Computer Graphics: 5-The Graphics Pipeline

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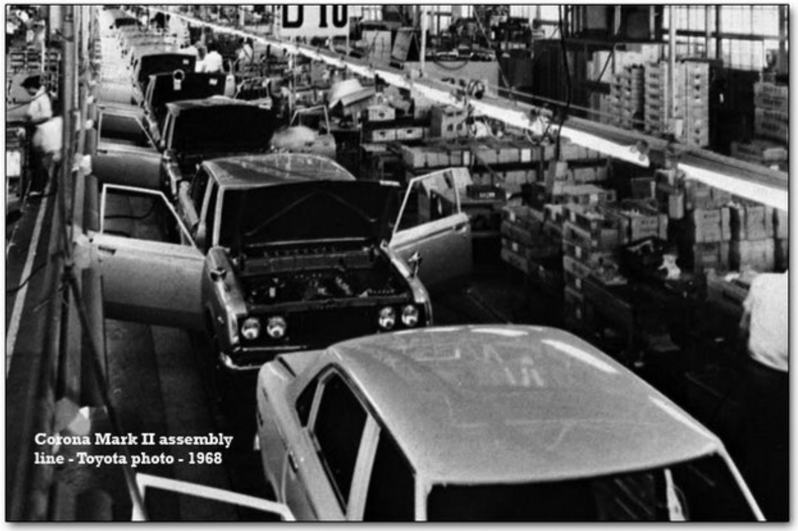
Introduction

- Themes of the this lesson(s) will be:
  - A trip down the Graphics pipeline
  - Detailed information on some of its stages

Graphics Pipeline

- What is the graphics pipeline?
  - Given an idea, we want to
    - Model the idea into
      - Geometry
      - Surface properties
      - Maybe model movement (for animation)
    - Generate pictures out of these models
  - Computer Graphics people have defined a workflow for generating pictures
  - Repeat over and over for each rendered picture one of a scene or animation
  - This process is done in stages, just like at a car factory



Graphics Pipeline: Overview

- The Graphics Application pipeline

Application → Geometry → Rasterization

Application	Geometry	Rasterization
• Supplies geometric data: – points, – polygons, – Curves • Converts into triangles	• Apply transformations • Shading • Clipping	• Fill pixel by pixel surviving triangles • Uses interpolation on vertex data

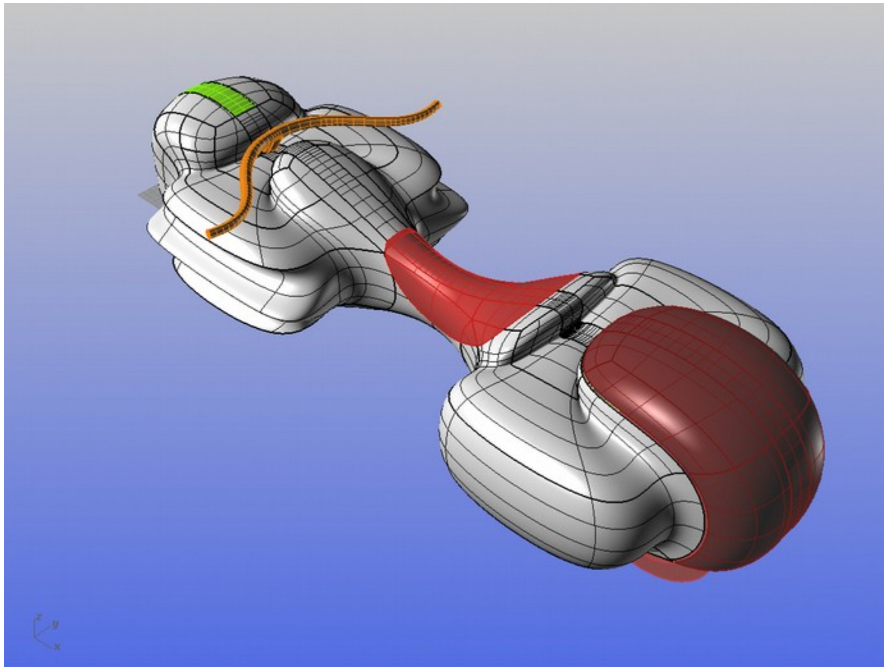
- Let us explain these different stages

Graphics Pipeline: Supply geometric data

Pipeline:

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
Converts into triangles	Shading	Interpolate: lighting+texture
	Clipping	

