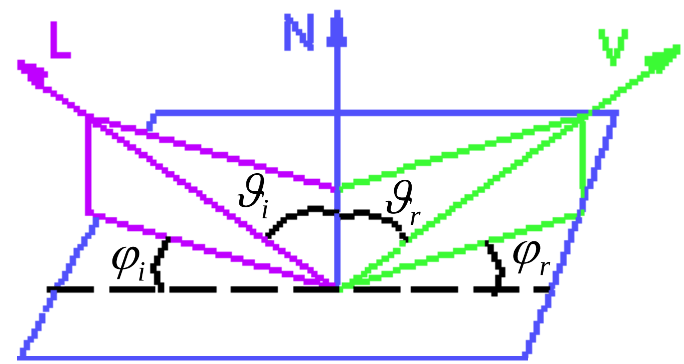
Advanced Concepts

Physics-based illumination models

Bidirectional reflectance distribution function: BRDF

$$\rho(\vartheta_i, \varphi_i, \vartheta_r, \varphi_r, \lambda)$$

λ : light wavelength



Global Illumination

Computing light interface between all surfaces

Radiosity

Ray tracing

Courtesy of Henrik Wann Jensen

Radiosity

Physics-based

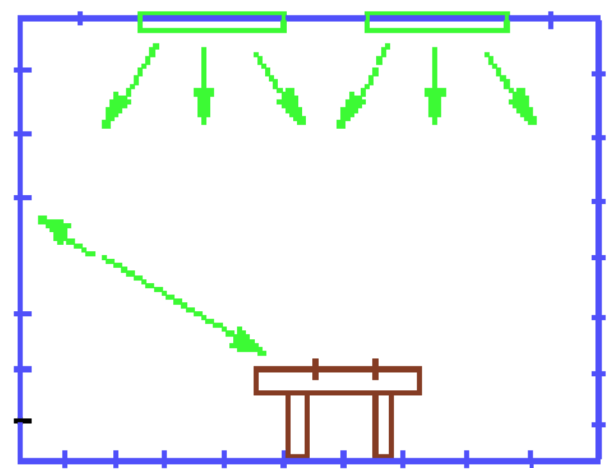
- heat transfer
- illumination engineering

