3D Graphics Programming Tools

Lighting

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Lighting versus “Colouring”

Today’s agenda

- Why do we need to calculate lighting?
- Definitions
- Ambient and directional light sources
- Diffuse and specular reflection
- Shading models

Light stage

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Solving the lighting problem

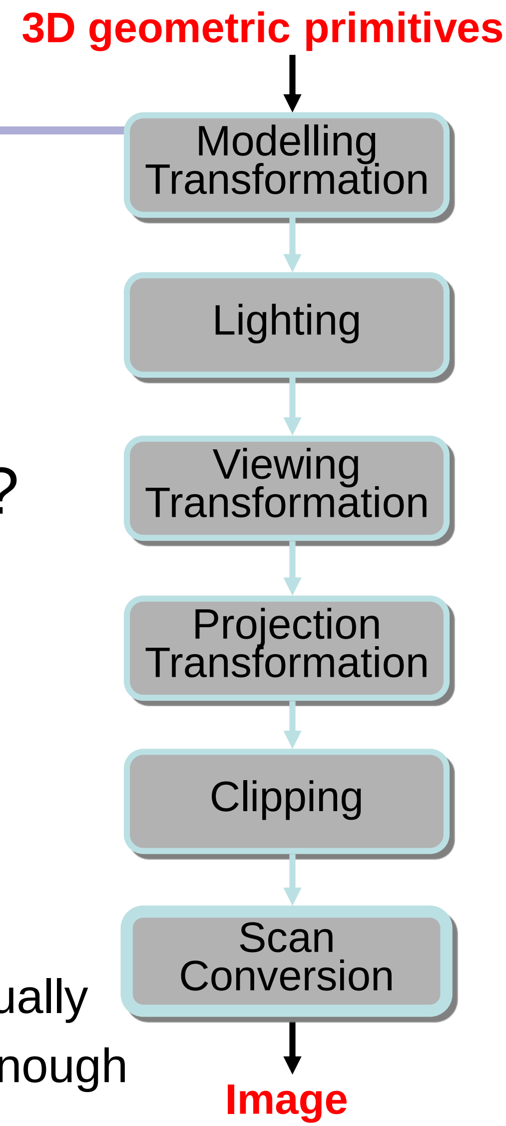
- Where are we?
  - We somewhat understand the perception of light (colour)
  - We know how to represent and generate colour using computers
- We now need to understand the interaction of light and objects

Lighting

- Later, we will learn how to rasterise
  – i.e., given a 3-D triangle and a 3-D viewpoint, we know which pixels represent the triangle
- But … what colour should those pixels be?

- To create a realistic image

  → need to simulate the lighting
  of the **surfaces** in the scene
  - Fundamentally → simulation of *physics* and *optics*
  - In reality → we use a lot of approximations (perceptually based hacks to do this simulation fast enough



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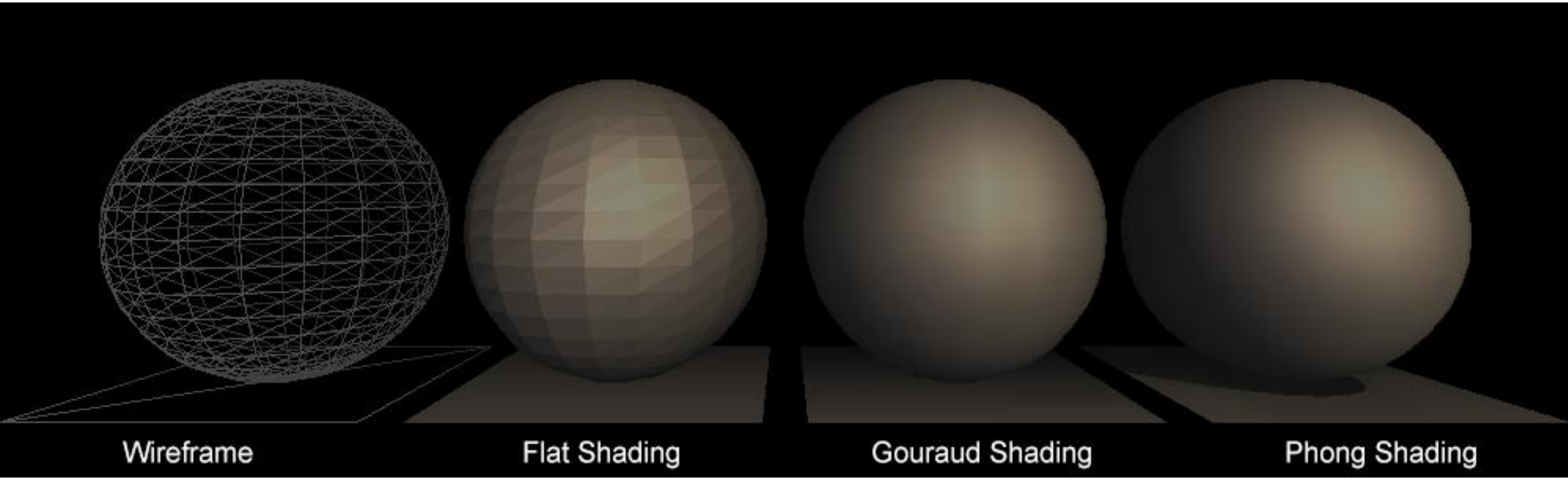
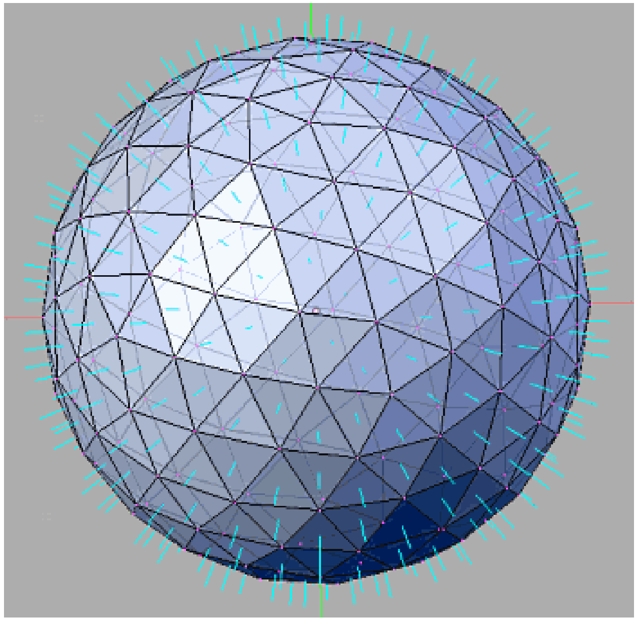
Modelling and Lighting





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Today's agenda

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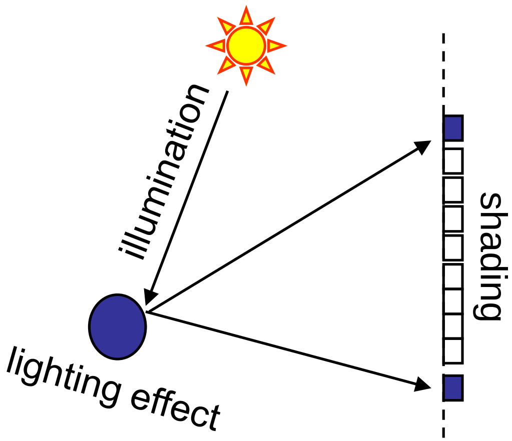
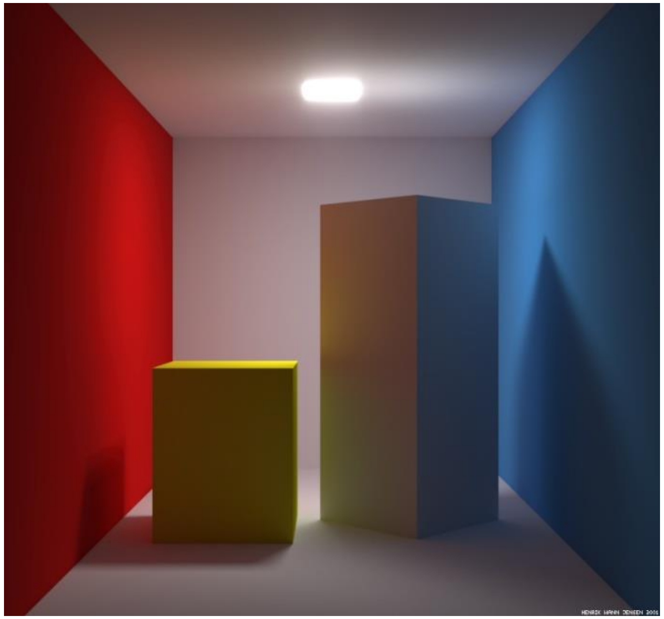
Definitions

- Illumination
  - the transport of energy from light sources to surfaces & points
    - Note: includes *direct* and *indirect illumination*
- Lighting
  - the process of computing the luminous intensity (i.e. outgoing light) at a particular 3-D point
- Shading
  - the process of assigning colours to pixels





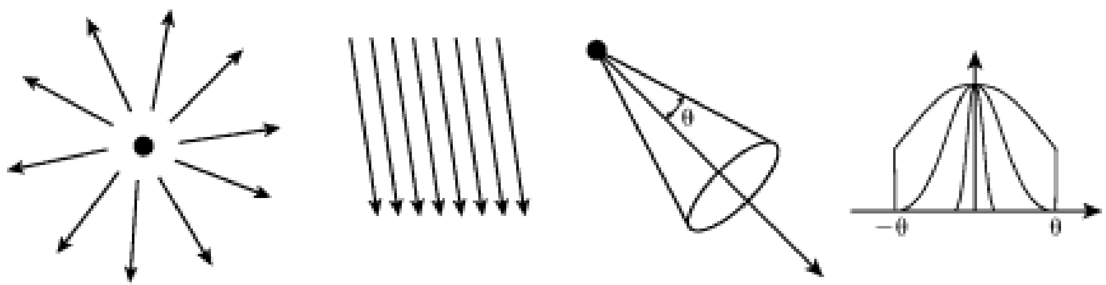
Definitions

- Illumination models → two categories:
  - Physically based
    - models based on the actual physics of light interacting with matter
  - Empirical
    - simple formulations that approximate observed phenomenon

- Interactive graphics
  - for simplicity → mostly use empirical models
  - increasingly → realistic graphics are using physically based models

Two components of lighting

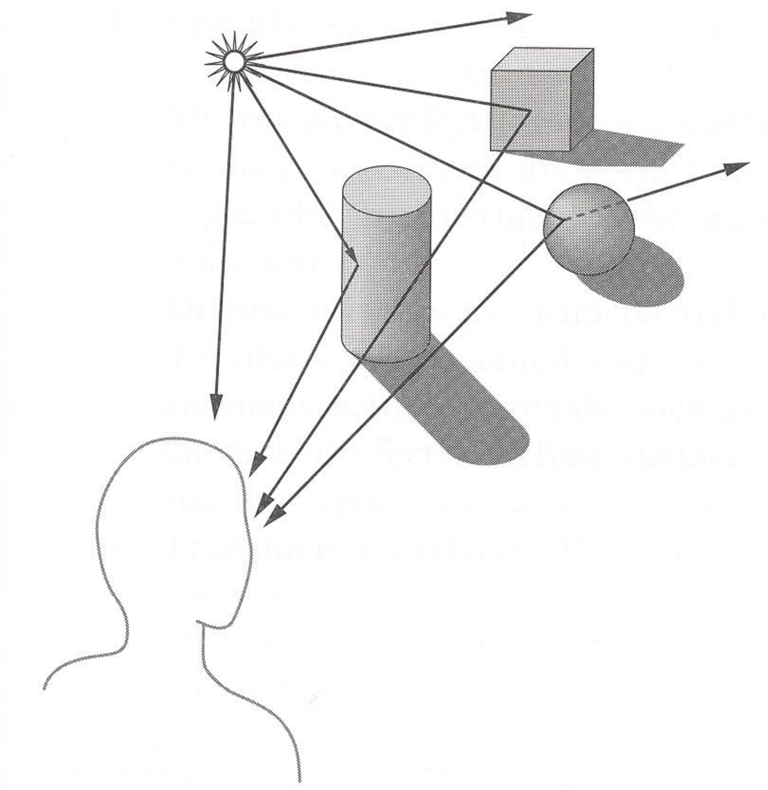
- Light sources (or emitters)
  - spectrum of emittance (*colour of the light*)
  - geometric attributes (*position*, *direction*, *shape*)
  - directional attenuation



- Surface properties
  - reflectance spectrum (*colour of the surface*)
  - subsurface reflectance
  - geometric attributes (*position*, *orientation*, *micro-structure*)

Light Models

- Light models: include 3 aspects of information:
  - Emission at light sources
  - Scattering at surfaces
  - Reception at the camera



- Desirable features …
  - Concise
  - Efficient to compute
  - “Accurate” (look real)

Today's agenda

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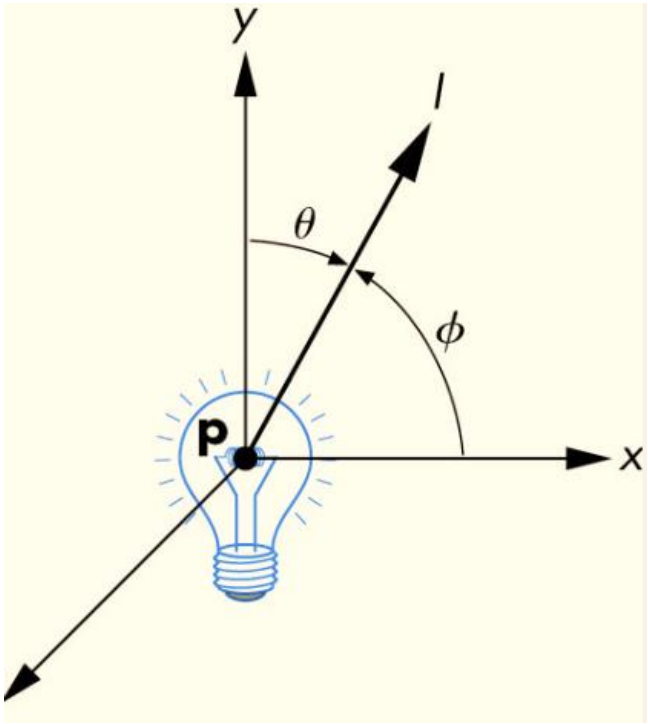
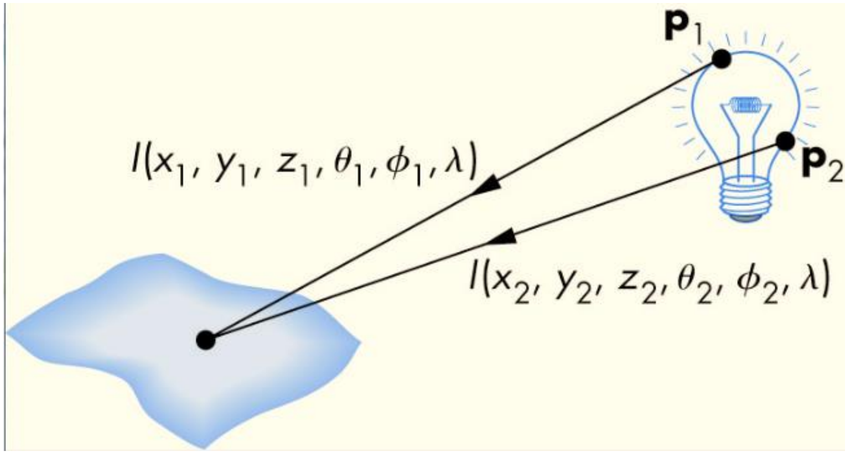
Modelling light sources

- I ($x,y,z,\theta,\phi,\lambda$) ...
  - describes the intensity of energy (I)
  - leaving a light source from location(x,y,z)
  - with direction (θ,ϕ)
  - at wavelength λ