- Modeling application supplies:
  - Objects
  - Lights
  - Surface properties:
    - Colour: basic colour, diffuse and specular reflection
    - Textures
    - Surface characteristics: bumps, transparency



Courtesy © Rhino3D

Graphics Pipeline: Convert into triangles

Pipeline: Application → Geometry → Rasterization

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
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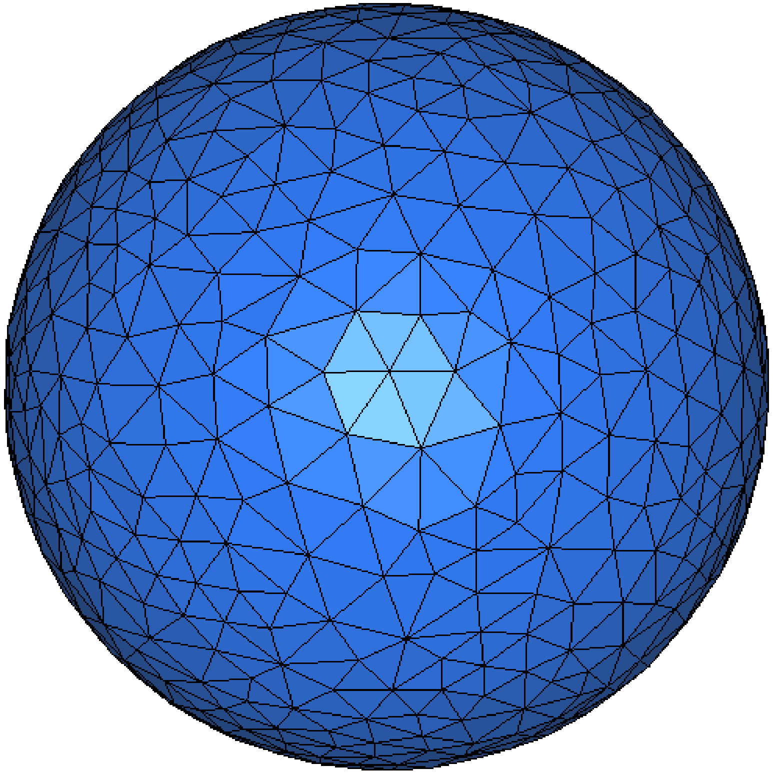
- First thing:
  - Everything triangles!
- Why?
  Simple!
  - They are polygons
  - They have always the same number of sides and vertices
  - This will get us into some trouble later…



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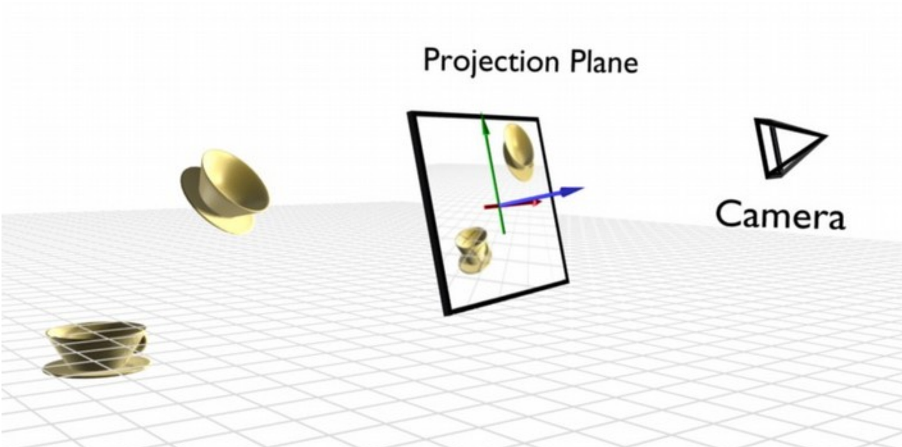
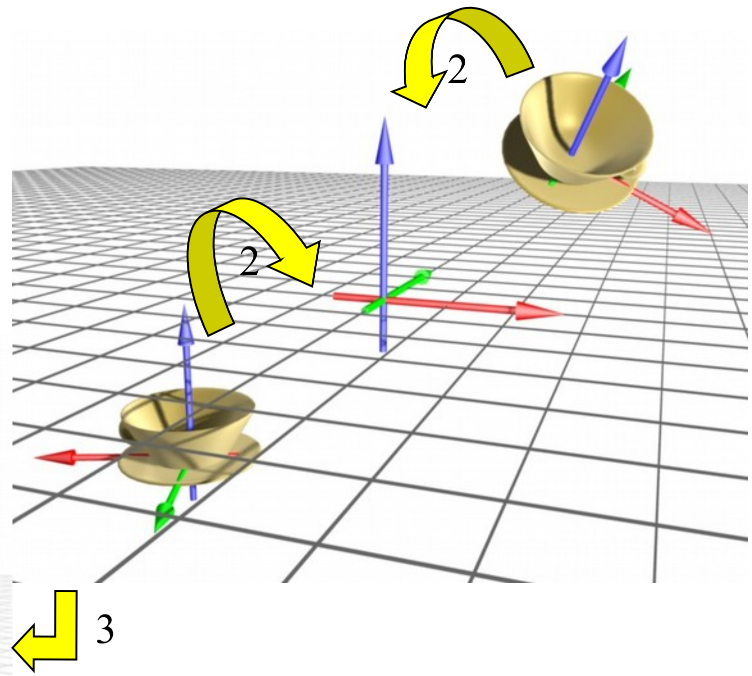
Graphics Pipeline: Apply transformations

