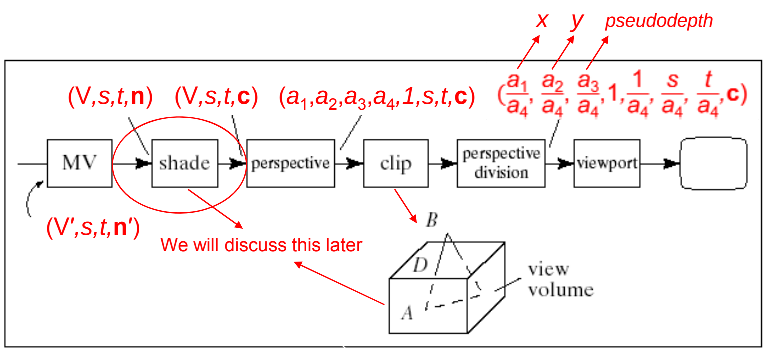
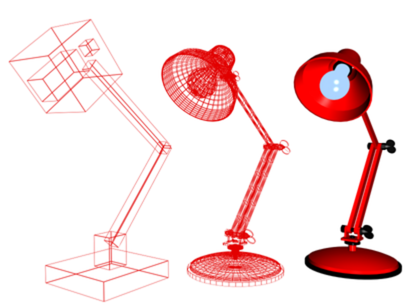
Reminder: The Pipeline



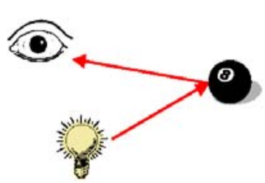


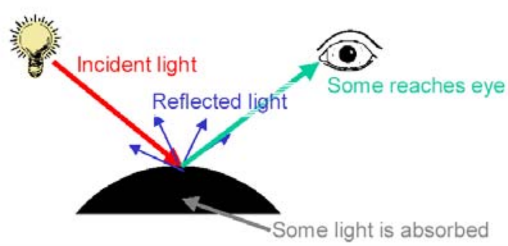
Determining and Object's Appearance

Ultimately, we're interested in modeling light transport in scene

- Light is emitted from light sources and interacts with surfaces
- on impact with an object, some is reflected and some is absorbed
- distribution of reflected light determines "finish" (matte, glossy, …)
- composition of light arriving at eye determines what we see

Let's focus on the local interaction of light with single surface point





Modeling Light Sources

In general, light sources have a very complex structure

- incandescent light bulbs, the sun, CRT monitors, …

To simplify things, we'll focus on point light sources for now

- light source is a single infinitesimal point
- emits light equally in all directions (isotropic illumination)
- outgoing light is set of rays originating at light point

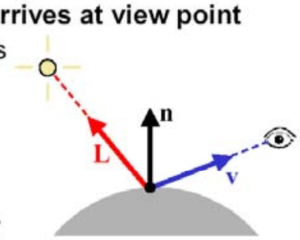
Creating lights in OpenGL

- glEnable(GL_LIGHTING) — turn on lighting of objects
- glEnable(GL_LIGHT0) — turn on specific light
- glLight(…) — specify position, emitted light intensity, …