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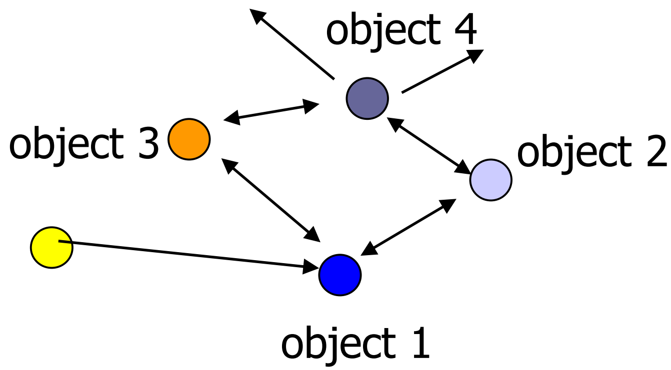
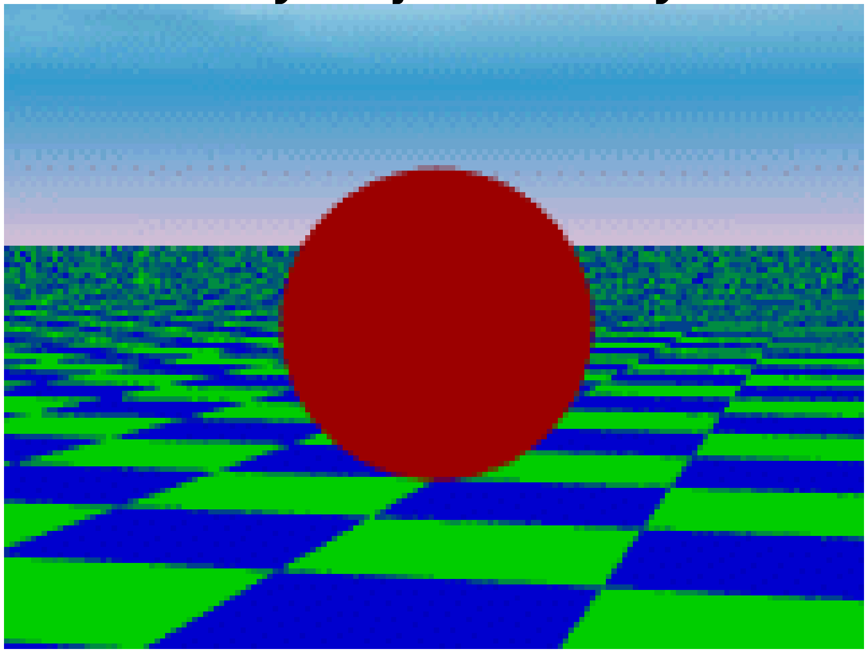
Ambient light sources

- Simulate indirect illumination from emitters, bouncing off intermediate surfaces (interaction from objects, environmental)
  - Objects not directly lit are typically still visible
    - e.g., the ceiling of a room, undersides of desks
  - Too expensive to calculate (in real time), so we use a hack called an ambient light source
    - No spatial or directional characteristics
    - Illuminates all surfaces equally
    - Amount reflected depends on surface properties



Ambient light model

- A scene lit only with an ambient light source
- The same for every object, everywhere and in any direction



Light position not important

Viewer position not important

Surface angle not important

$$I \cong k_a \cdot I_a$$

$$I_a = L(P_0) = L \quad \text{(constant)}$$

I_a: incident ambient light intensity

k_a: ambient reflection coefficient

I: resulting intensity

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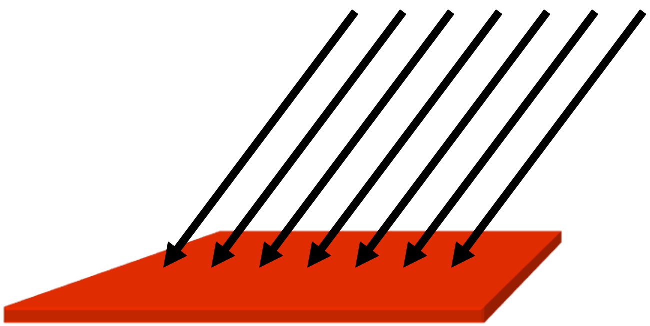
Distant light sources

- For a distant light source we make simplifying assumptions
  - direction is constant for all surfaces in the scene
  - all rays of light from the source are parallel
    - As if the source were infinitely far away from the surfaces in the scene
    - A good approximation to sunlight

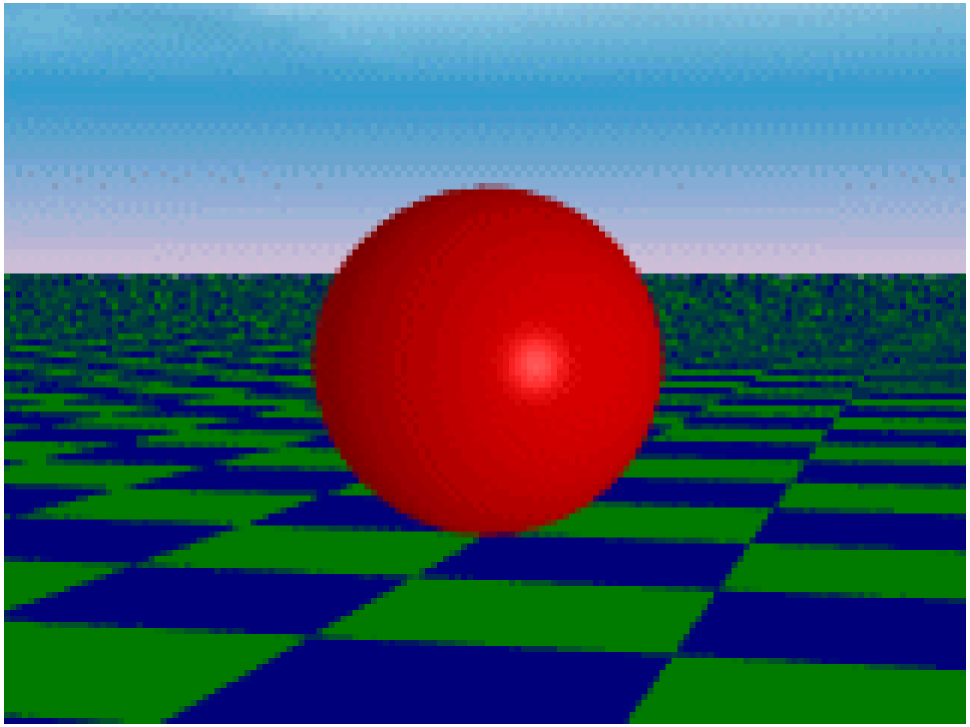
- The direction from the light source to a surface is important in lighting the surface

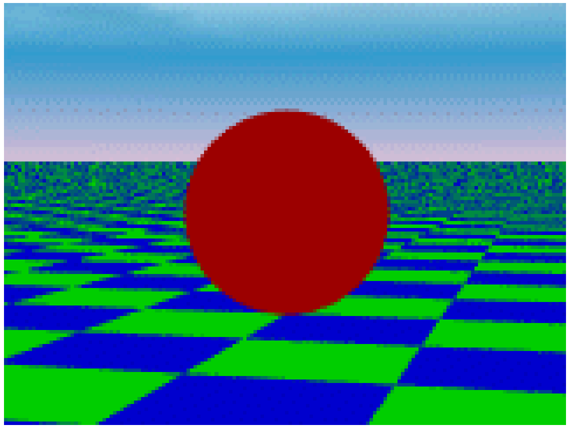
$$\vec{L}(P, P_0) = L \cdot \vec{l}$$



Distant light sources

- The same scene lit with a distant and an ambient light source





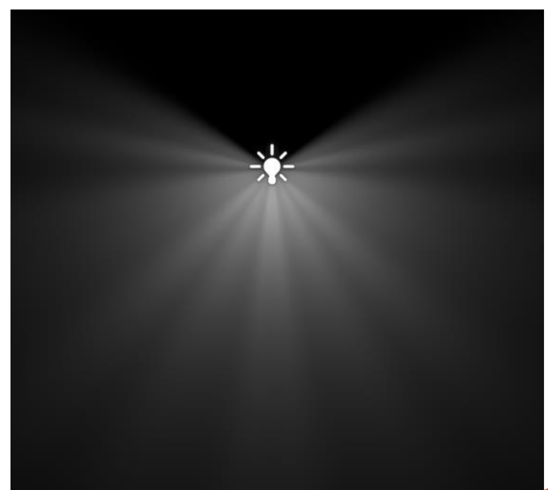
Point light sources

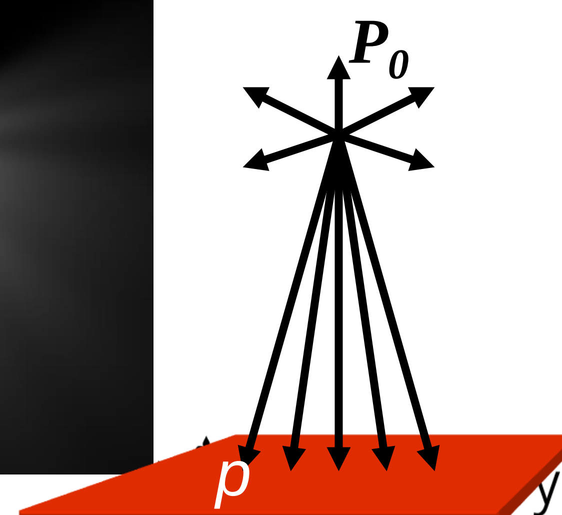
- Point light source
  - emits light equally in all directions from a single point
  - the direction to the light from a point on a surface differs for different points → need to calculate a normalised vector to the light source for every point we light

$$\vec{l} = \frac{P - P_0}{|P - P_0|}$$

  - The intensity of illumination received from a source located at P0 at a point P is proportional to the inverse square of the distance from the source

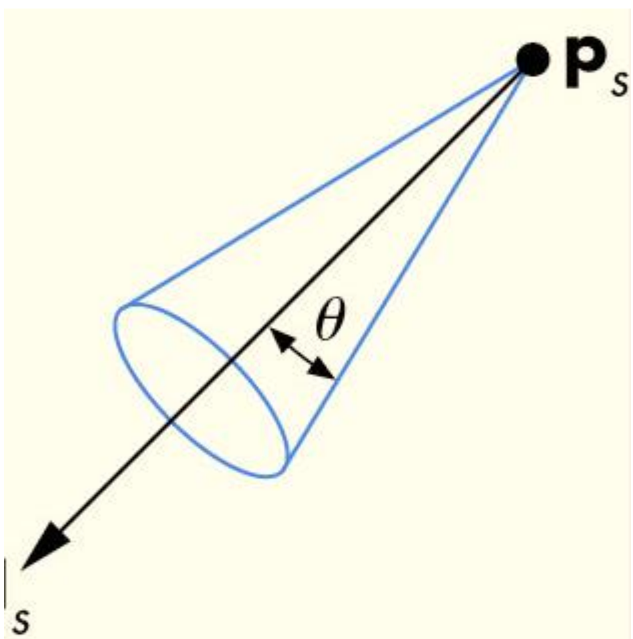
$$\vec{L}(P, P_0) = \frac{L(P_0) \cdot \vec{l}}{|P - P_0|^2}$$

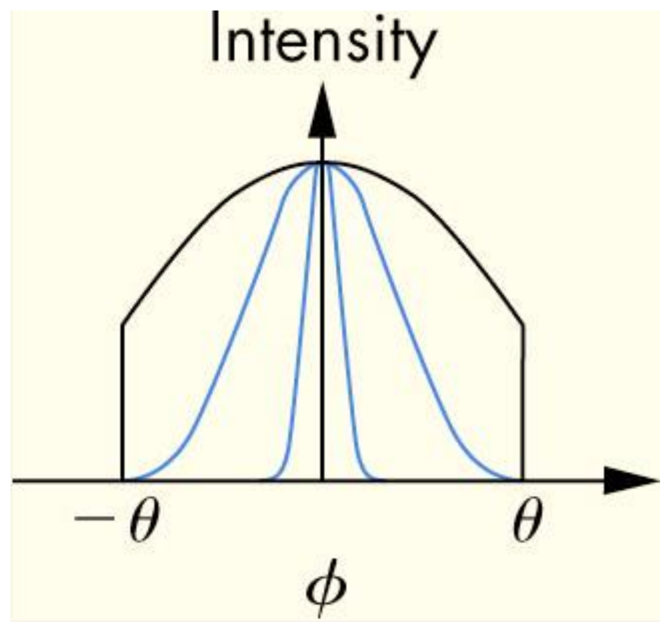




Spotlights

- Spotlights
  - Characterised by a narrow range of angles through which light is emitted.
  - Realistic spotlights are characterised by the distribution of light within the cone (usually with most of the light concentrated in the center of the cone).





$$\vec{L}(\cos\theta) = \vec{L}\left(s \cdot \frac{P - P_s}{|P - P_s|}\right)$$

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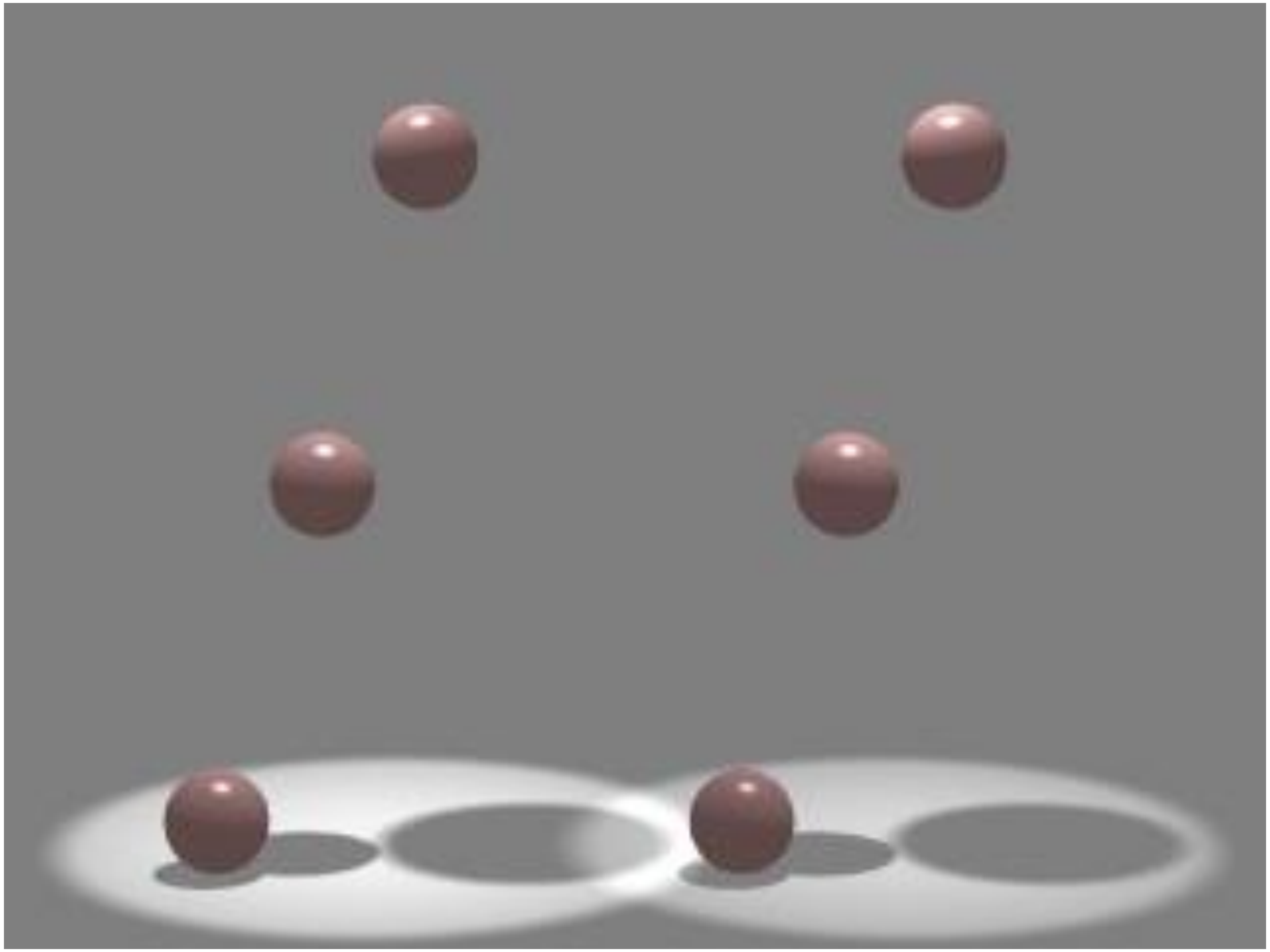
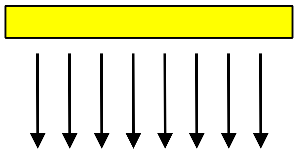
2 Spotlights