Suited for diffuse reflection

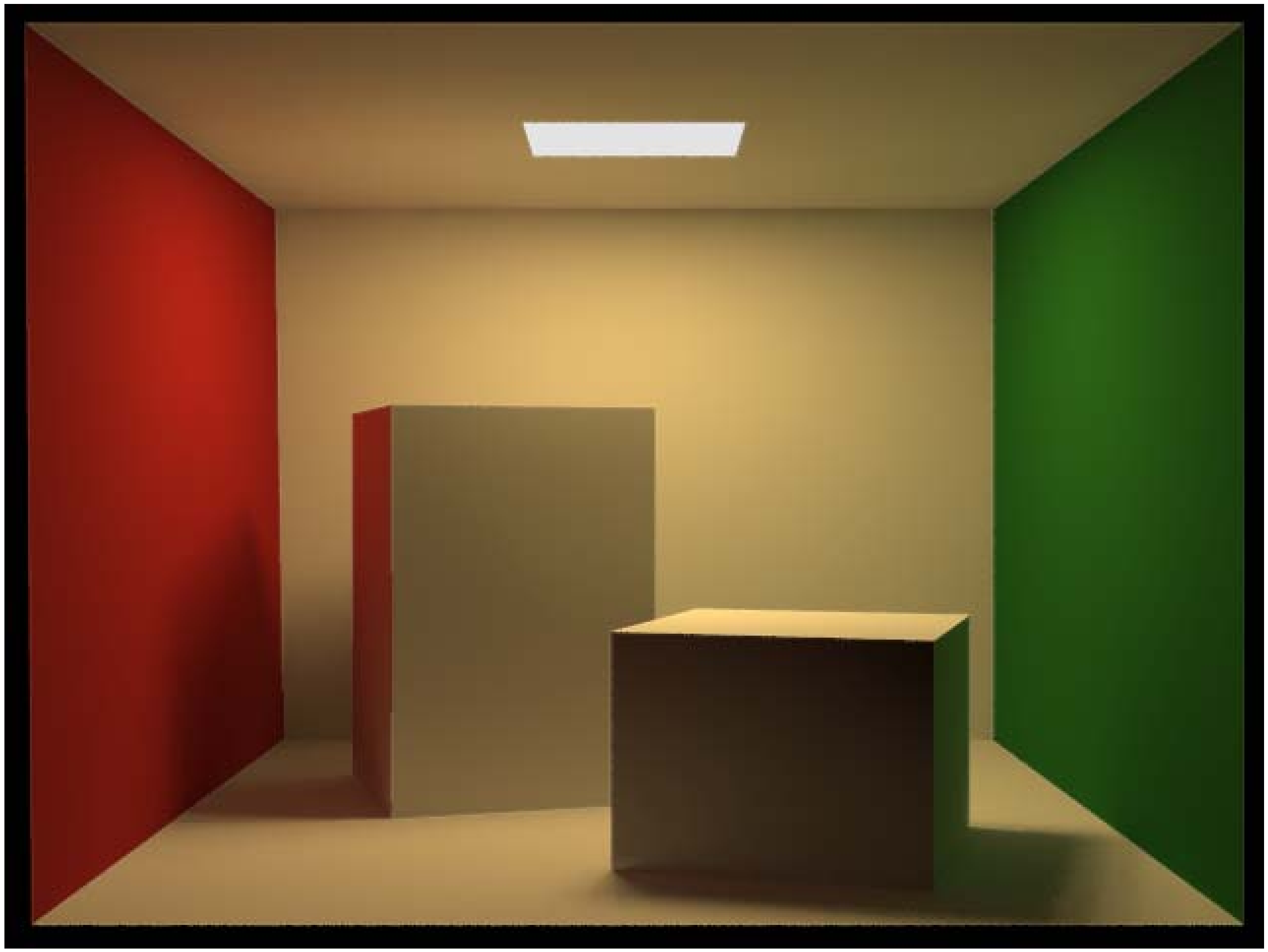
- Infinite inter-reflections

Area light sources

- Soft shadows



Example



Radiosity Algorithm

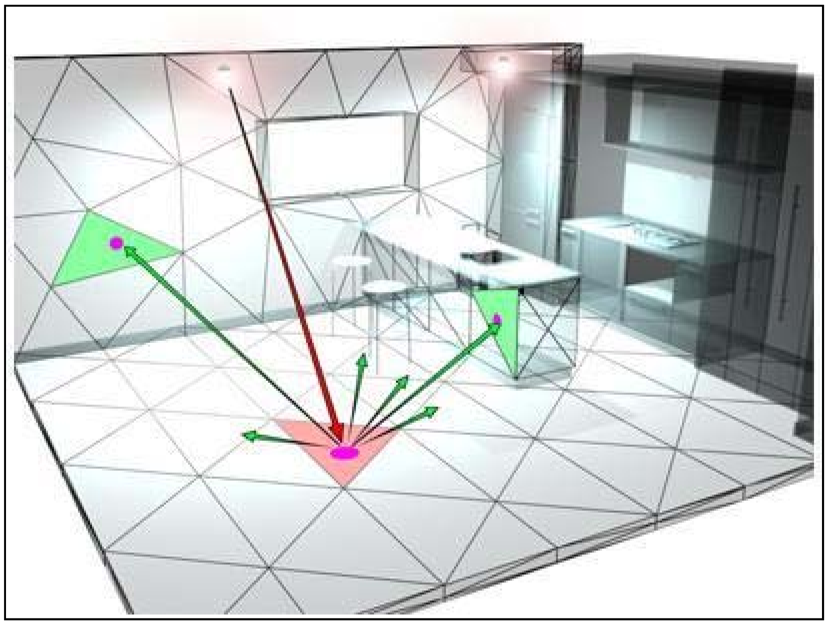
Break scene into small patches (polygons)

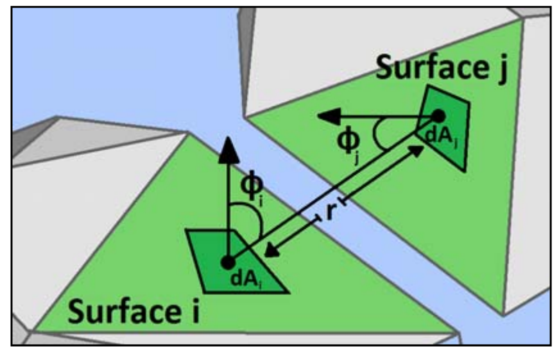
Assume uniform reflection and emission per patch

Energy balance for all patches:

Light leaving surface = Emitted light + Reflected light

Scene Polygonalization and Form Factors





Notation

- **Flux**: energy per unit time (W)
- **Radiosity** B: exiting flux density (W/m^2) for surfaces

  E: exiting flux density for light sources
- **Reflectivity** R: fraction of incoming light that is reflected (unitless)
- **Form factor** $F_{i,j}$: fraction of energy leaving polygon A_i and arriving at polygon A_j
  - *determined by the geometry of polygons i and j*

