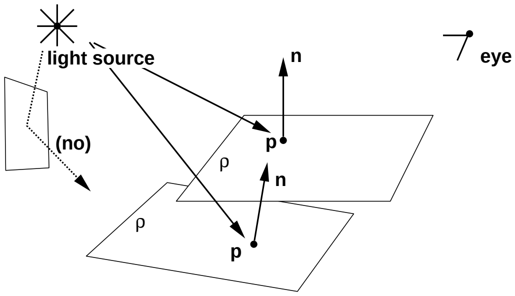
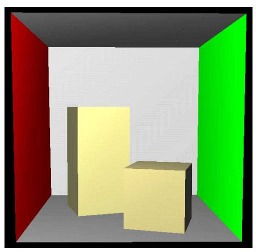
## Lecture 5: Thursday, 23 September 1999

Today: Illumination Models
Local (FvDFHP §14.1.1)

Also called *lighting, shading* models



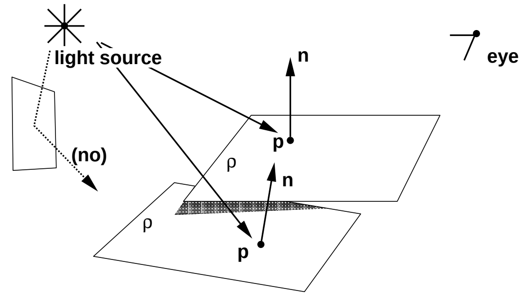

One or more "point" light sources
No occlusion (other than back-face determination)
*primary* light sources only (no reflection)



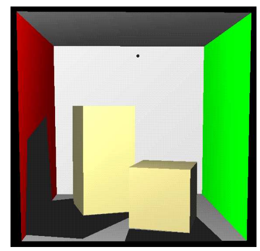


## Types of Illumination Models

Semi-Local



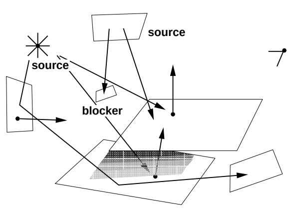

Shadow-tests for blocked *primary* sources
Point light sources yield *hard* shadows
No *secondary* light sources



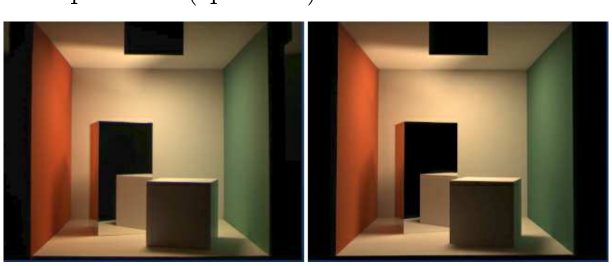


## Types of Illumination Models

Global (Ray-Tracing, Radiosity, Radiance)



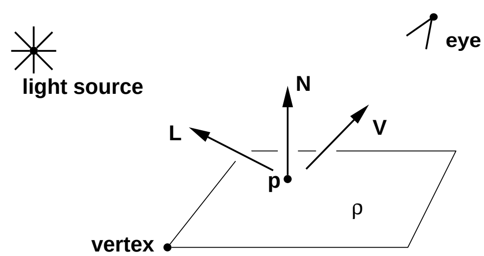

point, area, even volumetric light sources
handles *soft* shadows (penumbrae)
secondary, tertiary, etc., light sources
comprehensive treatment of occlusion
view-independent (diffuse) effects
view-dependent (specular) effects





## Local Illumination Models

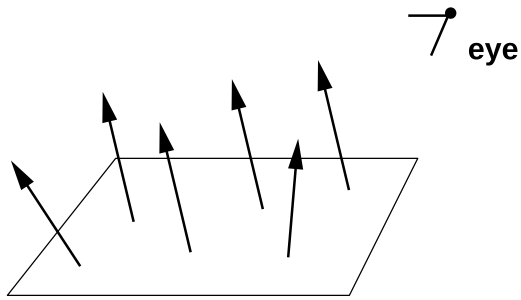
Given point **p**, normal **N**, light **L**, viewer **V**
*Shade* **p** according to reflectance properties $\rho$




**color = f ( p, N, light L, eye V, ρ )**

## Emissive Objects

Simplest illumination model possible (hack)