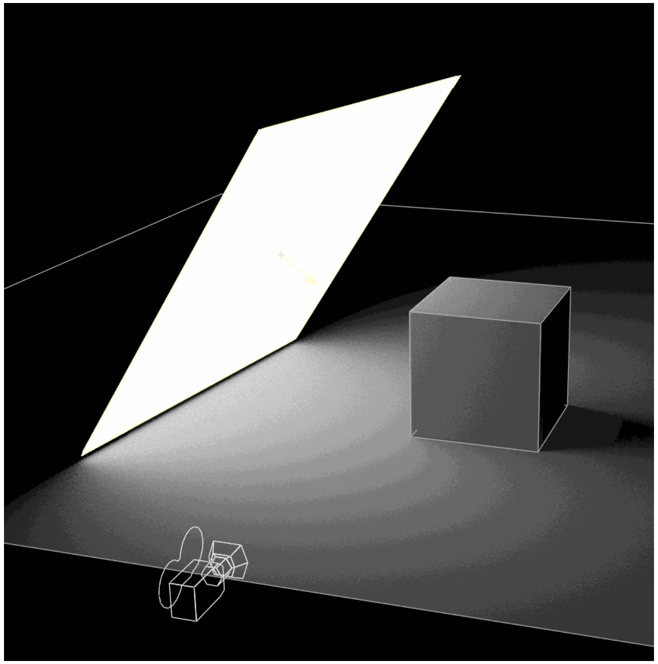


Other light sources

- Area light sources
  - 2-D emissive surface (usually a disc or polygon)
  - example: fluorescent light panels
  - capable of generating soft shadows



Area light



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Today's agenda

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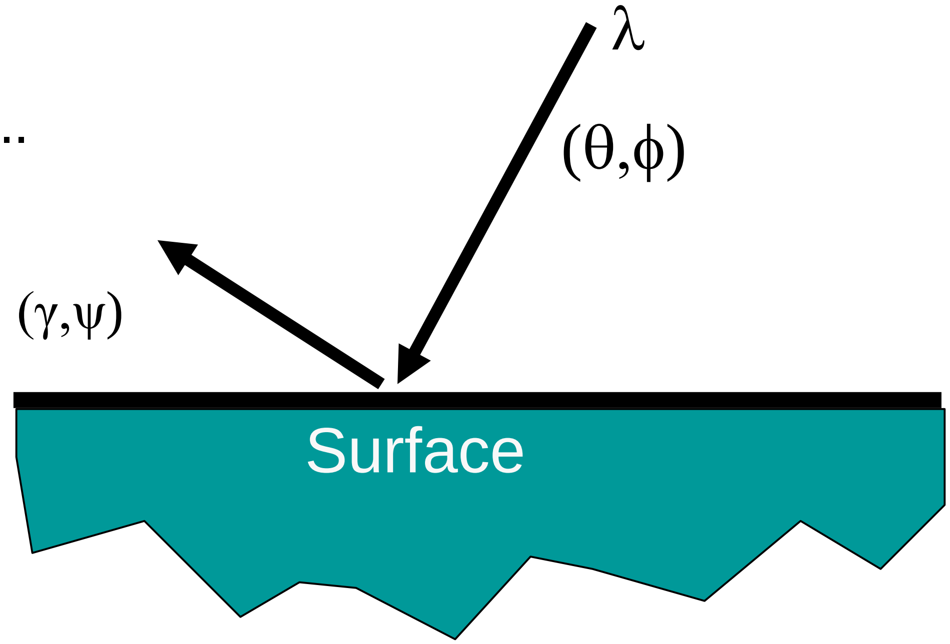
Modelling surface reflectance

- Incident light: $R_s(\theta,\phi,\gamma,\psi,\lambda)$
  - arriving from direction (θ,ϕ), ...
  - leaving in direction (γ,ψ), …
  - with wavelength λ



- Surface reflectance, ideally
  - measure radiant energy for "all" combinations of incident angles
    - too much storage
    - difficult in practice

Bi-directional reflection distribution (BRDF)

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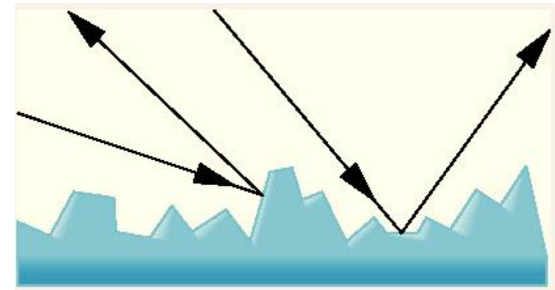
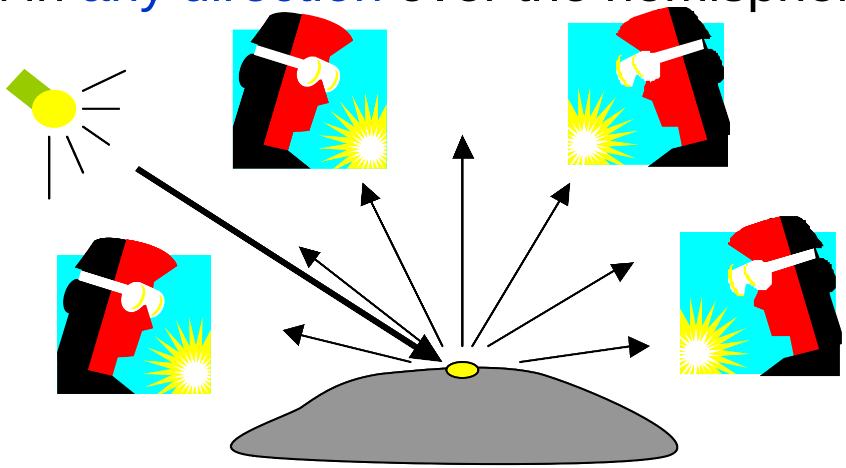
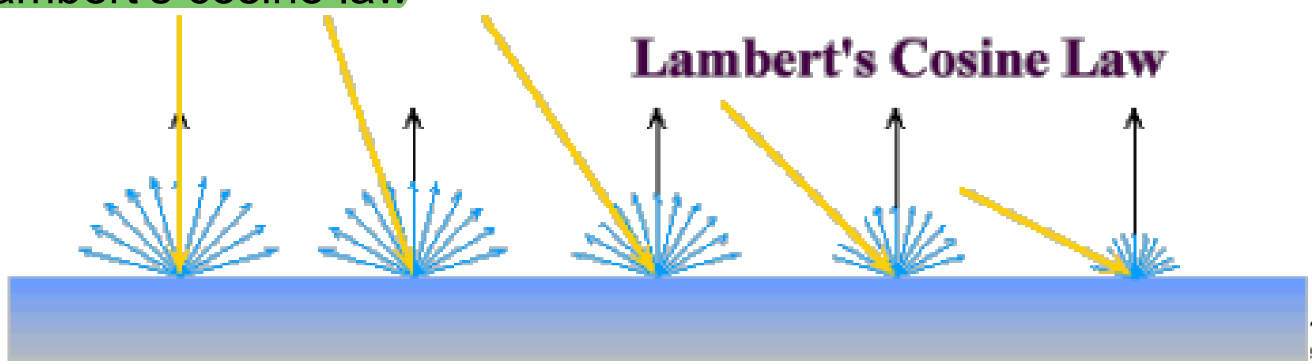
The physics of reflection

- Ideal diffuse reflection
  - is a very rough surface at the microscopic level
  - an incoming ray of light is equally likely to be reflected in any direction over the hemisphere:



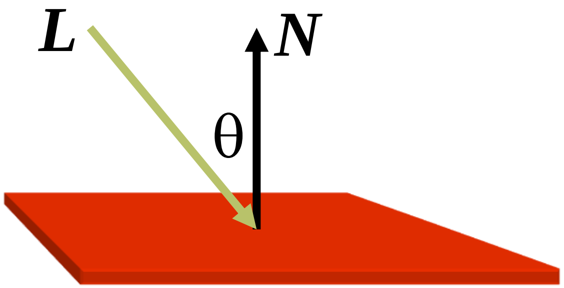


  - The amount of light reflected depends on angle of incident light
    - Lambert’s cosine law



Computing diffuse reflection

- The angle between the surface normal and the incoming light is the *angle of incidence*:



$$I_{diffuse} \cong I_l \cdot k_d \cdot \cos\theta, \quad 0 \le \theta \le \pi/2$$

angle between light vector and surface normal

diffusive reflection constant

incident light intensity

resulting intensity

In practice we use vector arithmetic:

- $I_{diffuse} = I_l \, k_d \, (\boldsymbol{N} \bullet \boldsymbol{L})$

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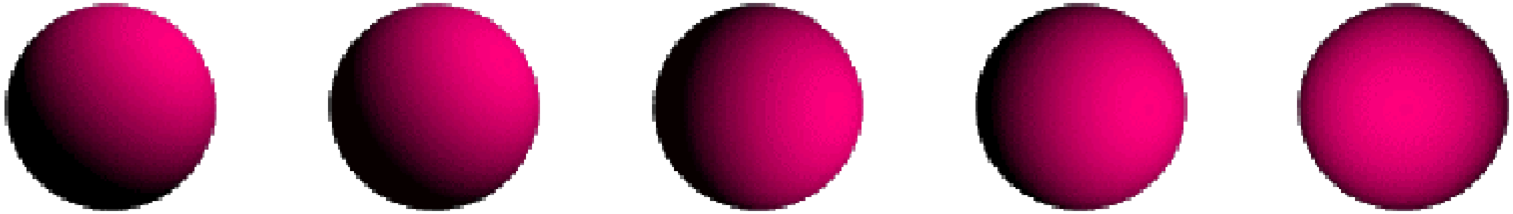
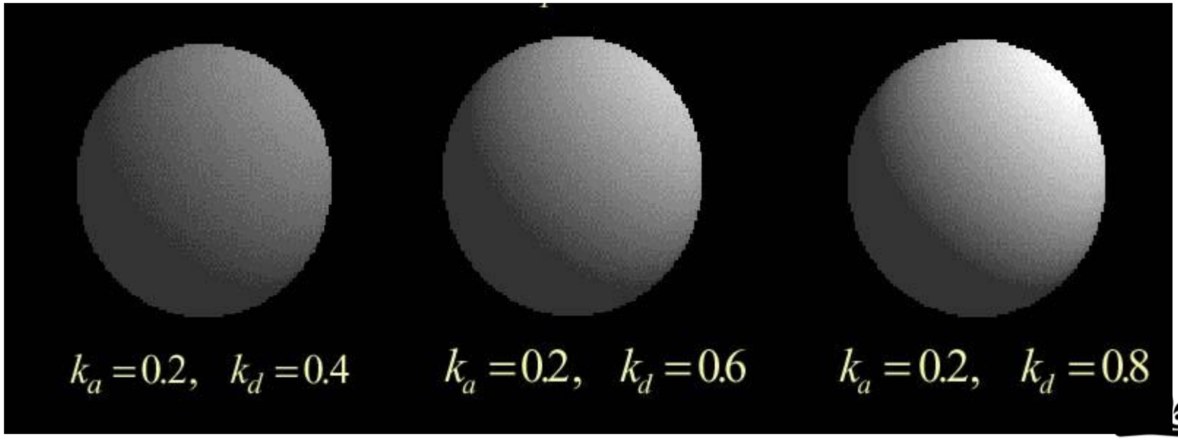
Diffuse lighting examples

- A Lambertian sphere seen at several different lighting angles (same reflection coefficient):

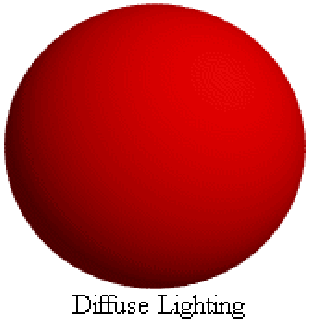


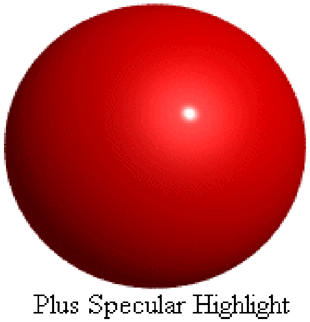
- Lambertian sphere of different coefficient (same lighting angles):



Specular reflection

- Shiny surfaces exhibit specular reflection
  - Polished metal
  - Glossy car finish





- A light shining on a specular surface causes a bright spot
  (*specular highlight*)
- Where these highlights appear is a function of the viewer's position
  → specular reflectance is view dependent

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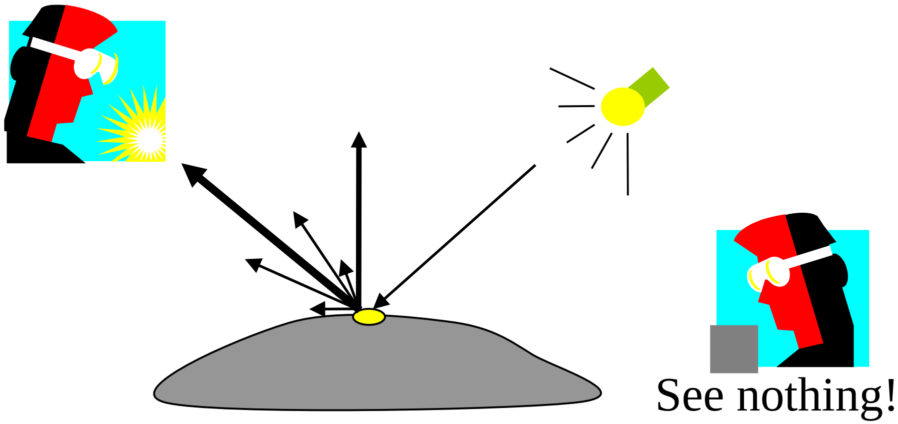
The physics of reflection

- Specular reflecting surface
  - is very smooth at the microscopic level
  - rays of light → likely to bounce off the micro-geometry in a mirror-like fashion
  - The smoother the surface, the closer it becomes to a perfect mirror

  - Reflection is strongest near mirror angle



The optics of reflection

– The incoming ray and reflected ray lie in a plane with the surface normal

– The angle that the reflected ray forms with the surface normal equals the angle formed by the incoming ray and the surface normal:

$$I \cong I_l k_s \cos^n \alpha$$

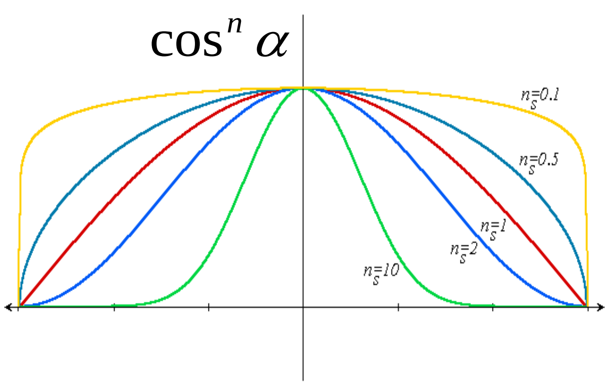
angle between reflection vector and view direction