Basic Local Illumination Model

We're only interested in light that finally arrives at view point

- a function of the light & viewing positions
- and local surface reflectance



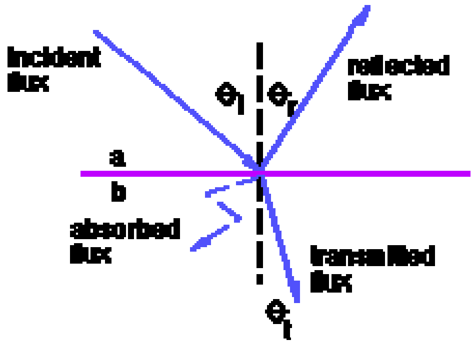
Characterize light using RGB triples

- can operate on each channel separately

Given a point, compute intensity of reflected light

Local Illumination Physics

Law of reflection and Snell's law of refraction

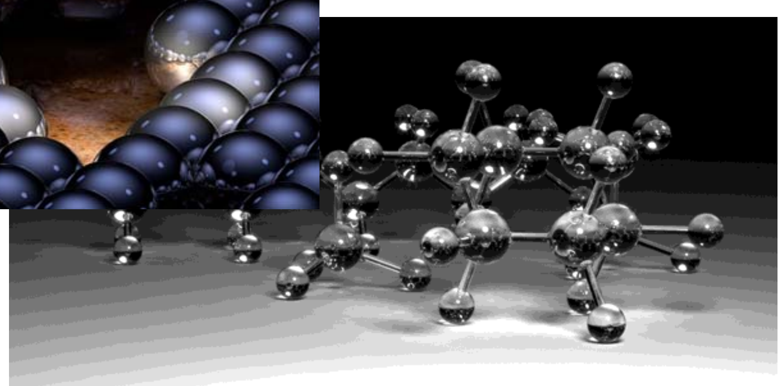


$$\theta_i = \theta_r$$

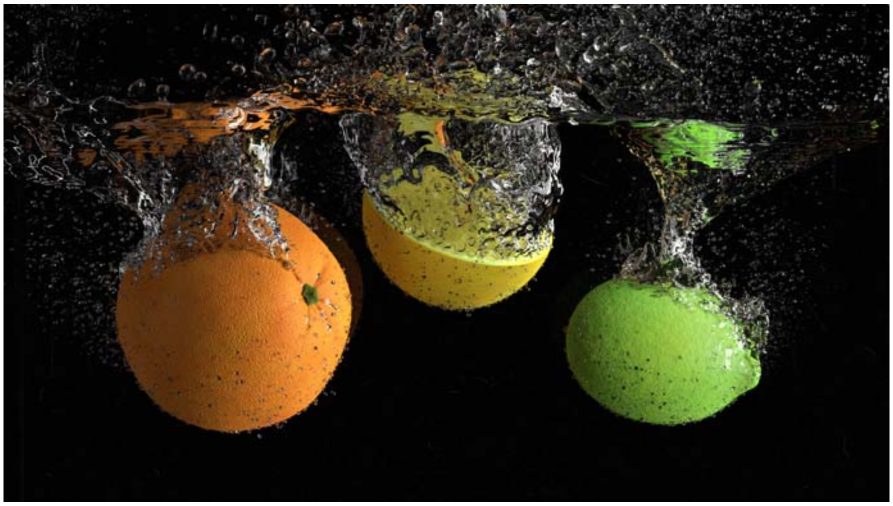
$$\frac{n_b}{n_a} = \frac{\sin(\theta_i)}{\sin(\theta_t)}$$

n: Refractive index

Reflection and Refraction
(Ray Tracing Rendering)

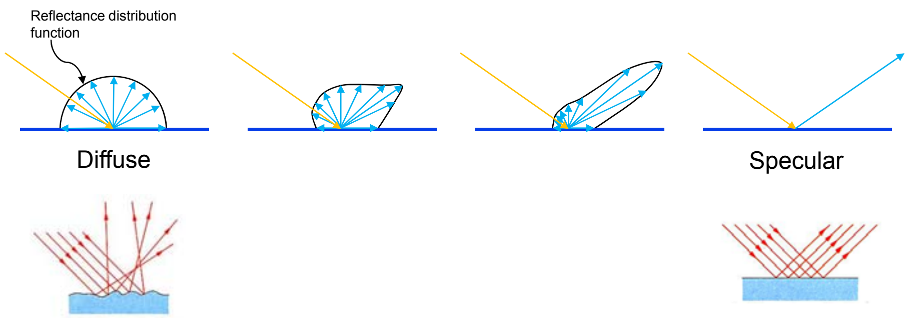


Refraction



What Are We Trying to Model ?