Every object emits light of some color, intensity

$I_e$ is the surface's *emissive intensity*

$I$ is the *reflected intensity* at shaded point

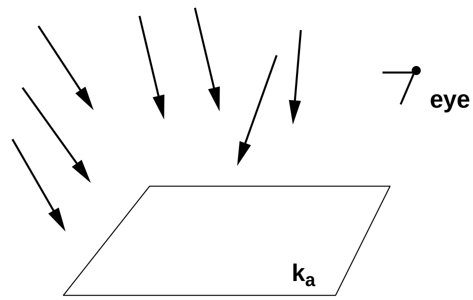
Examples:

Phosphorescent, bioluminescent materials



## Ambient Illumination

Ambient (perfused) light often present due to reflection




Quantitatively (I = Intensity; radiometric units later):

$k_a$ is the *ambient reflection coefficient*

$I_a$ is the *ambient light intensity*

Examples:

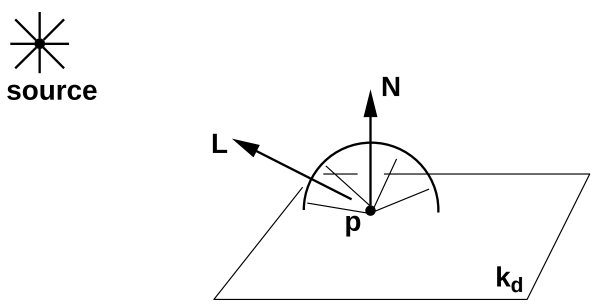
Cloudy day

Building interior in daytime with no lights on

Hmm... Doesn't appearance change with viewing direction?



## Ideal Diffuse Reflection: Qualitative




Ideal diffuse reflection occurs from perfect matte surfaces (not found in nature)

reflection depends on angle between surface normal and direction to light source

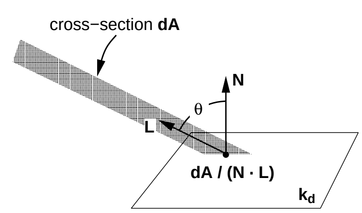
geometry causes *viewer dependence* to cancel out

**Surface looks equally bright from all directions**



## Ideal Diffuse Reflection: Quantitative

Geometry of diffuse reflection:



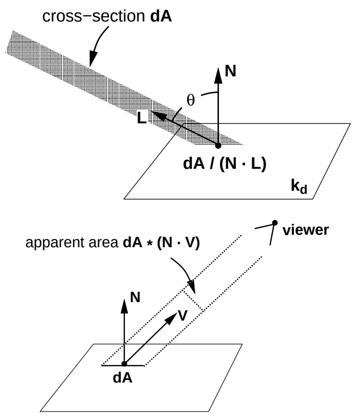

Beam with axis **-L**, area $dA$ impinges on surface element with normal **N**

Beam distributes energy over an area $dA \,/\, \cos\theta$

Energy per unit area varies as $\mathbf{N} \cdot \mathbf{L}$

## Lambert's Law

Lambert's law (17th century physicist, mathematician)




Diffuse reflected intensity $\propto \mathbf{N} \cdot \mathbf{V}$

But: *apparent area* $\propto 1/(\mathbf{N} \cdot \mathbf{V})$

Thus energy reflected toward viewer is

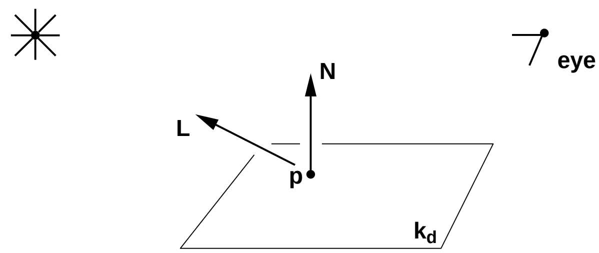
$\propto \mathbf{N} \cdot \mathbf{L}$, $\mathbf{N} \cdot \mathbf{V}$, $1/(\mathbf{N} \cdot \mathbf{V})$

Brightness is



## Ideal Diffuse Reflection

Shading term:




$I_l$ is intensity of point light source

$k_d$ is coefficient of diffuse reflection $0 \leq k_d < 1$

max prevents reflection from *backfacing* elements

(underlying solid body opaque, thus "self-occluding")