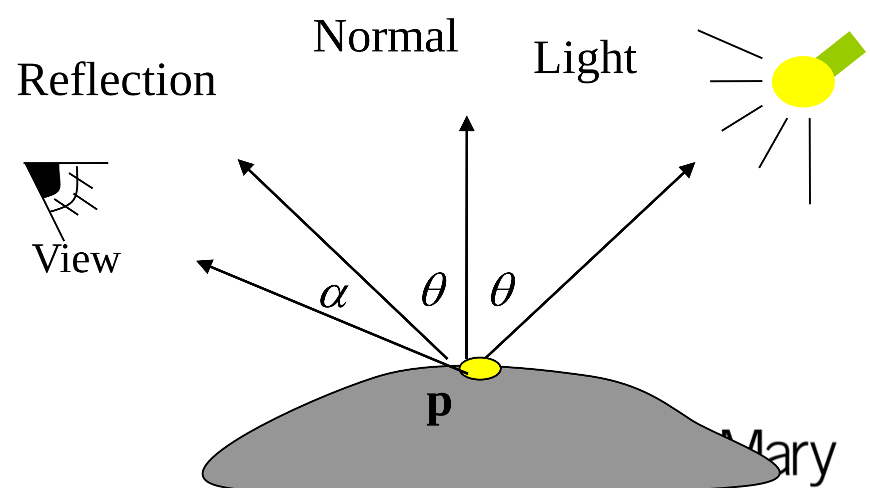
specular reflection exponent (n>=1)

specular reflection constant (0<=k_s<=1)

incident light intensity

resulting intensity



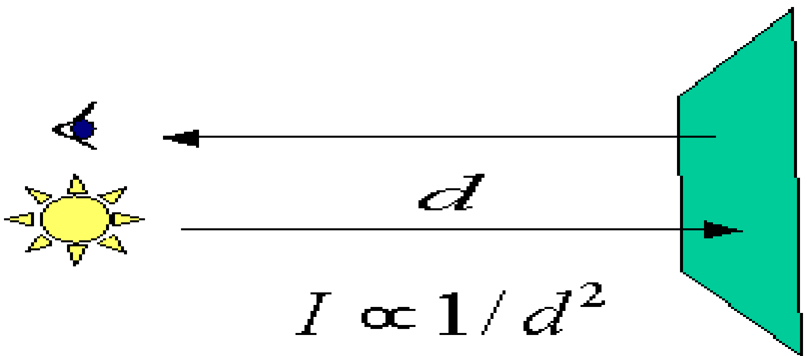


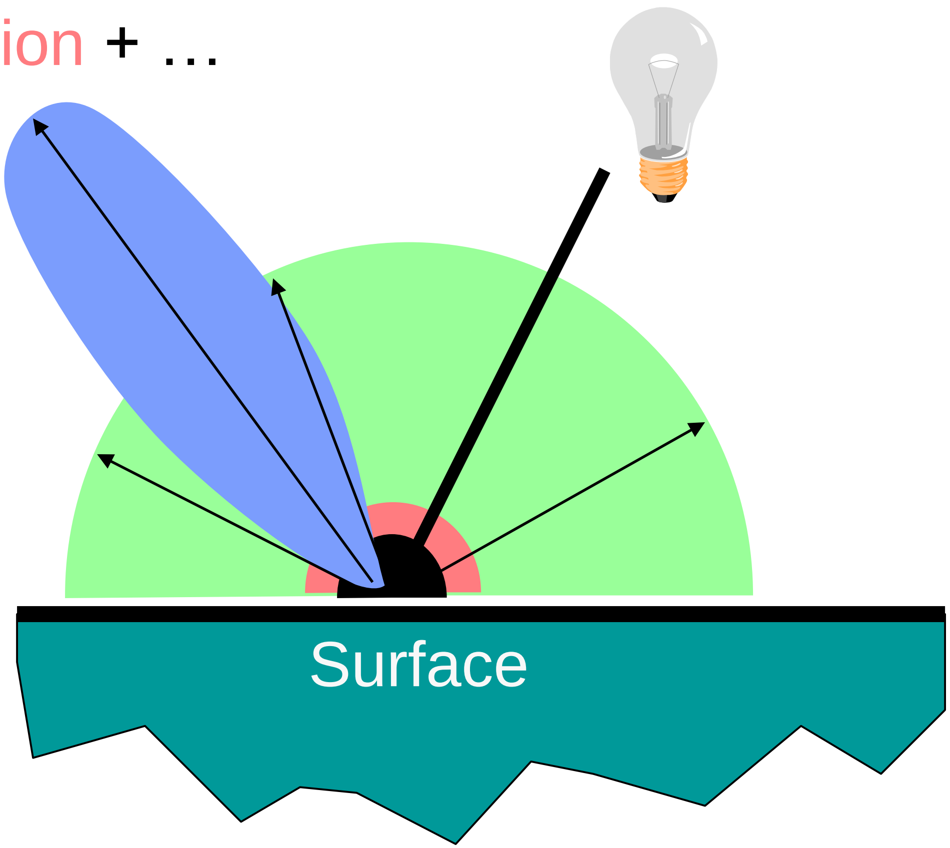
Combining everything

- Simple analytic model:

  ambient + diffuse reflection + specular reflection + emission + …

  with distance attenuation





Combining everything

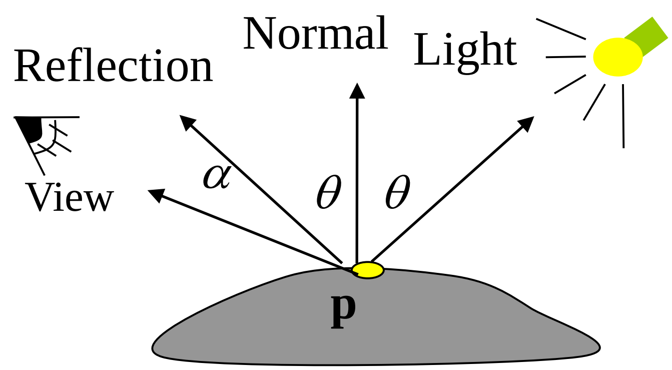
$$I = I_a + f_{att}(I_d + I_s) = I_a \cdot k_a + f_{att} I_l (k_d \cdot \cos\theta + k_s \cdot \cos^n \alpha)$$

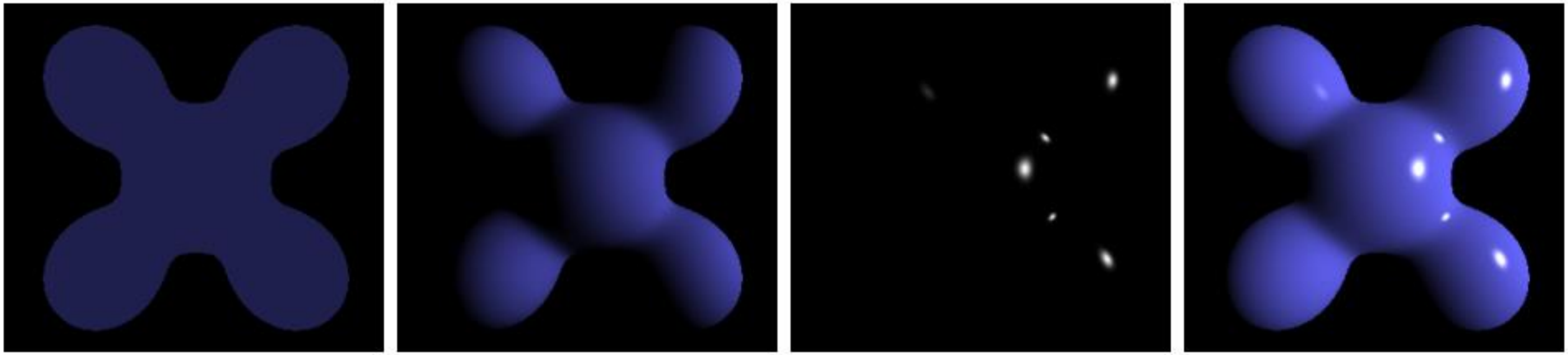
specular reflection

diffusive reflection

attenuation factor

ambient refection





Ambient + Diffuse + Specular Combined illumination

Multiple Colour Light Sources

$$I_\lambda = I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} (k_d \cdot \cos\theta_j + k_s \cdot \cos^n \alpha_j)$$

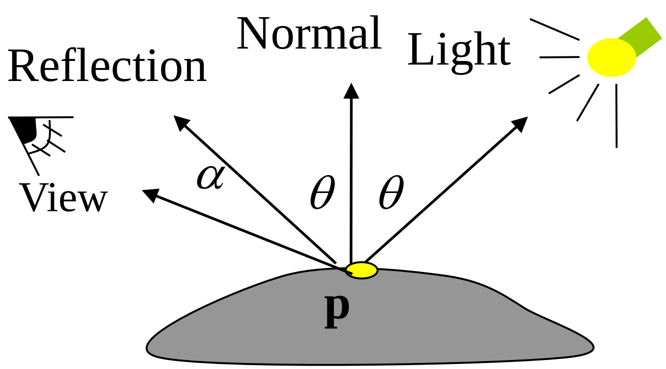
$$= I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} \left(k_d \cdot (\boldsymbol{N} \cdot \boldsymbol{L}_j) + k_s \cdot (\boldsymbol{R}_j \cdot \boldsymbol{V})^n \right)$$

view vector

reflection direction

lighting vector

normal of surface



- The ambient term contributes only once
- Repeat the diffuse and specular calculations for each light source
- Add the components from all light sources

Multiple Colour Light Sources

$$I_\lambda = I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} (k_d \cdot \cos\theta_j + k_s \cdot \cos^n \alpha_j)$$

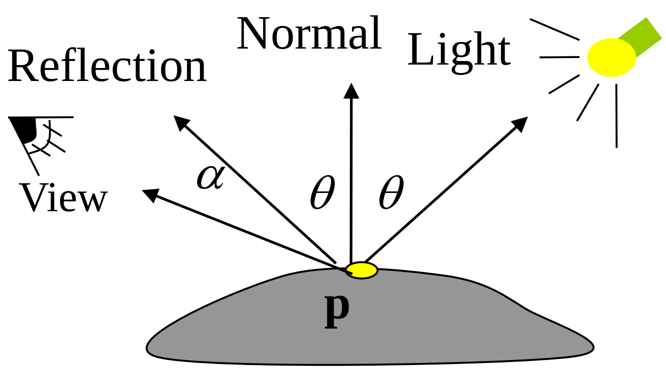
$$= I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} \left(k_d \cdot (\boldsymbol{N} \cdot \boldsymbol{L}_j) + k_s \cdot (\boldsymbol{R}_j \cdot \boldsymbol{V})^n \right)$$

view vector

reflection direction

lighting vector

normal of surface



Householder reflection:

$$\vec{\boldsymbol{R}} = \boldsymbol{H} \cdot \vec{\boldsymbol{L}} \quad where \quad \boldsymbol{H} = \boldsymbol{I} - 2\vec{\boldsymbol{N}} \cdot \vec{\boldsymbol{N}}^T$$

Direct illumination: summary

- Model for
  - determining the brightness (radiance) of a ray rooted at a point on a surface and oriented towards the camera
    - Ambient light contribution term
    - Diffuse light contribution term
    - Specular light contribution term

- Influencing factors
  - Light position
  - Sample point position
  - Camera position
  - Surface angle with respect to light vector
  - Surface angle with respect to camera vector

Direct illumination: changes/unchanged

- Camera moves from one position to another
  - Angle between light and surface unchanged
  - Angle between camera and surface changes
- A tracking camera follows object as it moves in scene
  - Angle between light and surface changes
  - Angle between camera and surface unchanged
- An object moves from one position to another
  - Both angles change

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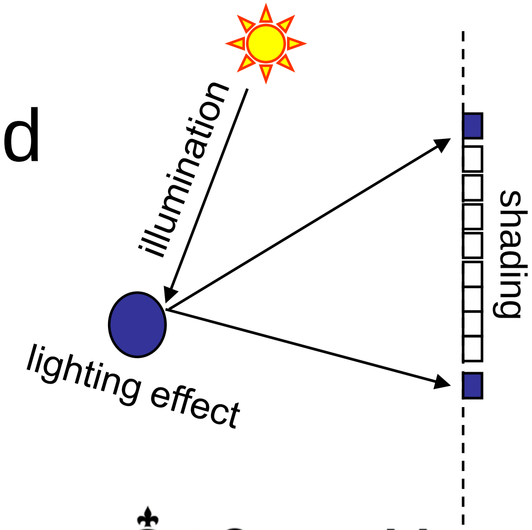
Shading

- Surfaces are often approximated by <u>polygons</u>, so we use various polygon shading techniques to make these approximations look more like the surfaces as we see in the real world.
- Shading model determines the shade of an object point or pixel by applying the illumination and lighting models
- The models are loosely physical, and emphasize:
  - Empirical success
  - Efficiency

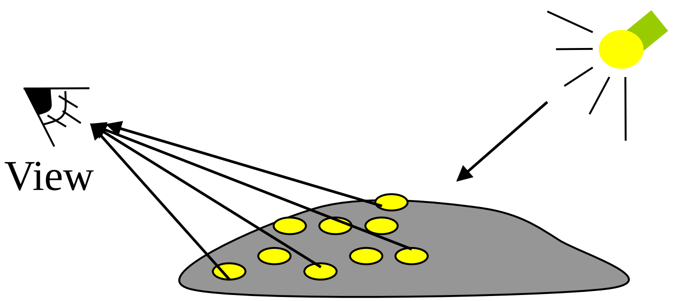


Shading models

Ideally, the renderer should apply lighting models at every visible point on each surface, but this approach requires too much computation.

Alternatively,

- Apply lighting models only to visible surfaces
- Apply lighting models at a subset of points.
- Interpolate the intensity at other points.



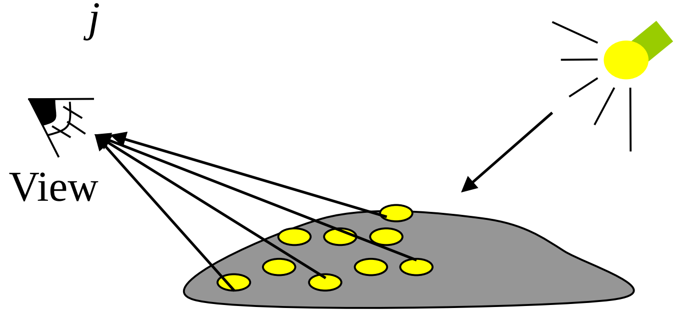
Shading models

Interpolation:

- Flat (Constant) Shading (**Nearest Neighbour Interpolation** of the illumination)
- Gouraud shading (Linear Interpolation of the **illumination**)
- Phong shading (Linear Interpolation of the **normal vectors**)

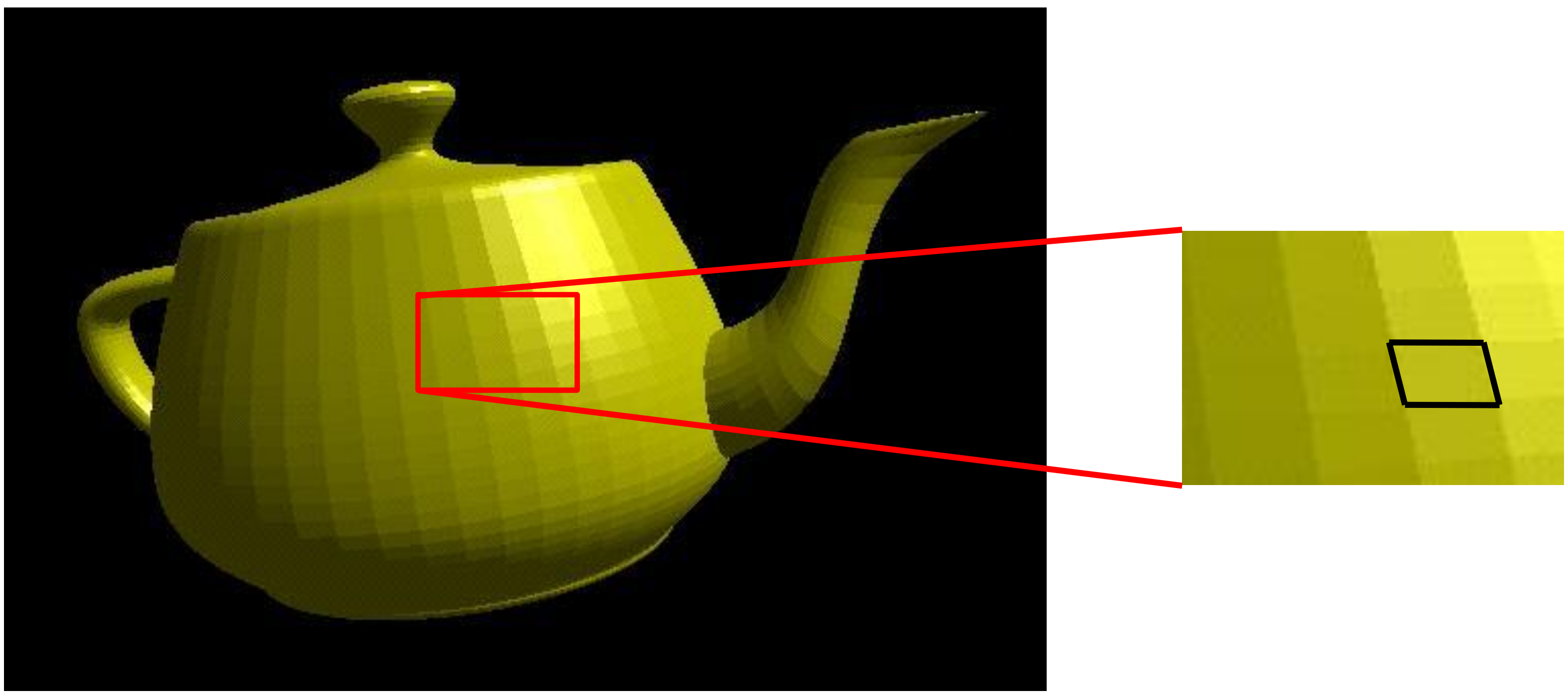
$$I_\lambda = I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} (k_d \cdot \cos\theta_j + k_s \cdot \cos^n \alpha_j)$$

$$= I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} \left(k_d \cdot (\vec{\boldsymbol{N}} \cdot \vec{\boldsymbol{L}}_j) + k_s \cdot (\vec{\boldsymbol{R}}_j \cdot \vec{\boldsymbol{V}})^n \right)$$



Flat (Constant) Shading

- Compute lighting once at one point per polygon and assign the color to the whole polygon.