From diffuse to specular reflectance



Diffuse Reflection

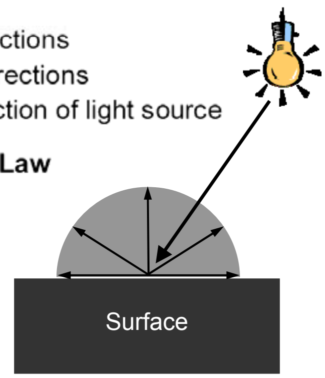
This is the simplest kind of reflection

- also called Lambertian reflection
- models dull, matte surfaces — materials like chalk

Ideal diffuse reflection

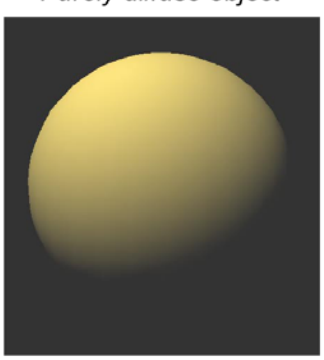
- scatters incoming light equally in all directions
- identical appearance from all viewing directions
- reflected intensity depends only on direction of light source

Light is reflected according to Lambert's Law

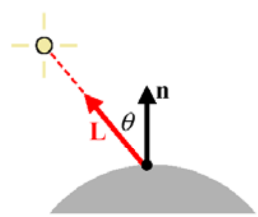


Lambert's Law for Diffuse Reflection

Purely diffuse object



$$\boxed{\begin{aligned} I &= I_L k_d \cos\theta \\ &= I_L k_d (\mathbf{n}\cdot\mathbf{L}) \end{aligned}}$$



I : resulting intensity

I_L : light source intensity

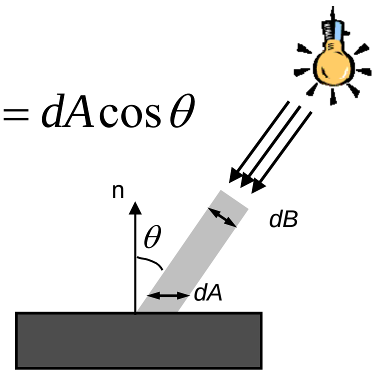
k_d : (diffuse) surface reflectance coefficient

$k_d \in [0,1]$

θ : angle between normal & light direction

Proof of Lambert’s Cosine Law

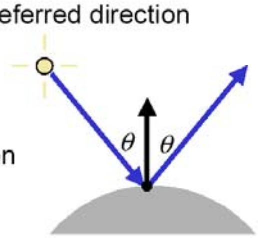
$$dB = dA \cos\theta$$



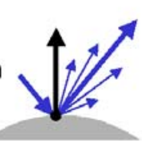
Specular Reflection

Diffuse reflection is nice, but many surfaces are shiny
- their appearance changes as the viewpoint moves
- they have glossy specular highlights (or specularities)
- because they reflect light coherently, in a preferred direction

A mirror is a perfect specular reflector
- incoming ray reflected about normal direction
- nothing reflected in any other direction



Most surfaces are imperfect specular reflectors
- reflect rays in cone about perfect reflection direction

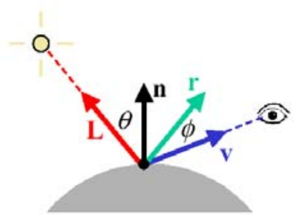


Phong Illumination Model

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

One particular specular reflection model

- quite common in practice
- it is purely empirical
- there's *no physical basis* for it



I : resulting intensity

I_L : light source intensity

k_s : (specular) surface reflectance coefficient

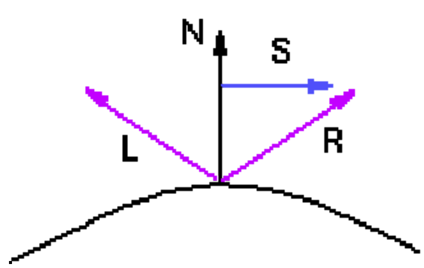
$k_s \in [0,1]$

ϕ : angle between viewing & reflection direction

n : "shininess" factor

Computing R

All vectors are unit length!