Pipeline: **Application** → Geometry → Rasterization

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
Converts into triangles	Shading	Interpolate: lighting+texture
	Clipping	

- Second thing:
  - Unify coordinate space, from object to world
- Third thing:
  - Convert to screen (camera) coordinates





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Graphics Pipeline: Shading

Pipeline:

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
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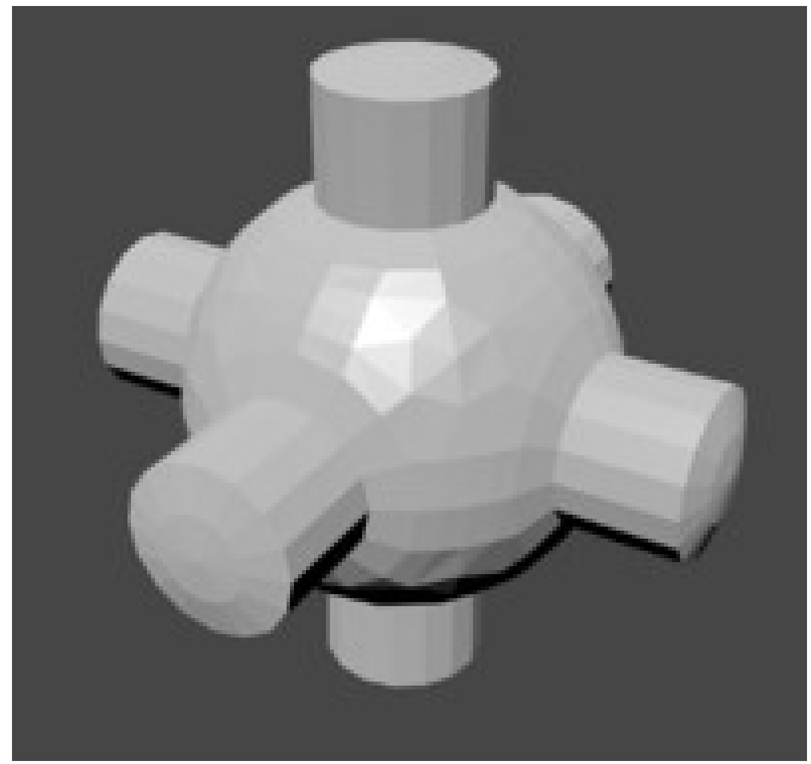
- Shading concerns simulating the interaction of light with the objects.
- The interaction is ruled by the illumination equation, which describes the resulting colour of the object.
- In its simplest form, one illumination value per triangle is computed
- But how is it computed?
  - To know this, we have to digress a bit...