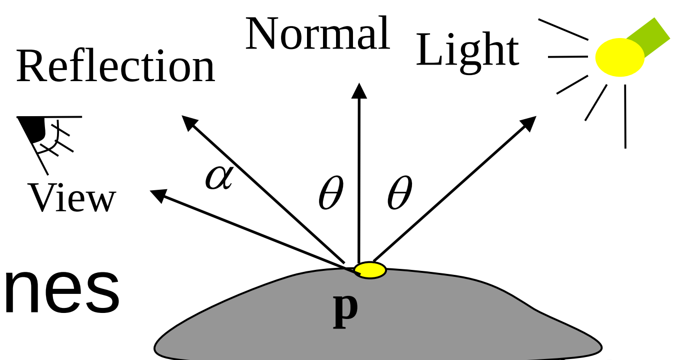


About Flat Shading

- Intensity interpolation: use constant
- Flat shading is good if:
  - The surface is faceted, not curved: ***N*** is constant.
  - Light source is very far away: ***L*** and ***R*** are constant
  - The viewer is very far away: ***V*** is constant

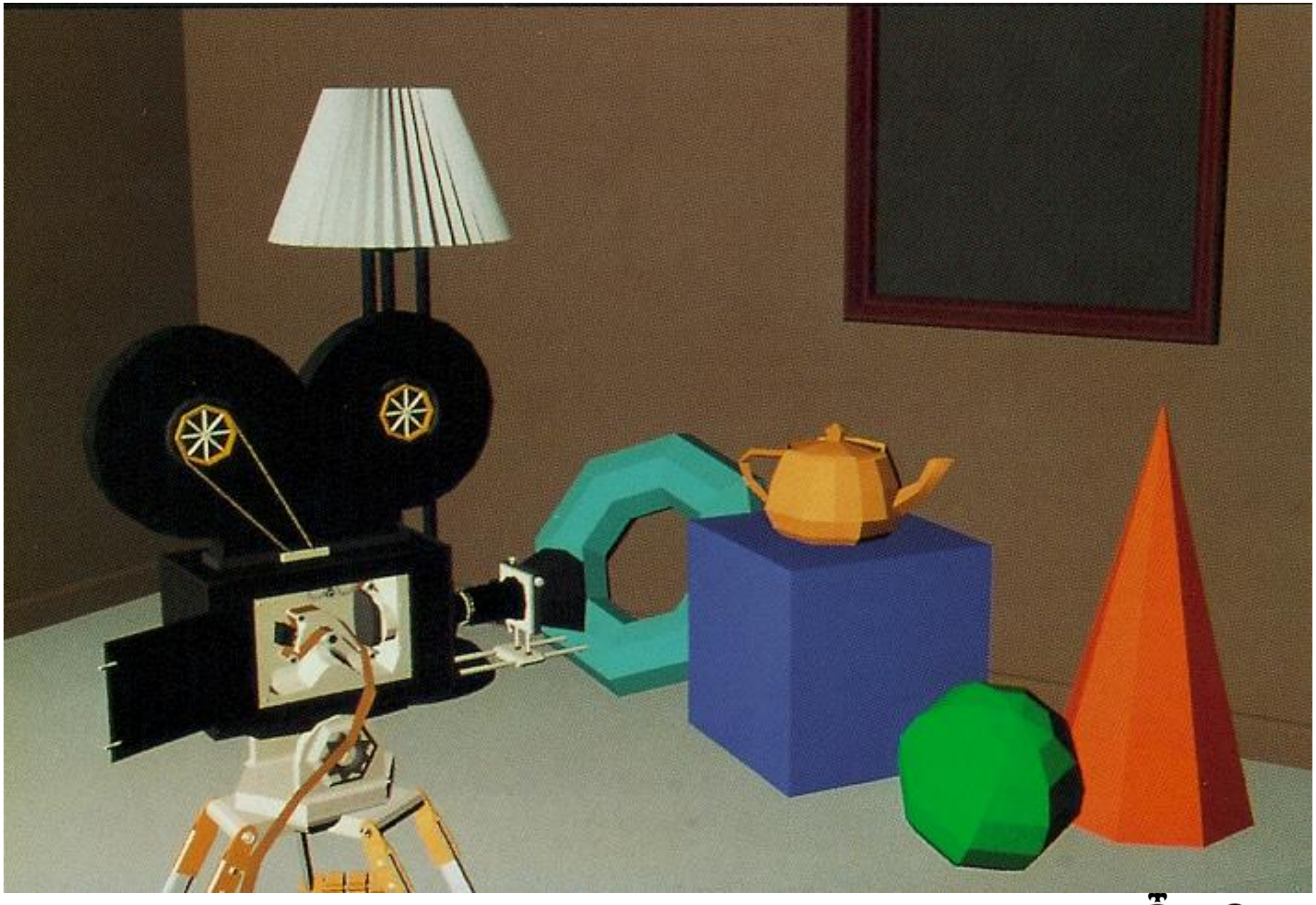
$$I_\lambda = I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} (k_d \cdot \cos\theta_j + k_s \cdot \cos^n \alpha_j)$$

$$= I_{a\lambda} \cdot k_a + \sum_j f_{att_j} I_{l\lambda_j} \left(k_d \cdot (\vec{\boldsymbol{N}} \cdot \vec{\boldsymbol{L}}_j) + k_s \cdot (\vec{\boldsymbol{R}}_j \cdot \vec{\boldsymbol{V}})^n \right)$$



- Good for coarse preview of scenes

Flat Shading Example



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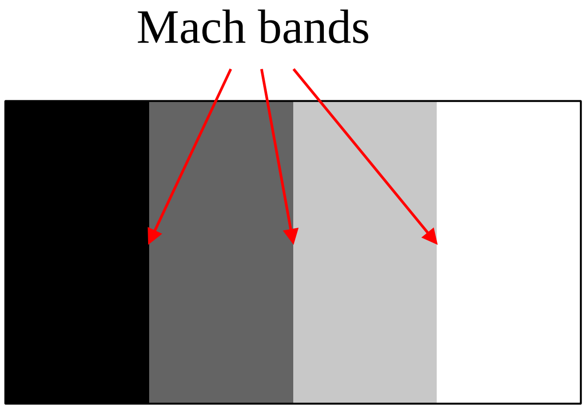
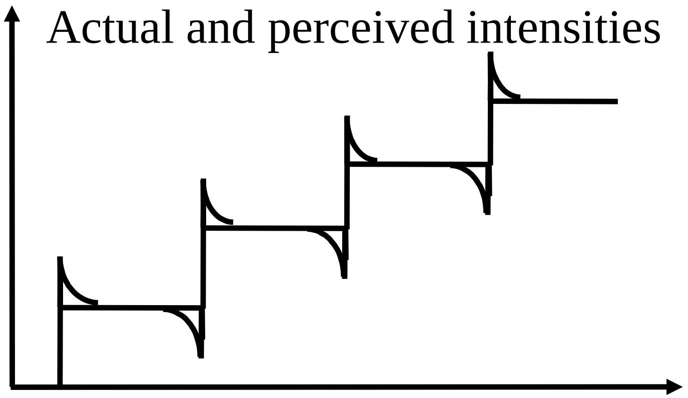
Problem: Mach Band Effect

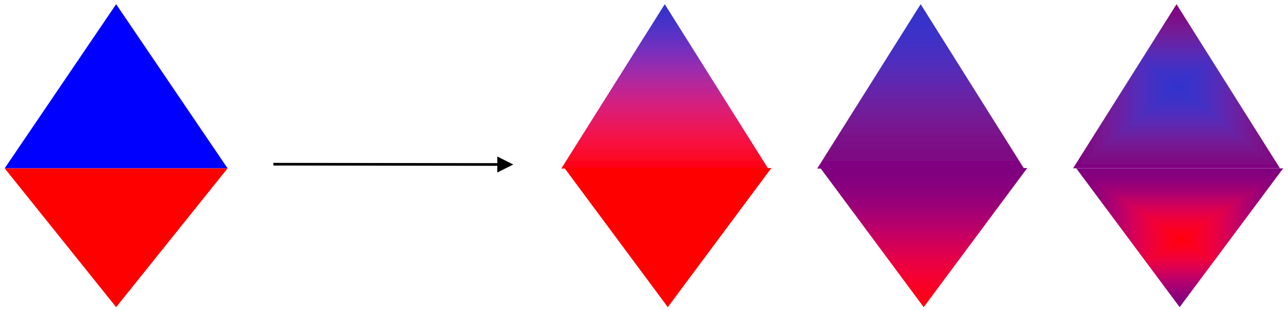
- Flat shading suffers from a perceptual artifacts – "Mach band effect"
- Mach band effect – for human eyes, imaginary dark and light lines appear at the face boundaries
- Intensity change is exaggerated : Dark facet looks darker and lighter looks even more lighter





Solution: Smooth Shading

- Fix the Mach band effect – remove edge discontinuity
- Compute at more points on each face

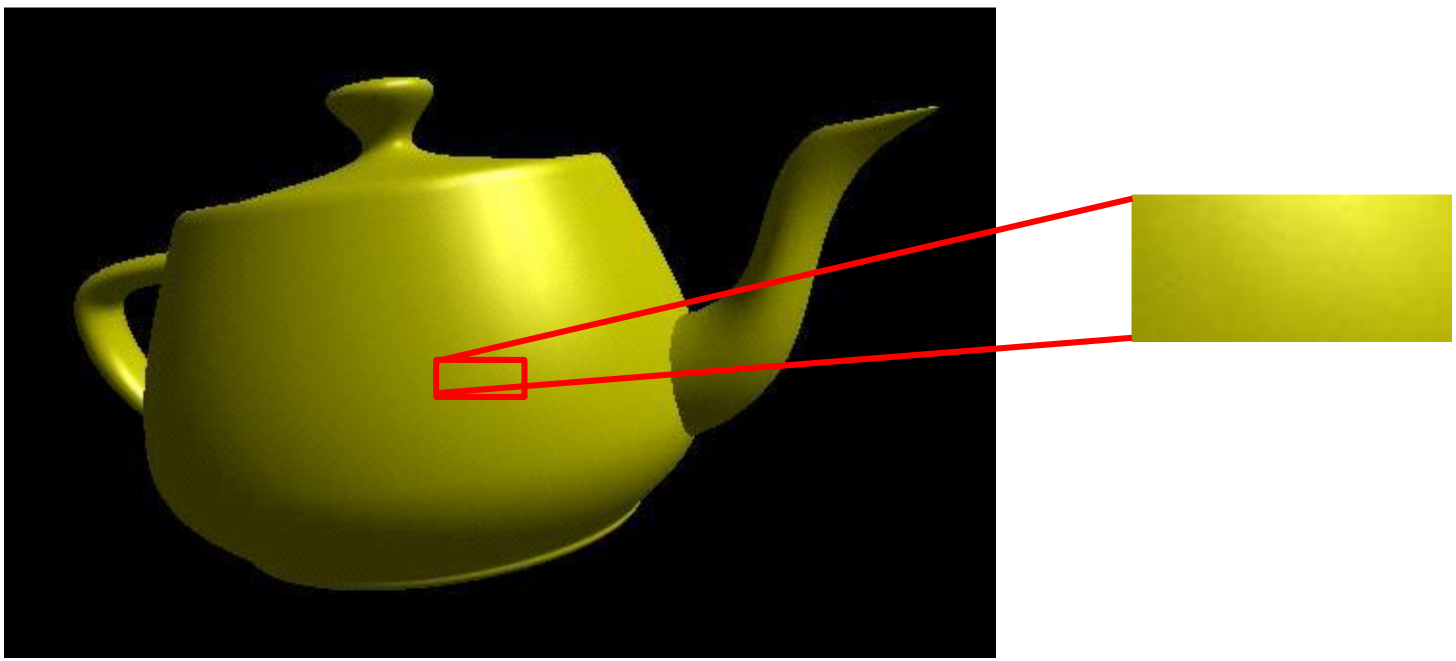


Flat shading Smooth shading

- Two popular methods: Gouraud, Phong

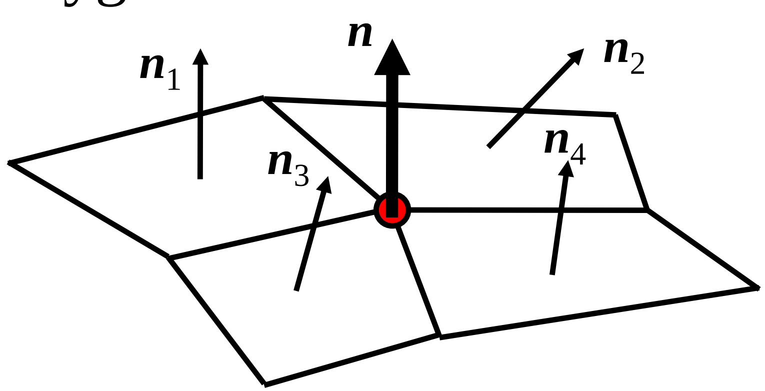
Gouraud Shading Idea

- Also called ***intensity interpolation shading***
- Lighting is calculated for each of the polygon vertices, colours are interpolated for interior pixels



About Gouraud Shading

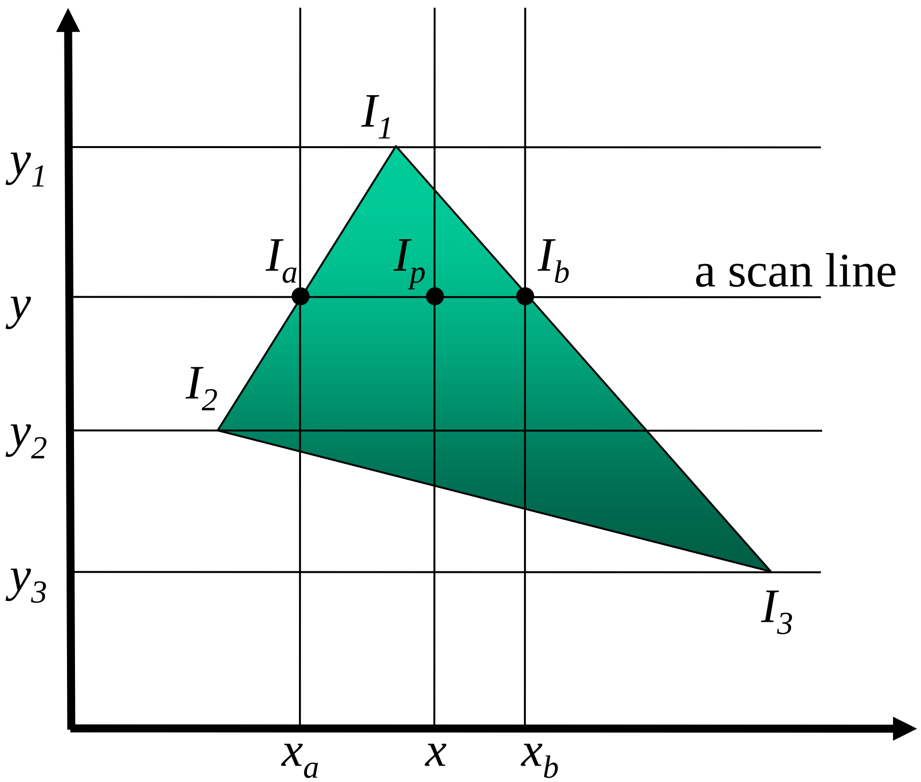
- Intensity interpolation: linear across a face
- Lighting calculation is only for vertices. Normals are only needed for each vertex of polygons.
- The normal at each vertex is the average of the normals of its adjacent faces.
- Fast, supported by most of the graphics accelerator
- Valid for small polygons



$$\boldsymbol{n} = (\boldsymbol{n}_1 + \boldsymbol{n}_2 + \boldsymbol{n}_3 + \boldsymbol{n}_4) / 4$$

Gouraud Shading Interpolation

- Use bilinear interpolation to find intensity I_p at a point along polygon edges and scan lines.