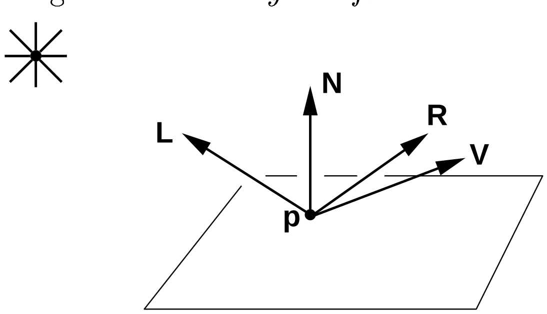
$\mathbf{L}$ effectively constant for distant light sources



## Ideal Specular Reflection

Occurs from ideal (perfect) mirror

Light along $\mathbf{L}$ bounces *only* in *reflected direction* $\mathbf{R}$




Quantitatively:

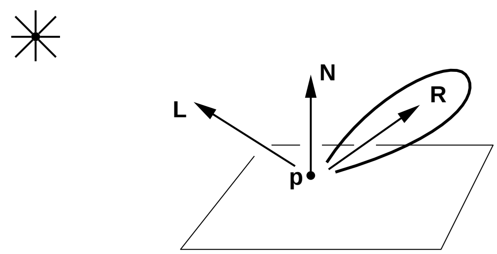
where $\delta(\mathbf{A}, \mathbf{B}) \equiv 1$ iff $\mathbf{A} = \mathbf{B}$, 0 otherwise

Uninteresting for most applications (non-physical)



## Generalized Specular Reflection: Qualitative

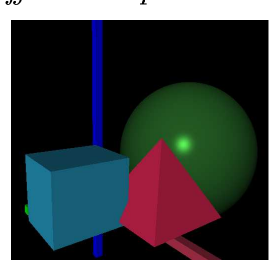
Occurs from "mirror-like" surfaces



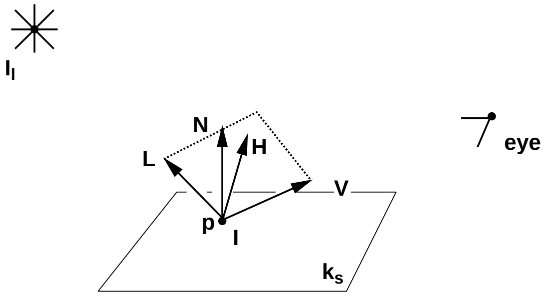

*Highlights* occur whose sharpness varies with surface shininess

Highlight *color* only weakly dependent on surface color

Reflection *falls off* around *peak* reflection direction $\mathbf{R}$



## Specular Reflection: Quantitative



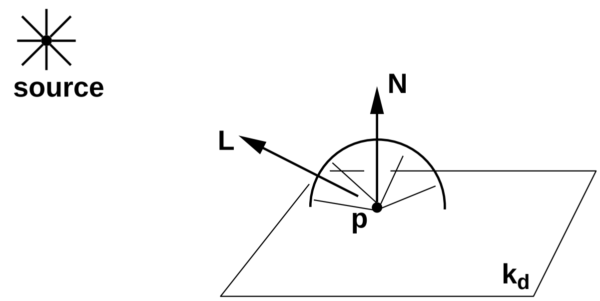

Usually written in terms of surface normal, half-vector

$\mathbf{H}$ = *half-vector* $(\mathbf{V}+\mathbf{L})/|\mathbf{V}+\mathbf{L}|$
$\mathbf{N}$ = surface normal
$\mathbf{V}$ = direction to viewer
$\mathbf{L}$ = direction to light source
$k_s$ = coefficient of specular reflection
$n$ = "shininess" parameter (sometimes $e$ or $s$):
  $n = 1$ yields smooth, broad highlight
  $n = \infty$ yields
  $n$ typically ranges from 1 to a few hundred



## Phong Illumination Model (CACM 18(6), June 1975)

Diffuse term (independent of viewing direction)

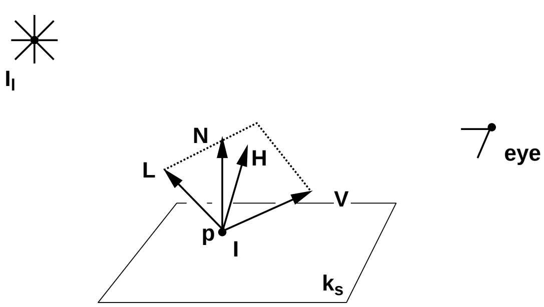



$I$ = reflected intensity
$k_d$ = coefficient of diffuse reflection
$\mathbf{N}$ = surface normal
$\mathbf{L}$ = direction to light source