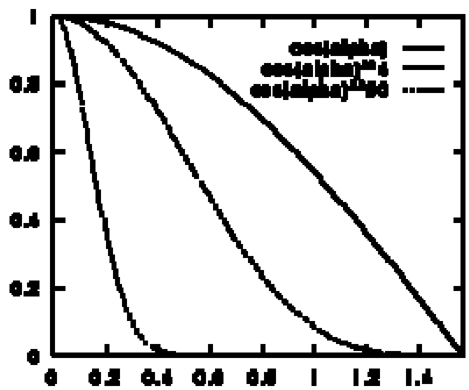


R = (N•L) N + S

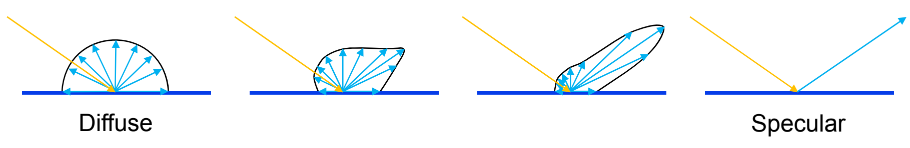
S = (N•L) N – L

R = 2N (N•L) – L

The Effect of the Exponent *n*



Comparison



Examples of Phong Specular Model

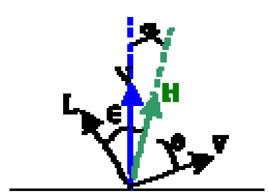
Diffuse only | *Diffuse + Specular (shininess 5)* | *Diffuse + Specular (shininess 50)*

The Blinn-Torrance Specular Model

Agrees better with experimental results

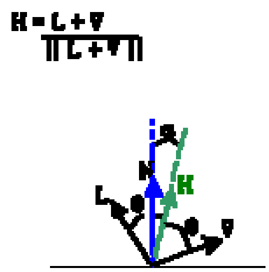
$I_s = I_L K_s (H \cdot V)^n$

Halfway vector H $\qquad H = \frac{L + V}{\| L - V \|}$



Advantages of the Blinn-Torrance Specular Model

- Theoretical basis
- N·H cannot be negative if N·L > 0 and N·V > 0
- If the light is directional and we have orthographic projection then N·H is constant



The Ambient Glow

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

- this tends to look rather unnatural
- in the real world, there's lots of ambient light

To compensate, we invent new light source

- assume there is a constant ambient "glow"
- this ambient glow is *purely fictitious*

Just add in another term to our illumination equation

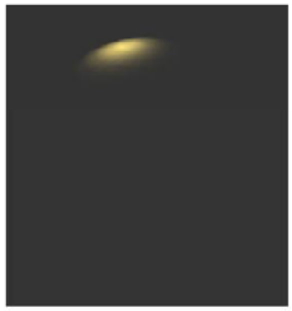
$$I = I_L k_d \cos\theta + I_L k_s \cos^n \phi + I_a k_a$$

I_a : ambient light intensity

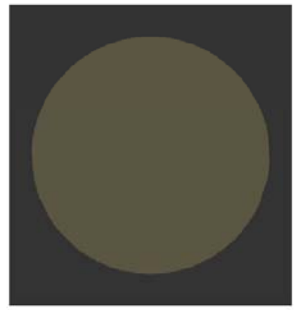
k_a : (ambient) surface reflectance coefficient

Our Three Basic Components of Illumination

Diffuse

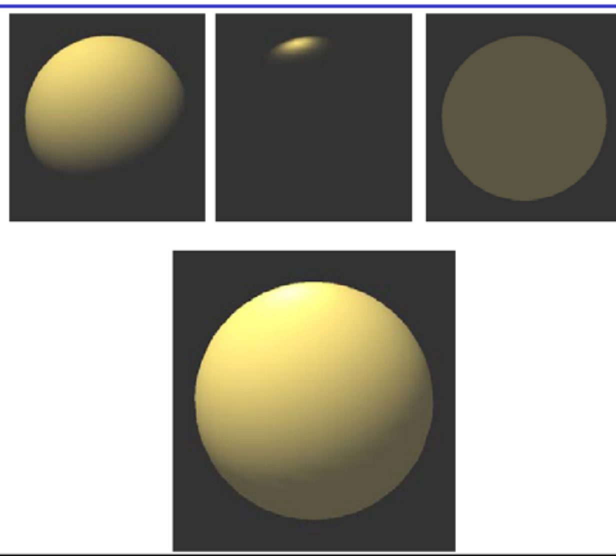


Specular



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:

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

$$I_r = I_{d\_r}k_{d\_r}(N \cdot L) + I_{s\_r}k_{s\_r}(R \cdot V)^n + I_{a\_r}k_{a\_r}$$

$$I_g = I_{d\_g}k_{d\_g}(N \cdot L) + I_{s\_g}k_{s\_g}(R \cdot V)^n + I_{a\_g}k_{a\_g}$$

$$I_b = I_{d\_b}k_{d\_b}(N \cdot L) + I_{s\_b}k_{s\_b}(R \cdot V)^n + I_{a\_b}k_{a\_b}$$

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?