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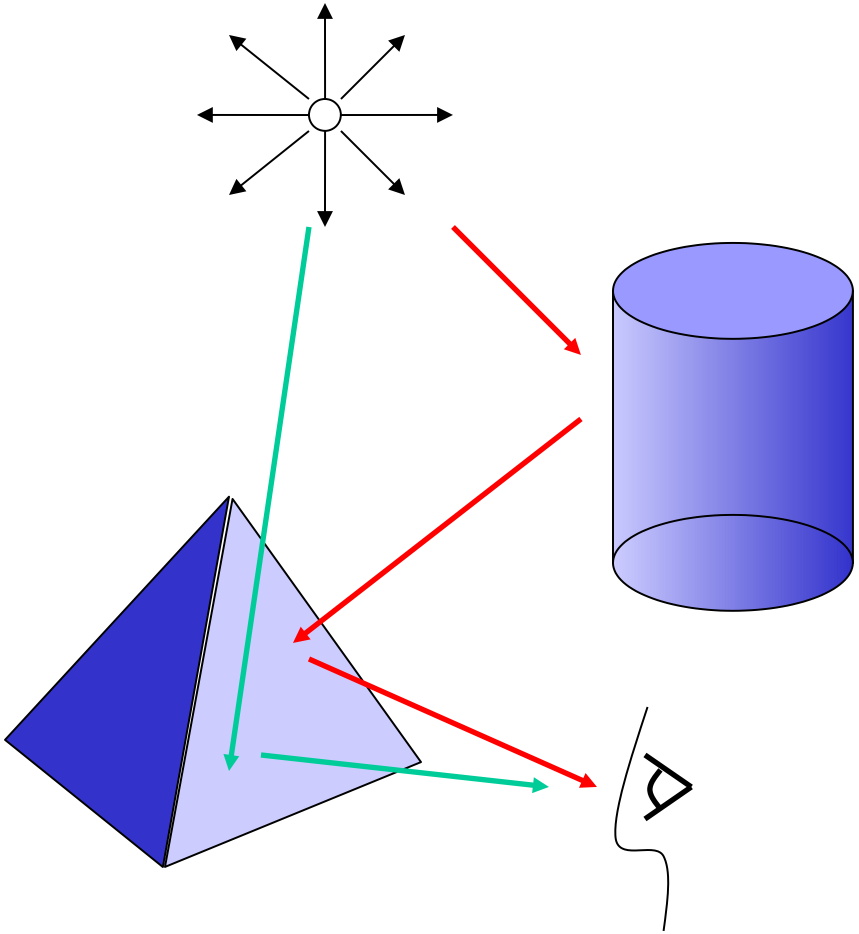
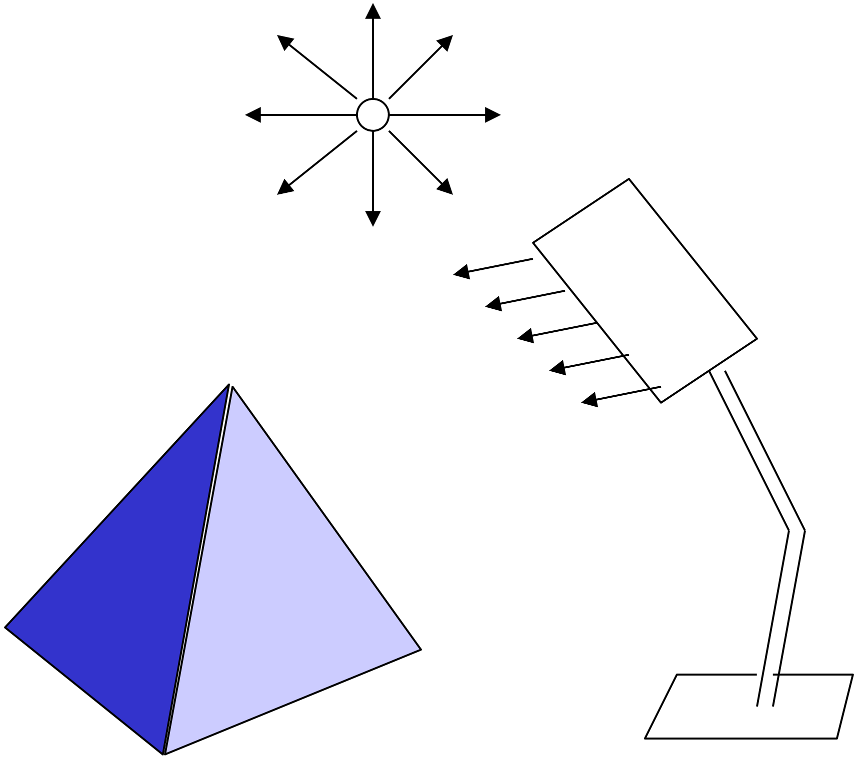
Illumination models