## Phong Illumination

Specular term (dependent on viewing direction)

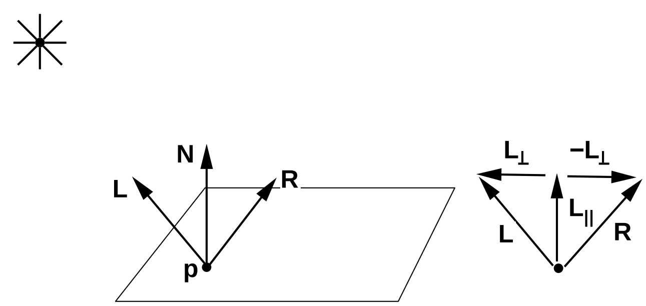



$\mathbf{H}$ = *half-vector* $(\mathbf{V}+\mathbf{L})/|\mathbf{V}+\mathbf{L}|$
$\mathbf{N}$ = surface normal
$\mathbf{V}$ = direction to viewer
$\mathbf{L}$ = direction to light source
$k_s$ = coefficient of specular reflection
$n$ = "shininess" parameter



## Computing the reflection vector R

$\mathbf{R}$ is $\mathbf{L}$ mirrored about $\mathbf{N}$



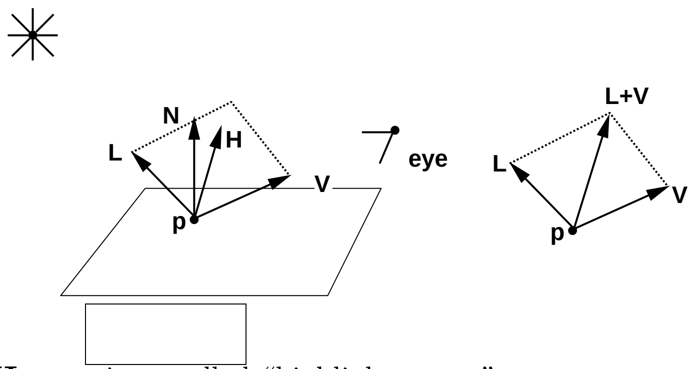

Partition $\mathbf{L}$ into components $\mathbf{L}_{\parallel}$ and $\mathbf{L}_{\perp}$; negate $\mathbf{L}_{\perp}$

$$\begin{aligned}\mathbf{R} &= \mathbf{L}_{\parallel} - \mathbf{L}_{\perp} \\ &= \mathbf{L}_{\parallel} - (\mathbf{L} - \mathbf{N}(\mathbf{L}\cdot\mathbf{N})) \\ &= \mathbf{N}(\mathbf{L}\cdot\mathbf{N}) - \mathbf{L} + \mathbf{N}(\mathbf{L}\cdot\mathbf{N}) \\ &= \end{aligned}$$

$\mathbf{L}$ (and therefore $\mathbf{N}\cdot\mathbf{L}$) are constant
  for distant sources (directional lights)
But – $\mathbf{L}$ varies for local light sources !

## Computing the half-vector H

**H** is simply halfway between **L** and **V**




**H** sometimes called "highlight vector"
hold **L**, **V** fixed, vary **N** to find maximal highlight



## Distance Attenuation

Model falloff of intensity with distance
Problem: inverse quadratic falloff works poorly
at long distances: varies too slowly
at short distances: varies too quickly
due to non-physicality of point light!
In practice, can model attenuation with parameters $c_k$:

$$f_{att}(d_L) = \min\left(\frac{1}{c_1 + c_2 d_L + c_3 {d_L}^2}, 1\right)$$

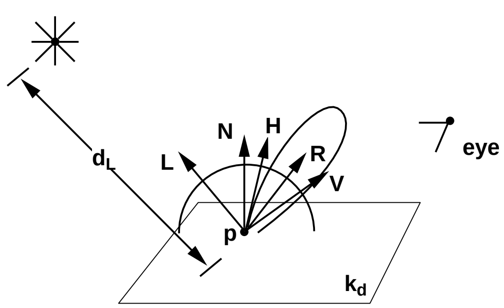
$d_L$ is distance from surface element **to light**
$c_1$ prevents blowup due to very close light sources
$c_2$ models linear falloff due to large area light sources
$c_3$ models quadratic falloff due to small, bright sources
min prevents $f_{att}(d_L)$ from becoming greater than 1
Determining reasonable $c_k$ problematic in practice