Energy Balance

$$\overbrace{B_i A_i}^{\substack{\text{Light} \\ \text{leaving surface}}} = \overbrace{E_i A_i}^{\substack{\text{Emitted} \\ \text{light}}} + \overbrace{R_i \sum_j B_j F_{j,i} A_j}^{\substack{\text{Reflected} \\ \text{light}}}$$

Therefore

$$B_i = E_i + R_i \sum_j B_j F_{j,i} \frac{A_j}{A_i}$$

Now $F_{j,i} A_j = F_{i,j} A_i$ (form-factor reciprocity)

Therefore

$$B_i = E_i + R_i \sum_j B_j F_{i,j}$$

or

$$E_i = B_i - R_i \sum_j B_j F_{i,j}$$

Linear System

Assume constant radiosity polygons (n of them)

Compute form factors F_{ij} for $1 \leq i,j \leq n$

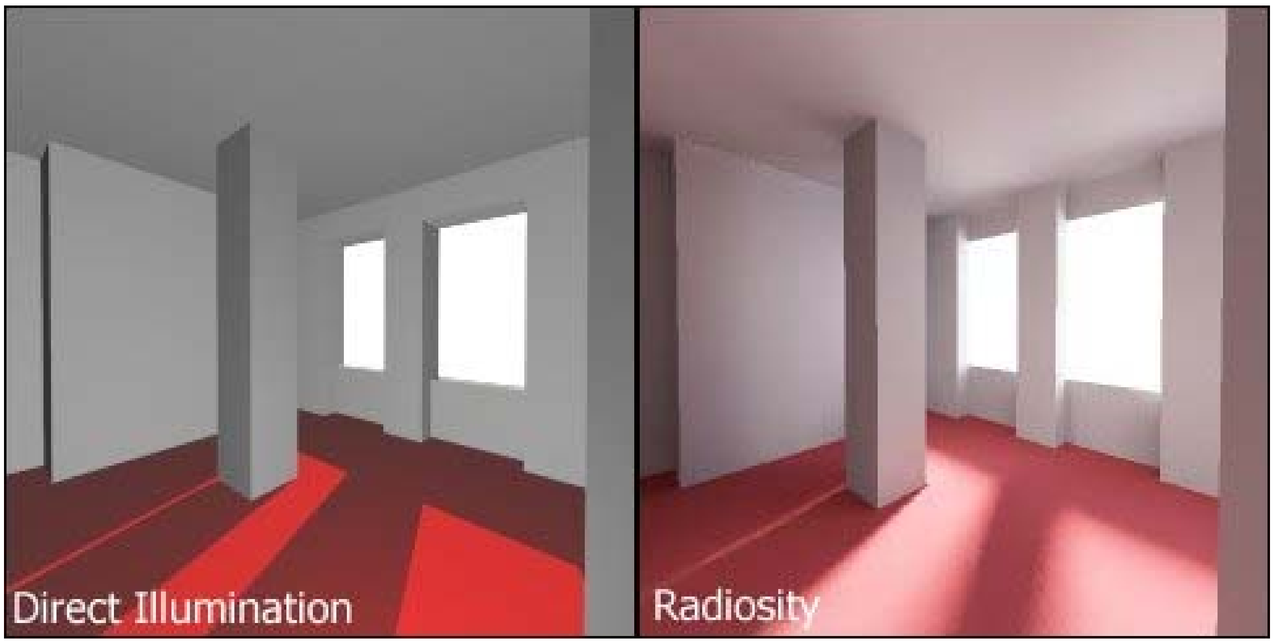
Assemble a system of n linear equations:

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_{n-1} \\ E_n \end{bmatrix} = \begin{bmatrix} 1 - R_1 F_{1,1} & -R_1 F_{1,2} & \dots & -R_1 F_{1,n} \\ -R_2 F_{2,1} & 1 - R_2 F_{2,2} & \dots & -R_2 F_{2,n} \\ \vdots & \vdots & \vdots & \vdots \\ -R_{n-1} F_{n-1,1} & \dots & 1 - R_{n-1} F_{n-1,n-1} & -R_{n-1} F_{n-1,n} \\ -R_n F_{n,1} & \dots & -R_n F_{n,n-1} & 1 - R_n F_{n,n} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_{n-1} \\ B_n \end{bmatrix}$$

n x n matrix

Solve the system for the exiting fluxes B_i

Comparison Between Direct Illumination and Radiosity



Shadow Details

Radiosity Factory

Museum

Radiosity Summary

Object space algorithm

Suited for diffuse (inter-)reflections

Area light sources

Nice, soft shadows