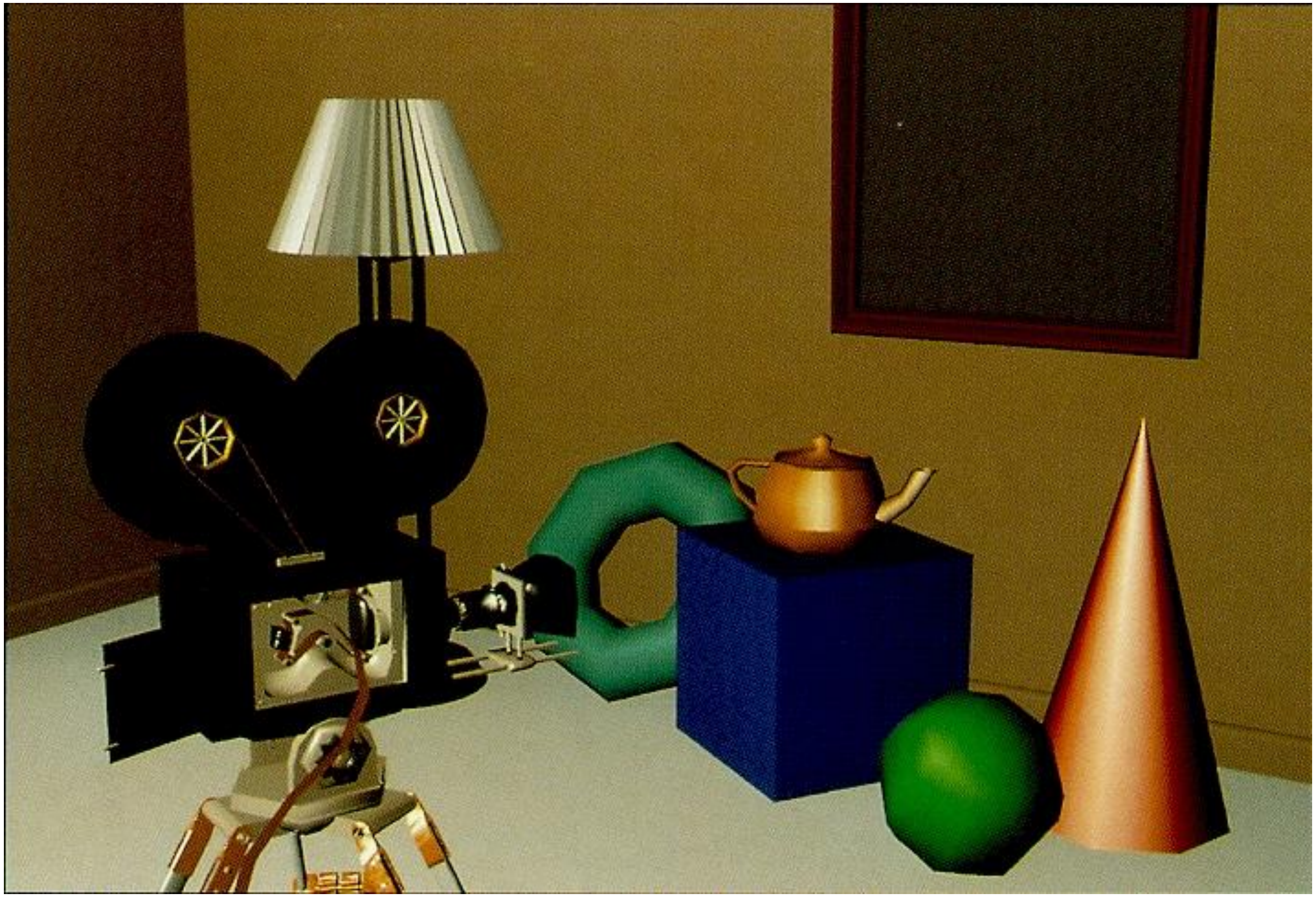


$$I_a = I_1 + (I_2 - I_1)\frac{y - y_1}{y_2 - y_1}$$

$$I_b = I_1 + (I_3 - I_1)\frac{y - y_1}{y_3 - y_1}$$

$$I_p = I_a + (I_b - I_a)\frac{x - x_a}{x_b - x_a}$$

Gouraud Shading Example



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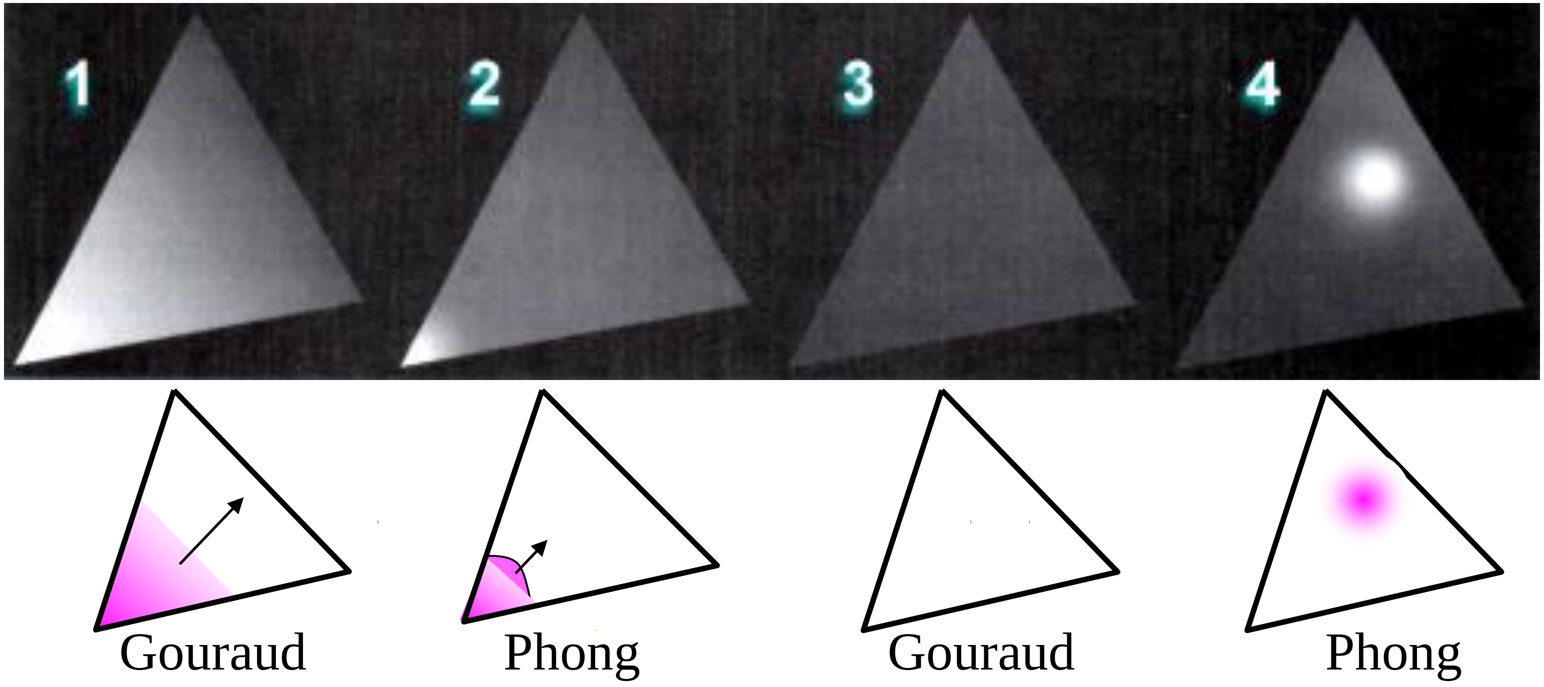
Gouraud Shading Problems

- Reduces Mach bands (but not entirely).
- May miss interior specular highlights if it's not at vertices.
- May spread specular highlights along edges.
- Some repetitive 3D patterns can be missed completely.



What happened?

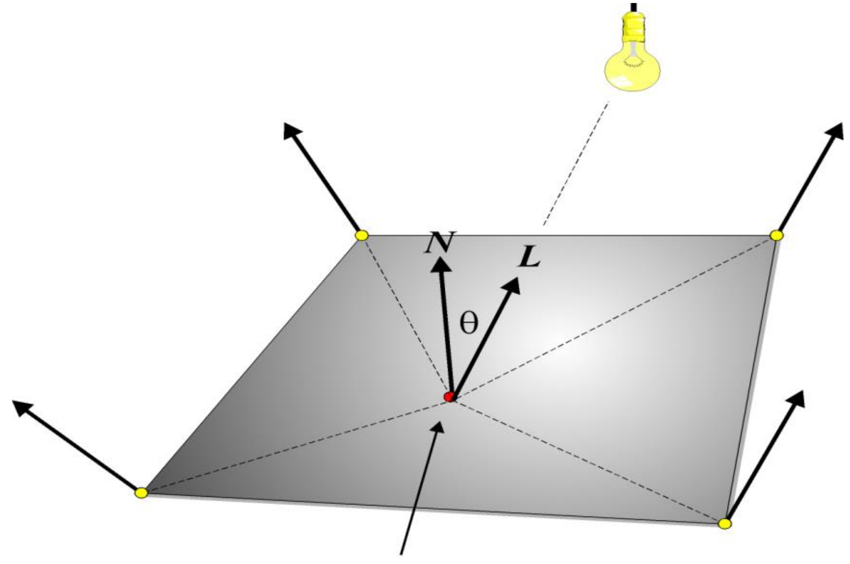
- Gouraud shading method:
  1. Compute the normal at each vertex
  2. Compute the intensity at the vertices with a lighting model with the normals
  3. Interpolate the intensity across a face with those at vertices.
- Gouraud method applies the lighting model at each vertex, then interpolates pixel **intensities**
  - This requires a normal **only at the vertices**

It didn’t use the **normals** in faces!

- We need to apply the lighting model at all pixels
  - This requires a normal (***N***) at each pixel, we need all the not-provided normals
  - ***N*** at each point can be interpolated from ***N*** at vertices

Phong Shading

- Also called ***normal-vector interpolation shading***
- Involves the following steps
  - A normal at a vertex is computed as the average of the normals of all the adjacent faces
  - Normals at each interior pixel are calculated by linear interpolation of the normals at the vertices



Interpolated normal at the interior point

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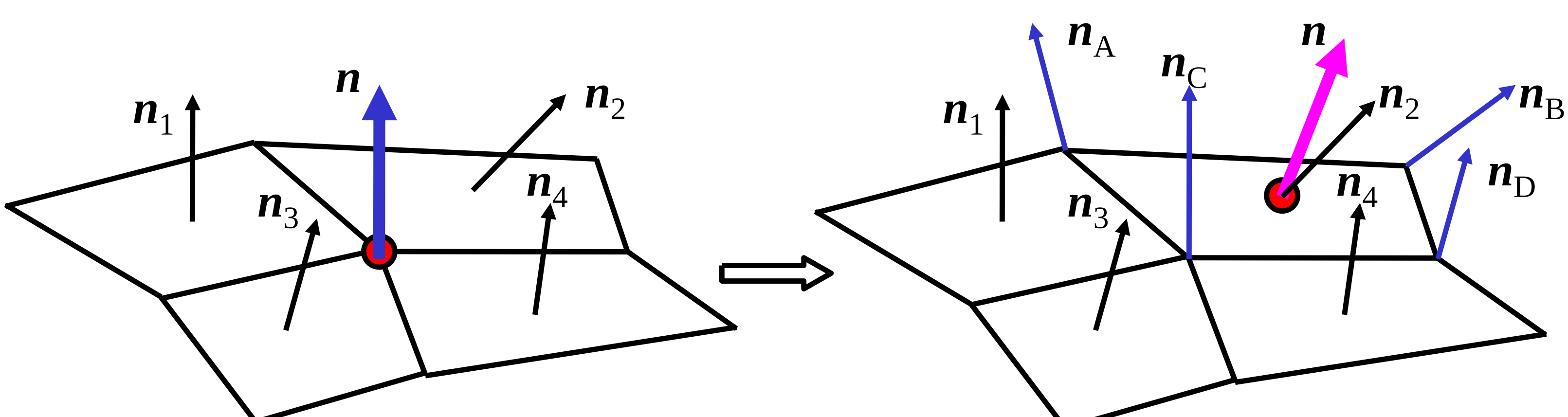
About Phong Shading

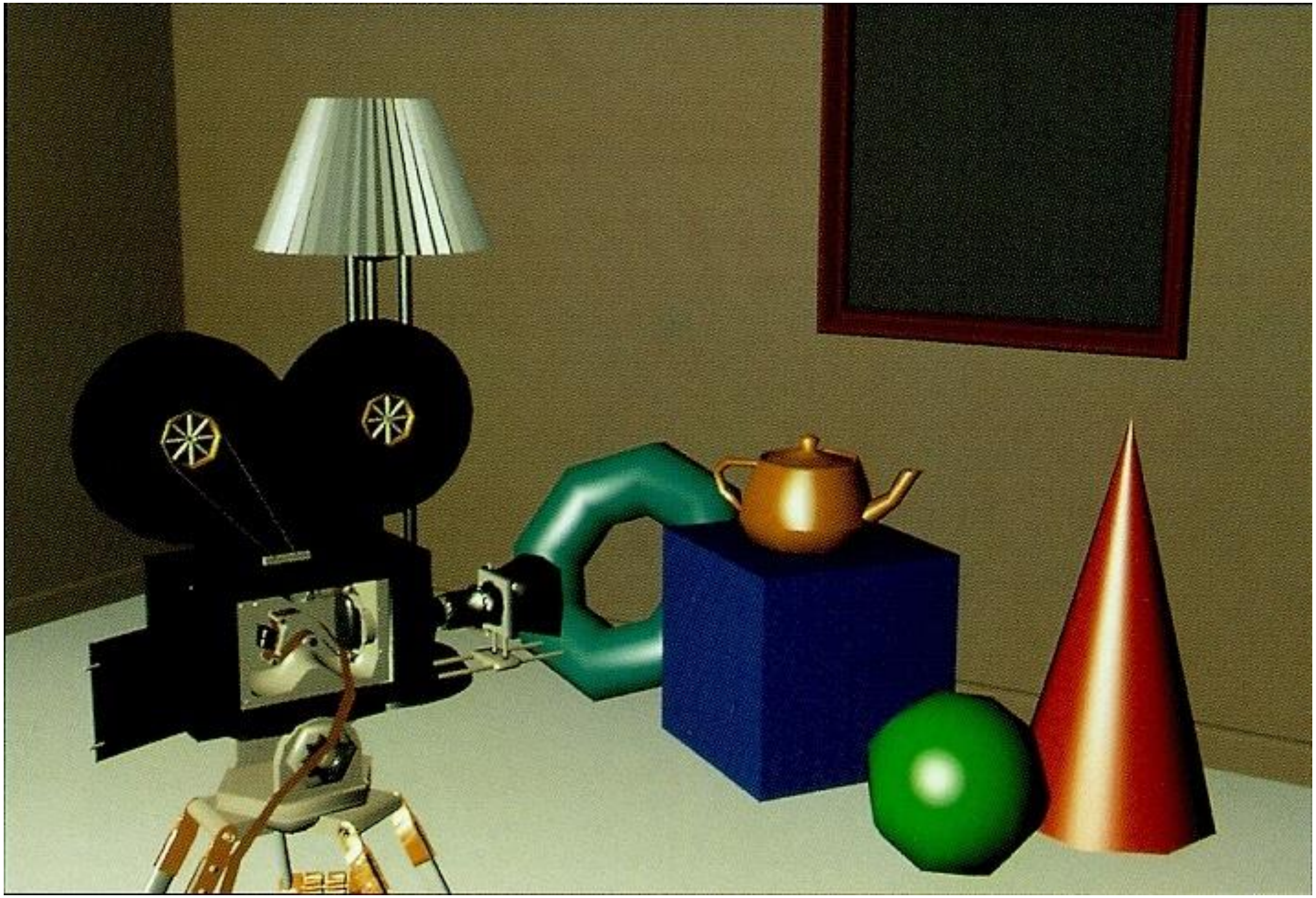
- Normal interpolation: bilinear across a face
- Interpolation is done after or before perspective transform
- Interpolation of normals is done like intensity interpolation in Gouraud shading
- More accurate, but slow. Not widely supported by hardware
- Good for smooth surfaces