- There are two types of illumination models in Computer Graphics
  - Local illumination models:
    - Light reflected by a surface (and therefore its colour) is dependent only on the surface itself and the direct light sources
  - Global illumination models:
    - Light reflected by a surface is dependent only on the surface itself, the direct light sources, and light which is reflected by the other surfaces on the environment towards the current surface



Lights

- To illuminate a surface, light is needed
- Two major models for light sources
  - Point light sources
    - By putting point light source at infinity one can simulate solar light
    - Diffusion cone can be restricted to simulate spotlights
      (use additional filter function for dimming light)
  - Area light sources (distributed)



Illumination models

- For any object in the environment, a shading function describing how its surface reacts to light is necessary
- For the enviroment, an illumination model is used, which determines what parts of the shading functions are used while rendering the scene
- This illumination model is expressed through an illumination equation
- Given a surface and an illumination model, through the illumination equation the color of its projected pixels on the screen can be computed
- For local illumination, the Illumination Equation is composed of different terms, each adding realism to the scene

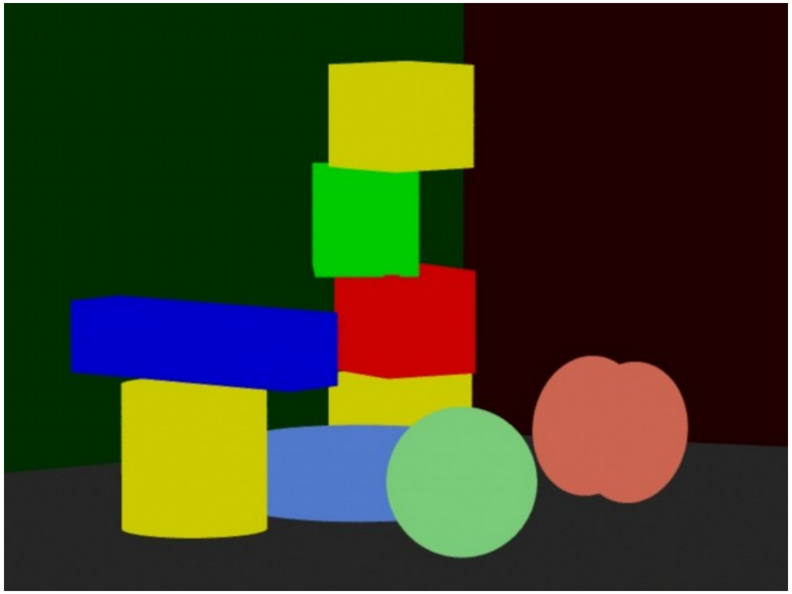
Ambient light

- In local illuminaton models, ambient light is used to model the light that does not come directly from a light source
  - i.e. under the table
- This is the basic colour of an object, to which the other components will be added

- Illumination equation:

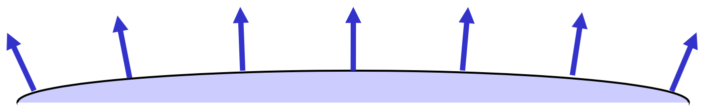
  $$I = k_a I_a$$

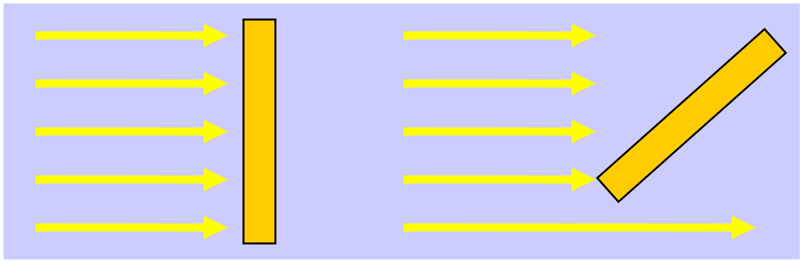
  where
  - k_a: says how much of ambient light is reflected by the object ($k_a \in [0,1]$)
  - I_a: Instensity of ambient light, equal for whole environment