Special cases

$$I_r = I_{d\_r}k_{d\_r}(N\cdot L) + I_{s\_r}k_{s\_r}(R\cdot V)^n + I_{a\_r}k_{a\_r}$$

$$I_g = I_{d\_g}k_{d\_g}(N\cdot L) + I_{s\_g}k_{s\_g}(R\cdot V)^n + I_{a\_g}k_{a\_g}$$

$$I_b = I_{d\_b}k_{d\_b}(N\cdot L) + I_{s\_b}k_{s\_b}(R\cdot V)^n + I_{a\_b}k_{a\_b}$$

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

Shading Polygons: Flat Shading

Illumination equations are evaluated at surface locations

- so where do we apply them?

We could just do it once per polygon

- fill every pixel covered by polygon with the resulting color

Shading Polygons: Flat Shading

Illumination equations are evaluated at surface locations

- so where do we apply them?

We could just do it once per polygon

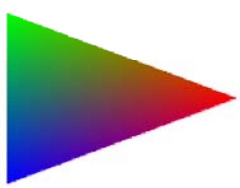
- fill every pixel covered by polygon with the resulting color

OpenGL — glShadeModel(GL_FLAT)

Shading Polygons: Gouraud Shading

Alternatively, we could evaluate at every vertex

- compute color for each covered pixel
- linearly interpolate colors over polygon



Misses details that don't fall on vertex

- specular highlights, for instance

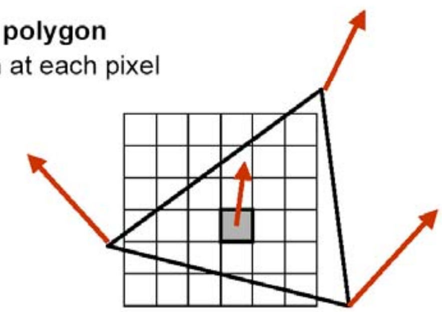
OpenGL — glShadeModel(GL_SMOOTH)

Shading Polygons: Phong Shading

Don't just interpolate colors over polygons

Interpolate surface normal over polygon

- evaluate illumination equation at each pixel

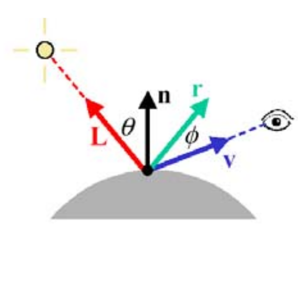


Summarizing the Shading Model

We describe local appearance with illumination equations

- consists of a sum of set of components — light is additive
- treat each wavelength independently
- currently: diffuse, specular, and ambient terms

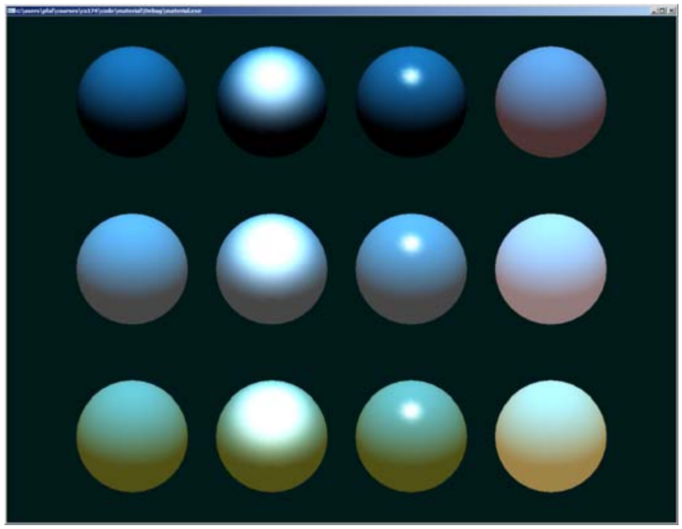
$$I = I_L k_d \cos\theta + I_L k_s \cos^n \phi + I_a k_a$$