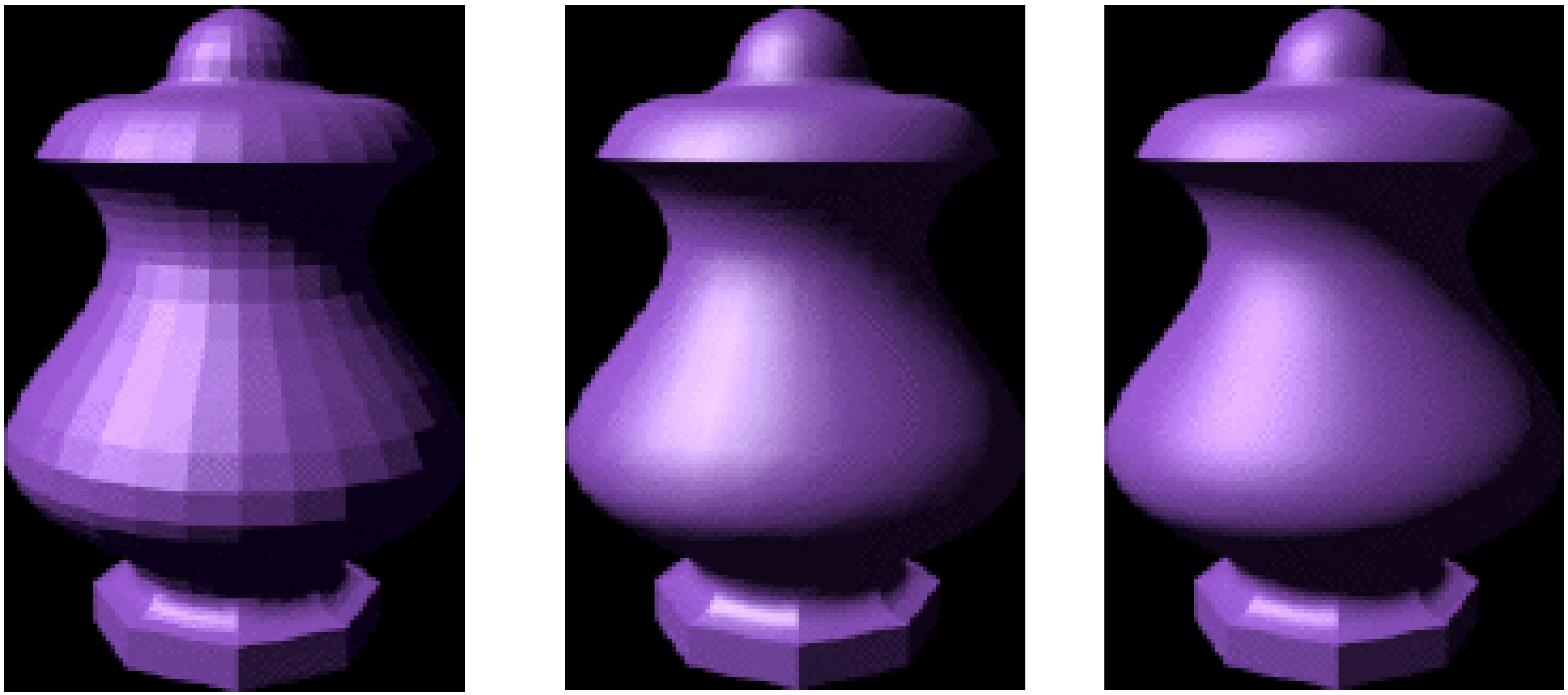
$\boldsymbol{n} = (\boldsymbol{n}_1 + \boldsymbol{n}_2 + \boldsymbol{n}_3 + \boldsymbol{n}_4) / 4$

$\boldsymbol{n} = a\boldsymbol{n}_A + b\boldsymbol{n}_B + c\boldsymbol{n}_C + d\boldsymbol{n}_D$

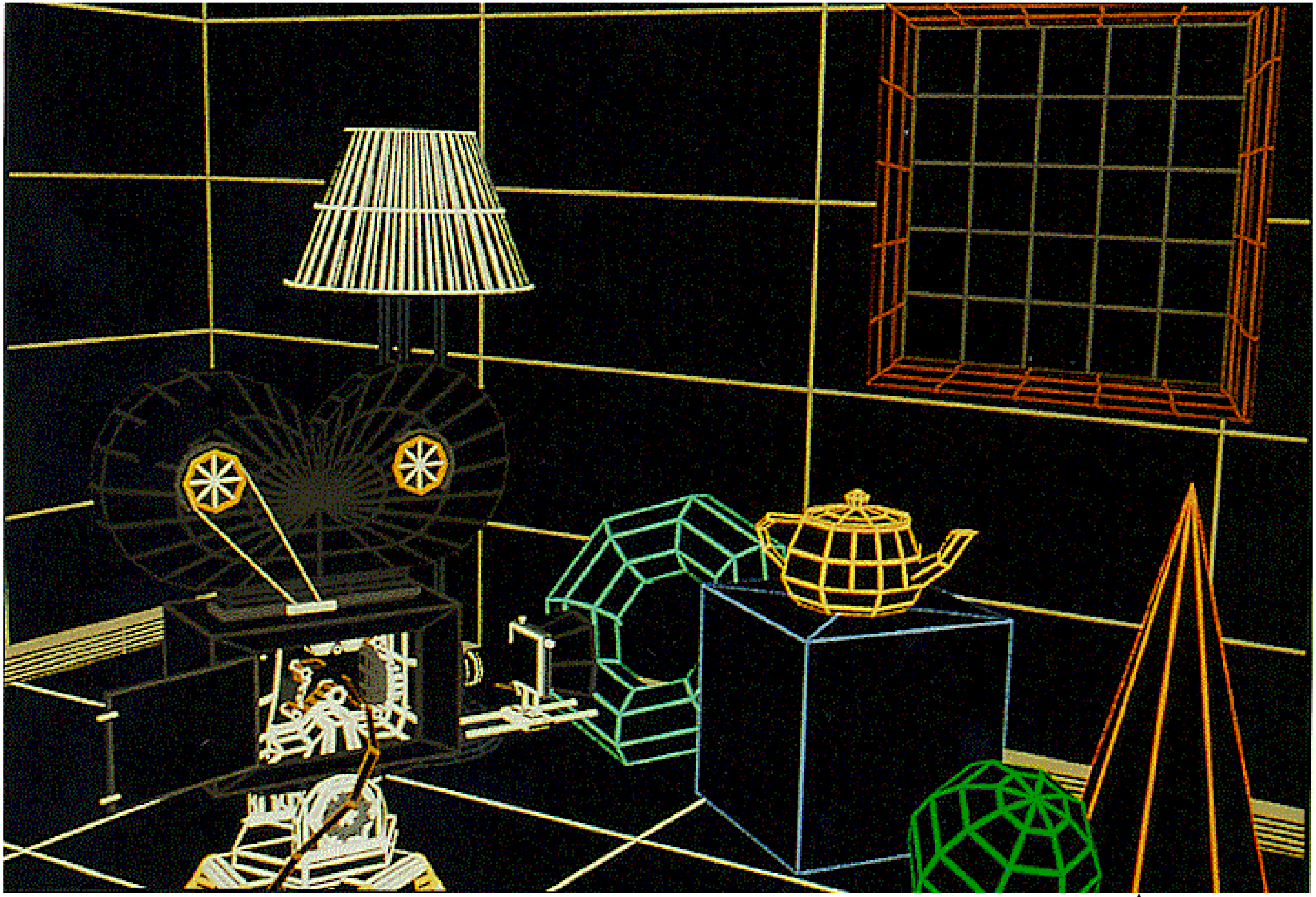
Phong Shading Example



Flat, Gouraud and Phong Shading

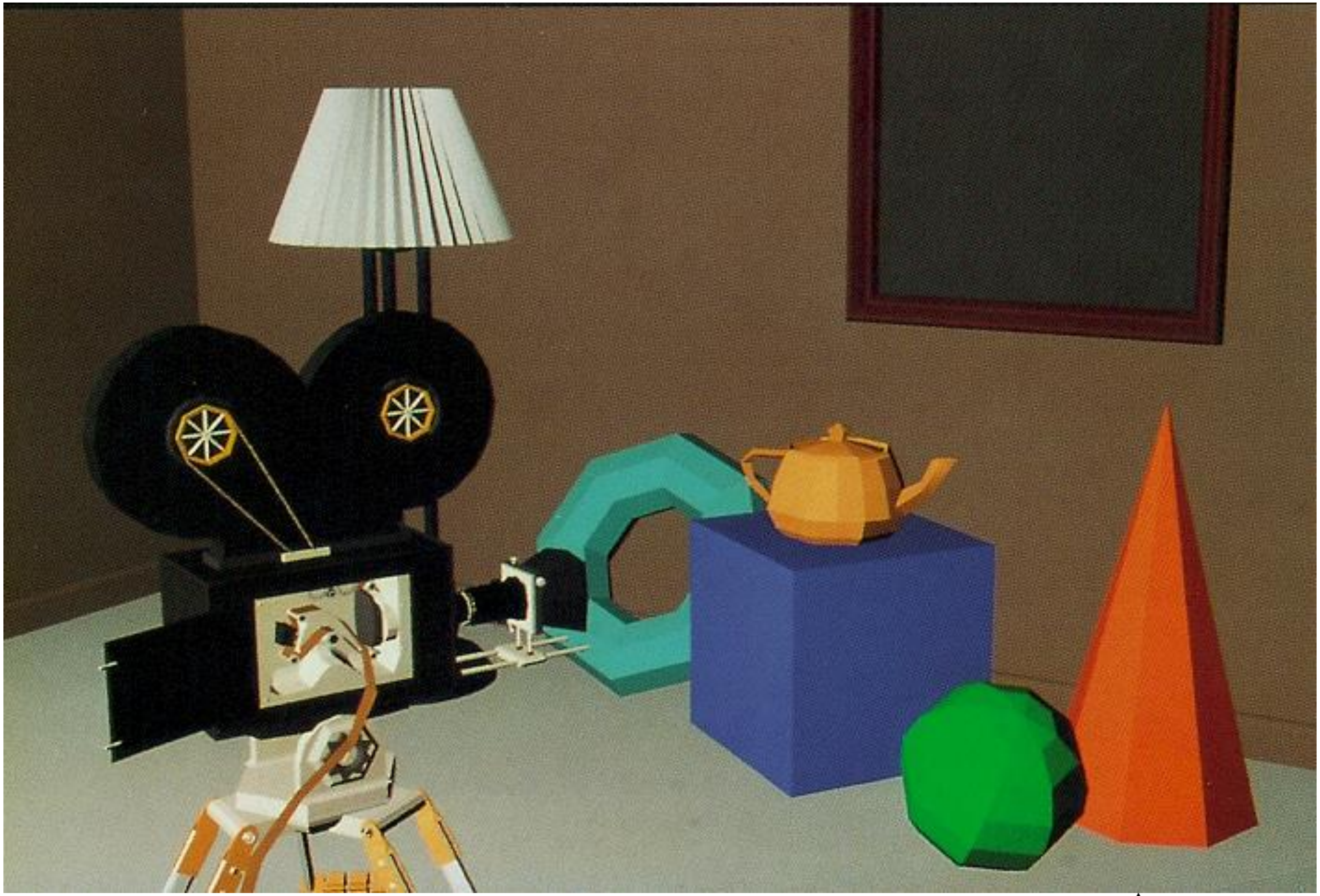


Coloured lines



Ambient lighting

Flat shading



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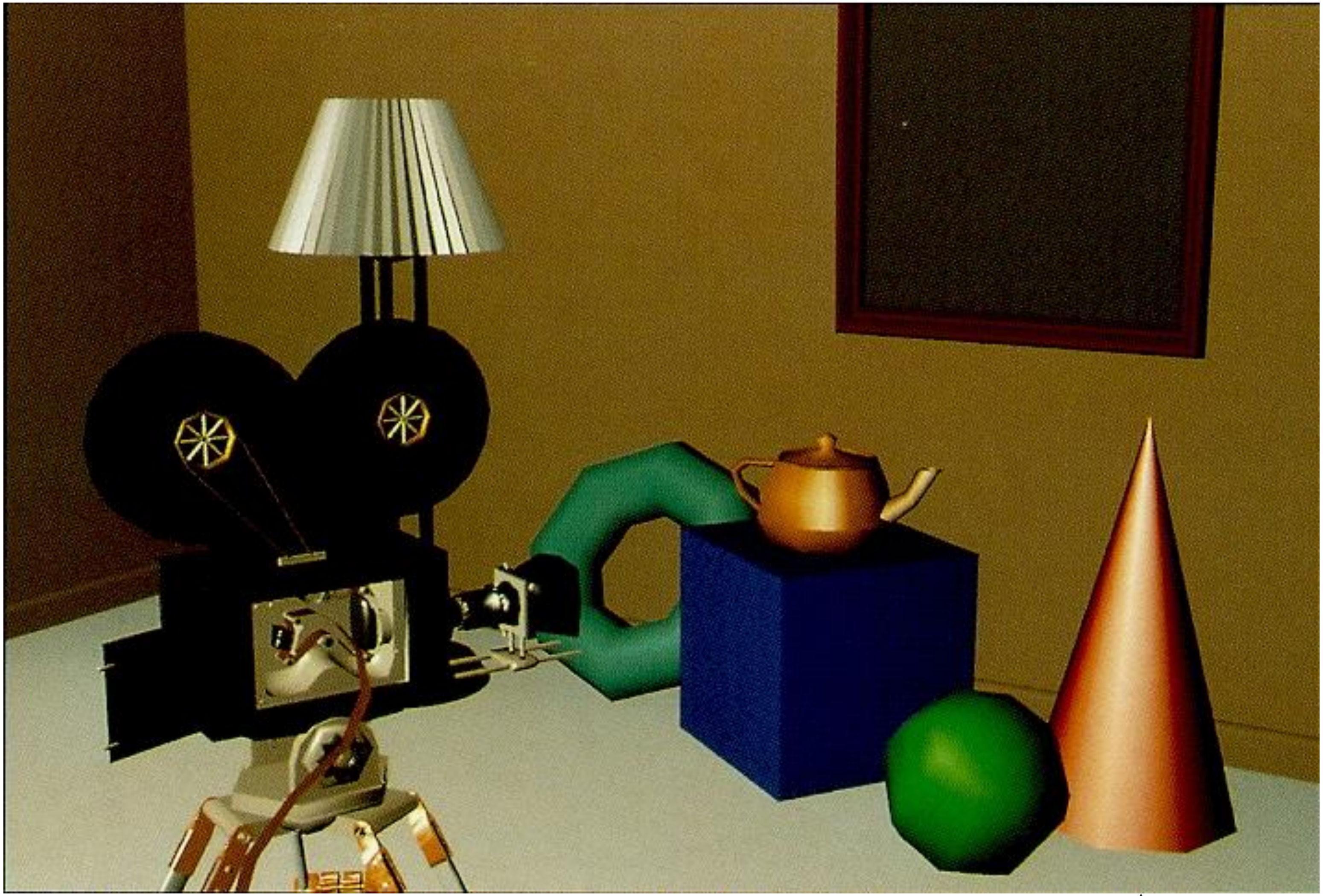
Gouraud shading