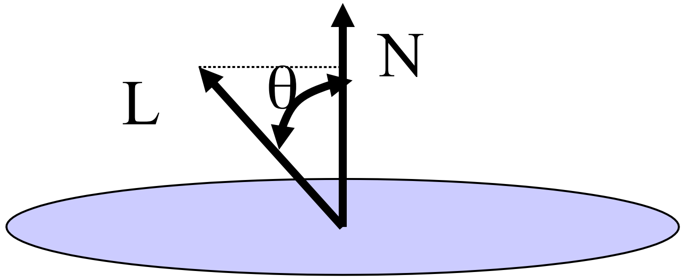
Diffuse reflection: Lambert Law

- Suppose one has a directed light source (point or sunlight)
- Some materials reflect the light equally in all directions
  - Example: chalk
- Lambert observed that the more the incident angle to a surface parts from the surface normal, the darker the colour of the surface
- He also noticed, that objects show the same intensity even if the viewer is moving around
- The reason is that viewers percieve the same amount of light per angle on the retina, no matter what their viewing angle





- Reflected light intensity must therefore be dependent from the projection of the light vector onto the normal to the surface



Diffuse reflection: Lambert Law

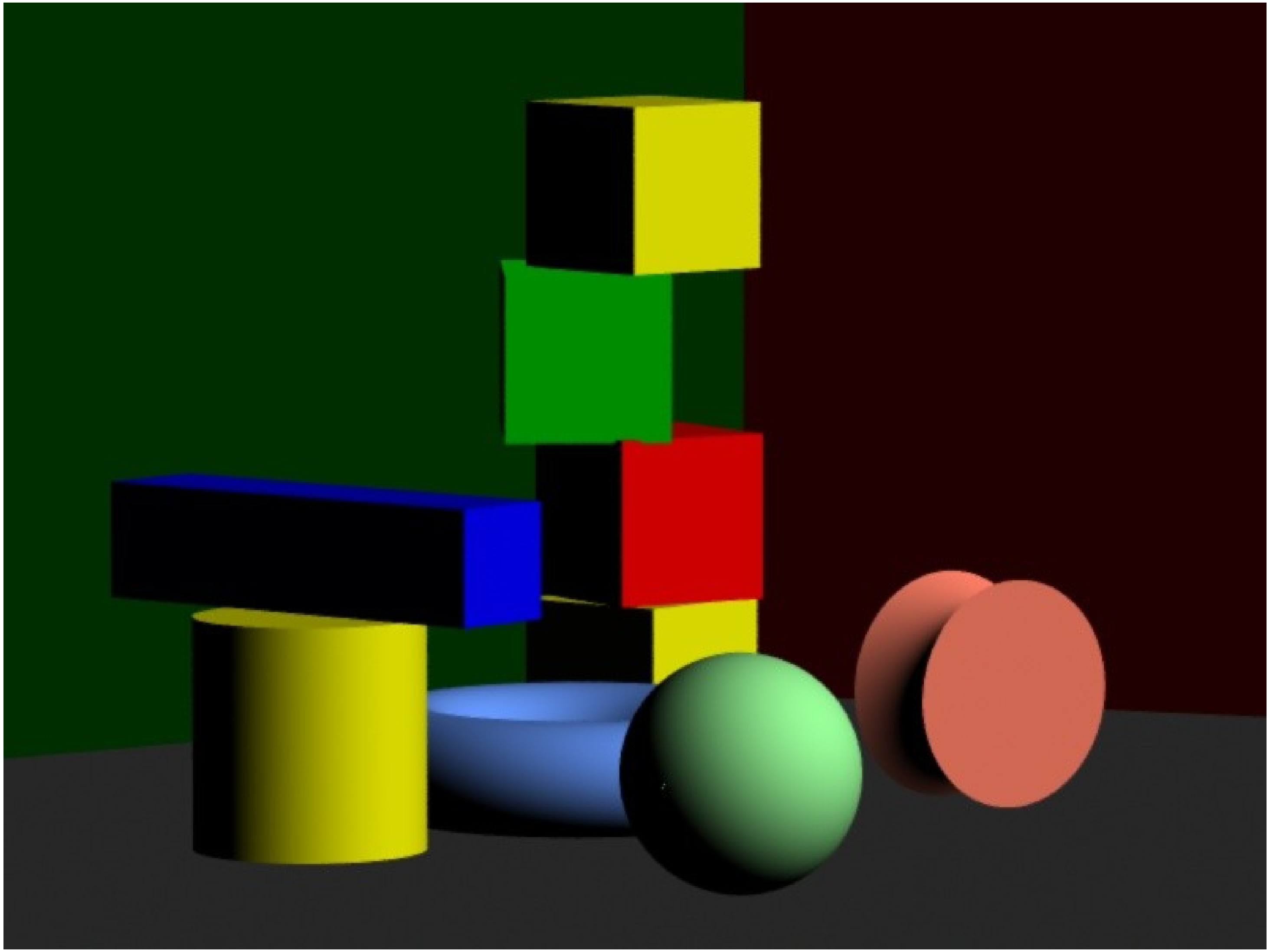
- Thus, the total reflected light is given by