## Phong Illumination – Aggregate

Monochromatic lights and surfaces:

$$I = I_a k_a + f_{att}(d_L) I_l [k_d(\mathbf{N} \cdot \mathbf{L}) + k_s(\mathbf{N} \cdot \mathbf{H})^n]$$




Colored lights and surfaces:

$$I_\lambda = I_{a\lambda} k_a C_{d\lambda} + f_{att}(d_L) I_{l\lambda} [k_d C_{d\lambda}(\mathbf{N}\cdot\mathbf{L}) + k_s(\mathbf{N}\cdot\mathbf{H})^n]$$

Typically, one equation for each *spectral component*
e.g., R ($\lambda = 620$nm), G ($\lambda = 550$nm), B ($\lambda = 440$nm)
Note: specular term independent of *material properties*
*Approximation*, with empirically derived parameters
CAUTION: Phong model is not physically correct!
Spectral integration; fall off; energy conservation



## When to Apply Lighting Equation?

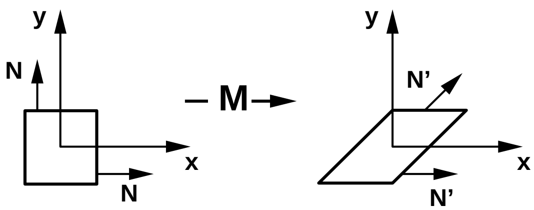
Apply in object space
Adv: easy to compute normals
Disadv: Must transform lights to object space
So: apply in world coordinates
Adv: lights usually specified in world space
This is most common practice, but:
1) What about vertices outside frustum?
2) How are obj. space normals handled?
Some systems shade pixel fragments at end of pipe!

## Transforming Normal Vectors

Suppose we apply a transformation $\mathbf{M}$ to an object
What are the normals of the transformed object?
Suppose we are shearing in $x$. Then

$$\mathbf{M} = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Look at normals $(0,1)$ and $(1,0)$ of a square:




If we apply $\mathbf{M}$, we get $(1,1)$ and $(1,0)$ !



## Transforming Normal Vectors

Object vertices $\mathbf{v}$ are transformed as $\mathbf{Mv}$
Consider vector $\mathbf{v}$, and $\mathbf{n}$ such that $\mathbf{n} \perp \mathbf{v}$

$$\mathbf{n}^T \mathbf{v} = 0$$

(This is the implicit eq'n of something. What?)
For any (non-singular) transformation matrix $\mathbf{M}$

$$\mathbf{n}^T \mathbf{M}^{-1} \mathbf{M} \mathbf{v} = 0$$

which can be rewritten as

$$(\mathbf{n}^T \mathbf{M}^{-1})(\mathbf{M}\mathbf{v}) = 0$$

thus the *transpose* of the transformed normal is

$$\mathbf{n}^T \mathbf{M}^{-1}$$

and the transformed normal itself is

$$(\mathbf{n}^T \mathbf{M}^{-1})^T = \mathbf{M}^{-T} \mathbf{n}$$

Normal $\mathbf{n}$, under action of $\mathbf{M}$, becomes $\mathbf{M}^{-T}\mathbf{n}$



## Example: Shear

For example above,

$$\mathbf{M} = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

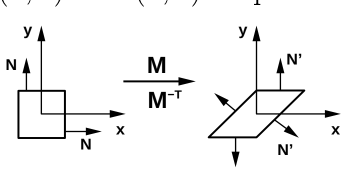
Its inverse $\mathbf{M^{-1}}$ is

$$\mathbf{M^{-1}} = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Its inverse transpose $\mathbf{M^{-T}}$ is

$$\mathbf{M^{-T}} = \begin{pmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Now normals $(0,1)$ and $(1,0)$ map to:




$(0,1)$ and $(1,-1)$, respectively
Note length change! How do we fix this?



## Lighting: Simplifying Assumptions

Incorrect modeling of *light source geometry*
  Can't get finite energy from zero volume!
Incorrect modeling of *absorptive media* (haze, etc.)
  Bogus intensity attenuation with distance
No modeling of *scattering* due to air, etc.
  Decreasing contrast, increasing blueness with distance
No dependence on wavelength $\lambda$, thin film, etc.
No dependence on polarization
No dependence on azimuthal angle of incidence
No dependence on time
**Things are not so simple in reality!**