Must shade every pixel covered by polygon

- flat shading: constant color
- Gouraud shading: interpolate corner colors
- Phong shading: interpolate corner normals

Examples



Guerrilla CG Tutorial 03: Smooth Shading

Guerrilla CG Tutorial 04: Smooth Shading Examples

Problems with Shading Algorithms

Orientation dependence

Silhouettes

Perspective distortion

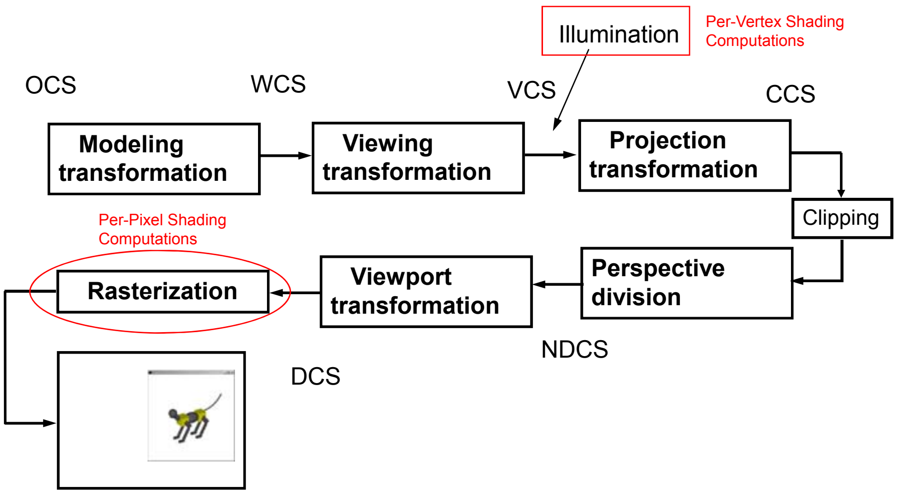
- It happens in screen space, so need to use hyperbolic interpolation

T-vertices

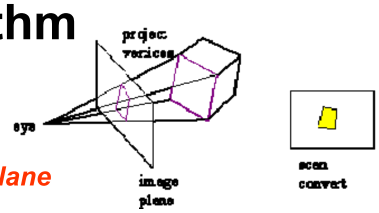
- If you do not have smooth normals, color changes if polygon order changes

Generation of vertex normals

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

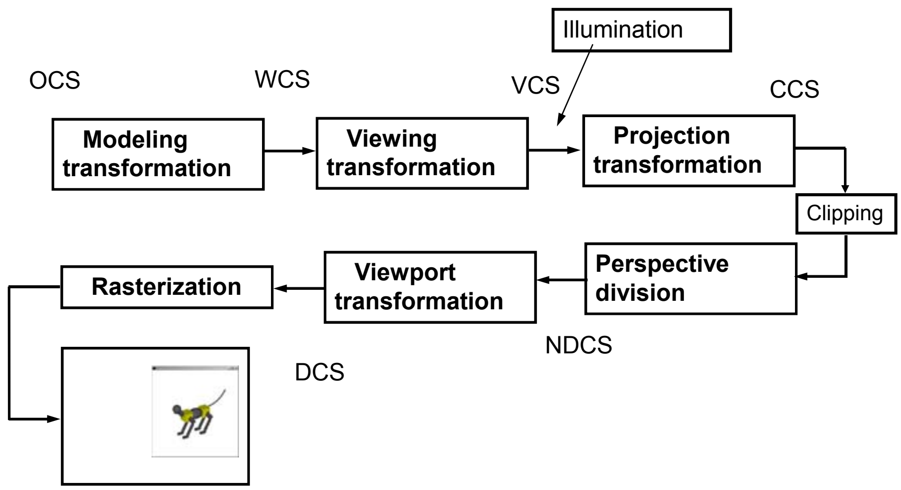
if z-value is smaller than pixel's z-value currently in z-buffer
calculate pixel color
draw pixel
update pixel z-value in z-buffer

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
- transparent objects — light can be transmitted through surface

Global illumination

- reflections of objects in other objects
- indirect diffuse light — ambient term is just a hack