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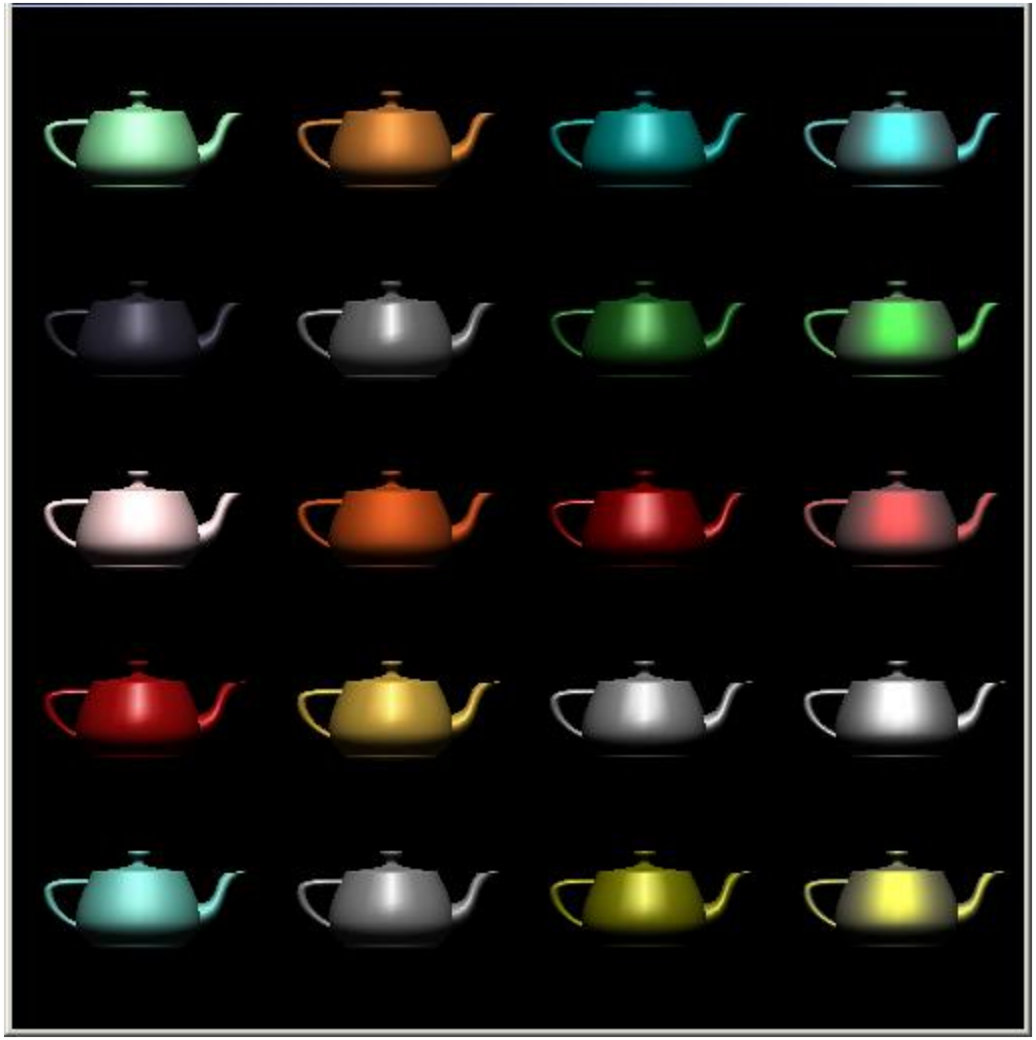
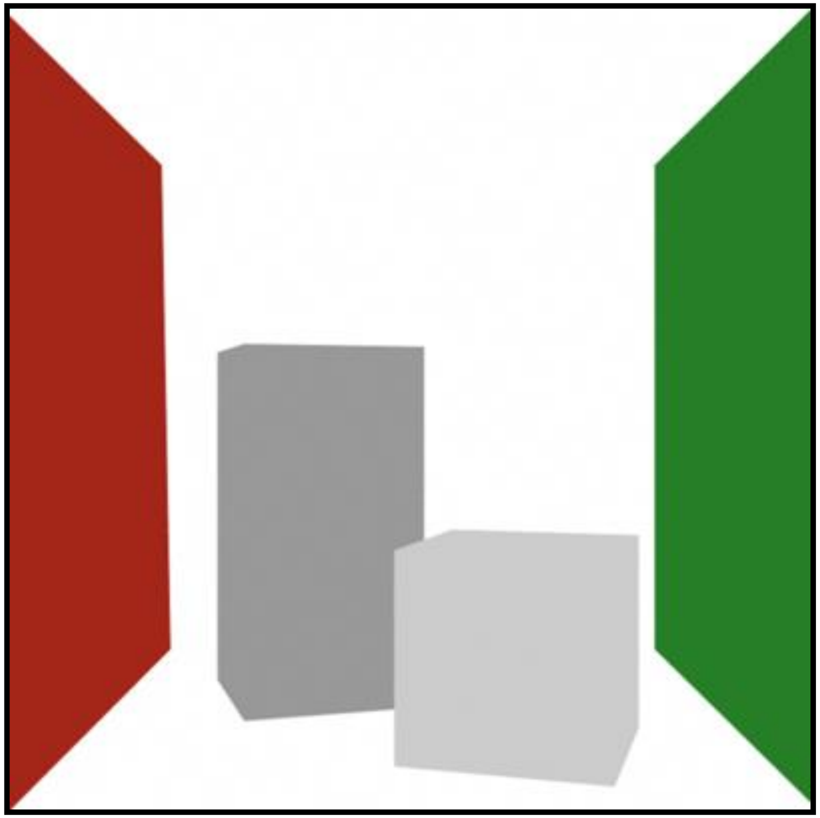
Phong shading

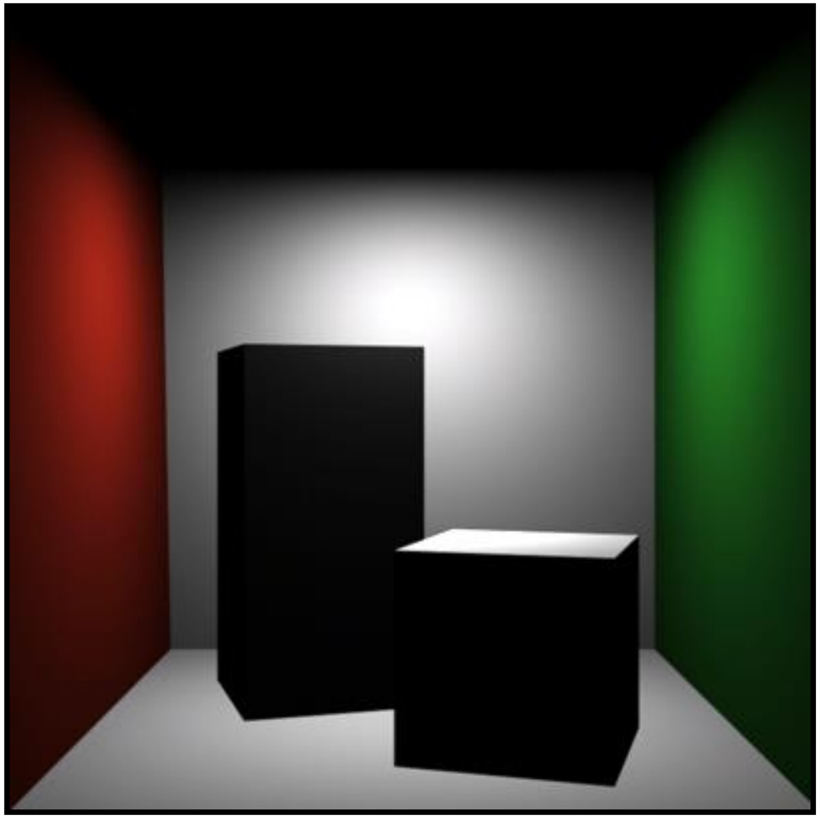
Teapot Examples



Lighting example: diffuse reflection



Surface Color



Diffuse Shading

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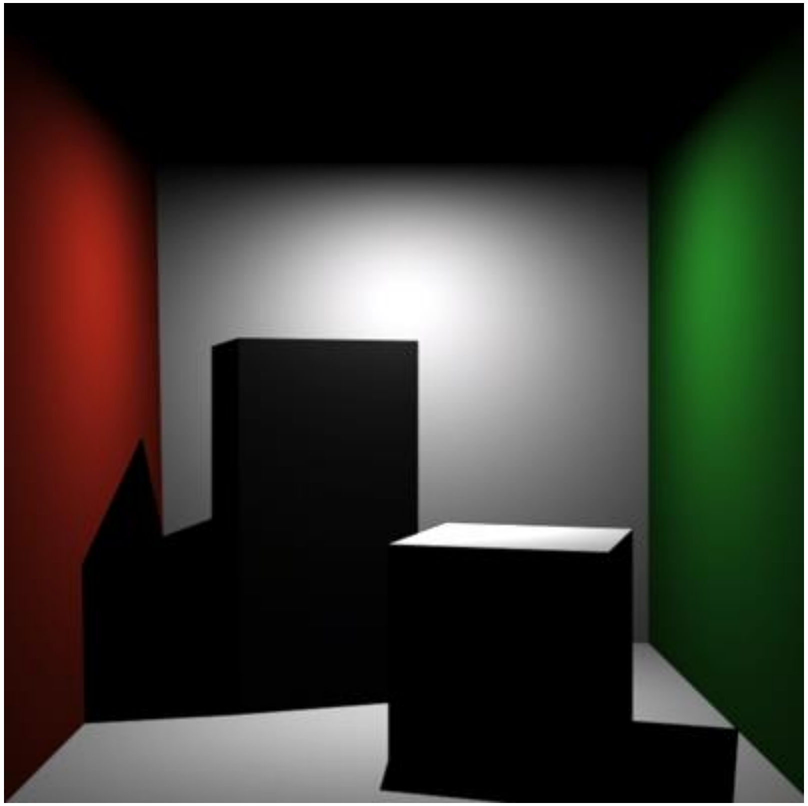
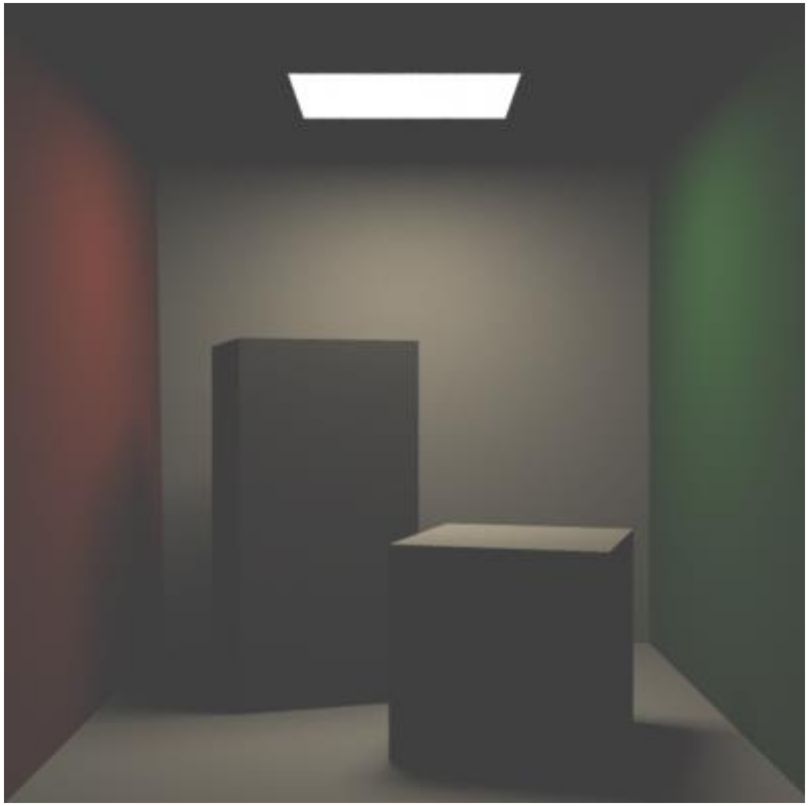
Lighting example: soft shadows



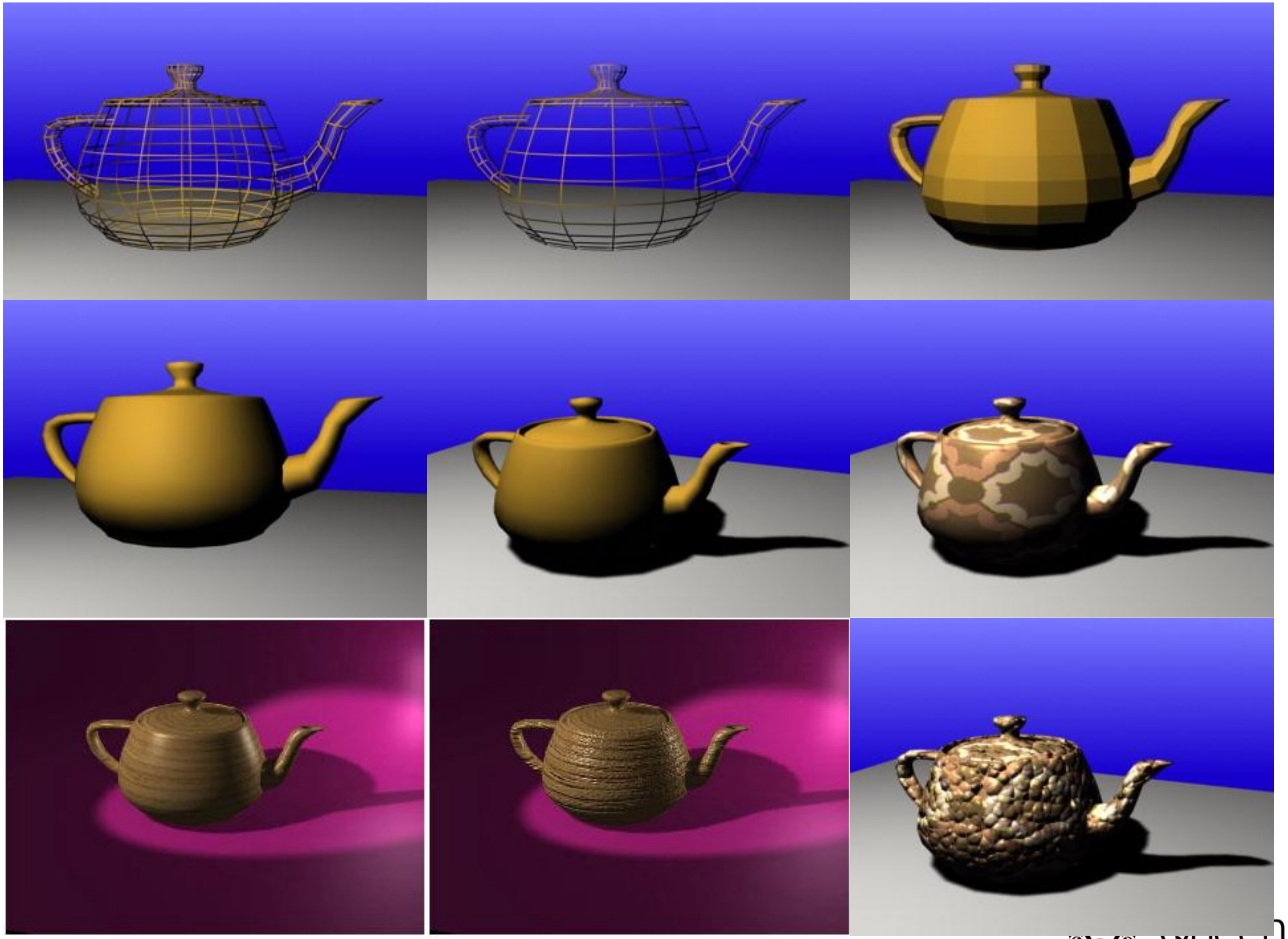
Hard Shadows
Point Light Source



Soft Shadows
Area Light Source

With more surface details

The whole story



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