$$I_{diff,Lam} = I_P k_d \cos\theta$$

  where
  - I_P: Intensity of incident light at surface
  - k_d: diffuse reflection coefficient of the material $\in [0,1]$
  - Θ: angle between normal to surface and direction of incident light
- Or, by using normalized vectors N and L

$$I_{diff,Lam} = I_P k_d (N \cdot L)$$

Diffuse reflection: Lambert Law



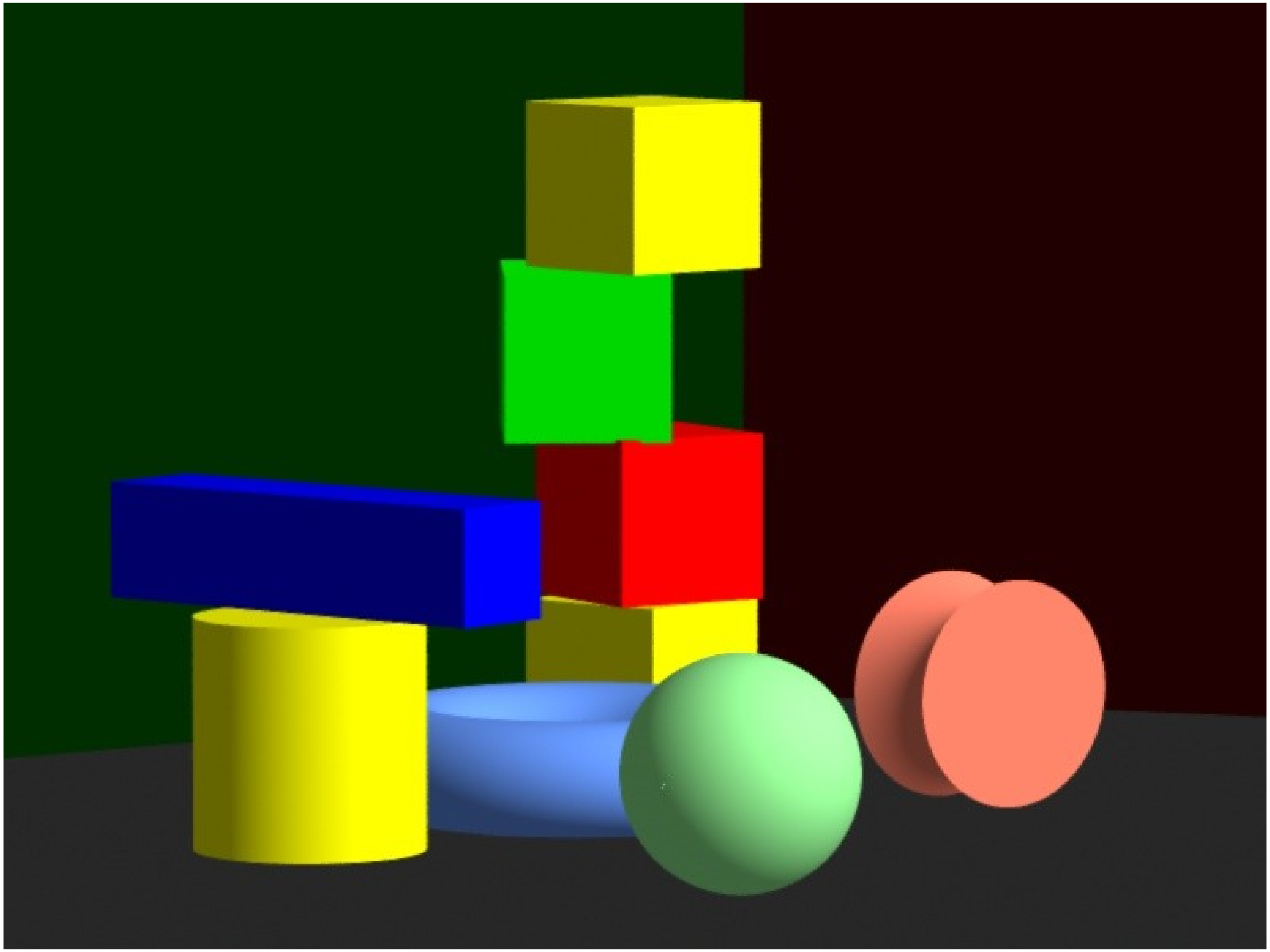
Ambient + Diffuse Illumination

- The two lighting models presented above can be combined

$$I_{diff}=I_a k_a + I_P k_d \cos\theta$$

to obtain an illumination equation that encompasses both illumination methods presented