Realistic surface detail

- can make an orange sphere
- but it doesn't have the texture of the real fruit

Realistic light sources

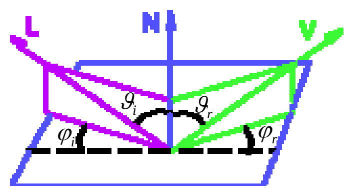
Advanced Concepts

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

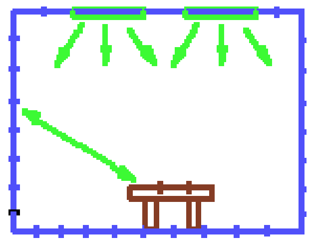
- heat transfer
- illumination engineering

Suited for diffuse reflection

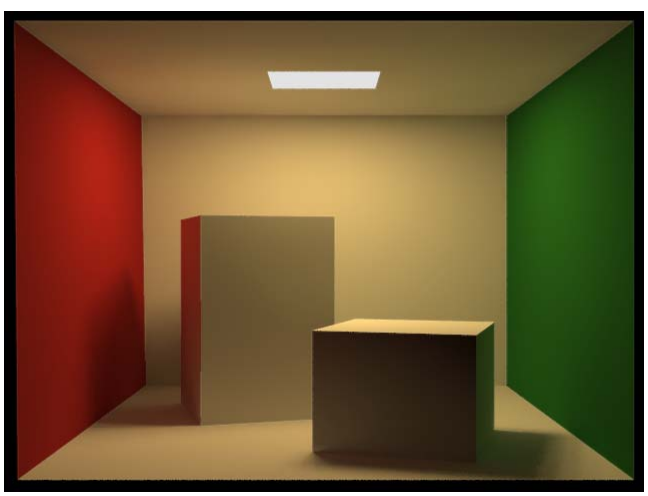
- Infinite inter-reflections

Area light sources

- Soft shadows



Example



Radiosity Algorithm

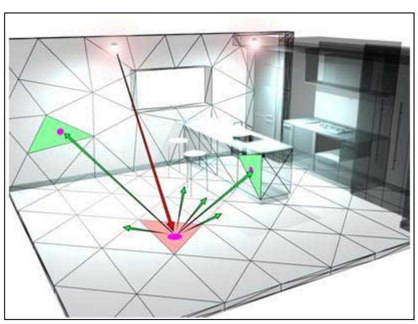
Break scene into small patches (polygons)

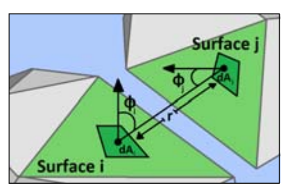
Assume uniform reflection and emission per patch

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

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

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 $1 \le i,j \le n$

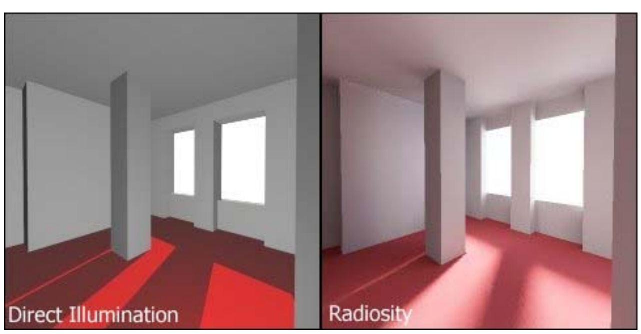
Assemble a system of n linear equations:

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_{n-1} \\ E_n \end{bmatrix} = \begin{bmatrix} 1-R_1F_{1,1} & -R_1F_{1,2} & \cdots & -R_1F_{1,n} \\ -R_2F_{2,1} & 1-R_2F_{2,2} & \cdots & -R_2F_{2,n} \\ \vdots & \vdots & \vdots & \vdots \\ -R_{n-1}F_{n-1,1} & \cdots & 1-R_{n-1}F_{n-1,n-1} & -R_{n-1}F_{n-1,n} \\ -R_nF_{n,1} & \cdots & -R_nF_{n,n-1} & 1-R_nF_{n,n} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_{n-1} \\ B_n \end{bmatrix}$$

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*