Ambient + Diffuse Illumination



Light source attenuation

- In fact, light does not travel through space keeping its illuminating power at the same level.
- Farther objects get less light than closer ones, because it is partially absorbed by particles in the air
- If constant light intensity is used, then one would get a kind of illumination which is similar to the sunlight
- To solve this problem, an attenuation factor is added to the illumination equation, decreasing light intensity with distance from the light source

- The resulting illumination equation is

$$I = I_a k_a + f_{att} I_p k_d (\overline{N} \cdot \overline{L})$$

  where the attenuation factor is:
  - $f_{att} = \frac{1}{d_L^2}$

    which gives a too hard decay of light
  - or $f_{att} = \frac{1}{Max(\left| c_1 d_L^2 + c_2 d_L + c_3 \right|, 1)}$

    where the coefficients are chosen ad hoc

Adding colour

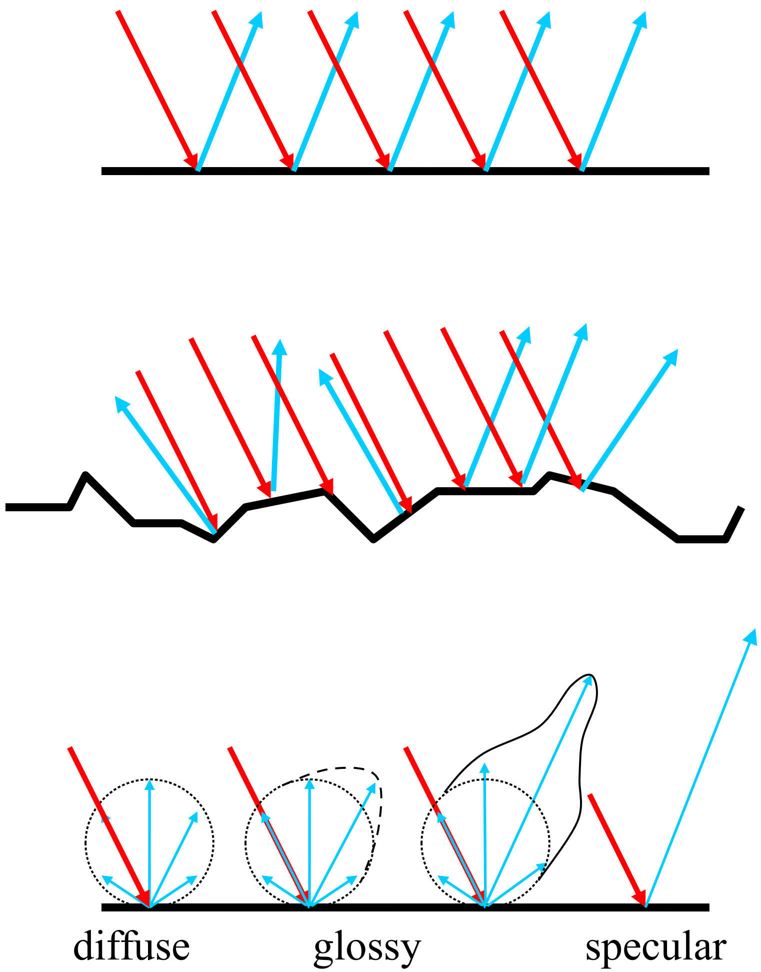
- In order to add colour, the computation of the illumination function is repeated three times, one for each of the colour components RGB.
- The illumination equation is therefore repeated for each one of the three components, and colur components are computed separately
- In general, for a wavelength λ in the visible spectrum, we have that

$$I_{\lambda} = I_{a\lambda} k_a O_{d\lambda} + f_{att} I_{p\lambda} k_d O_{d\lambda} \left(\overline{N} \cdot \overline{L} \right)$$

where $O_{d\lambda}$ is the Object reflection characteristics constant at a certain wavelength

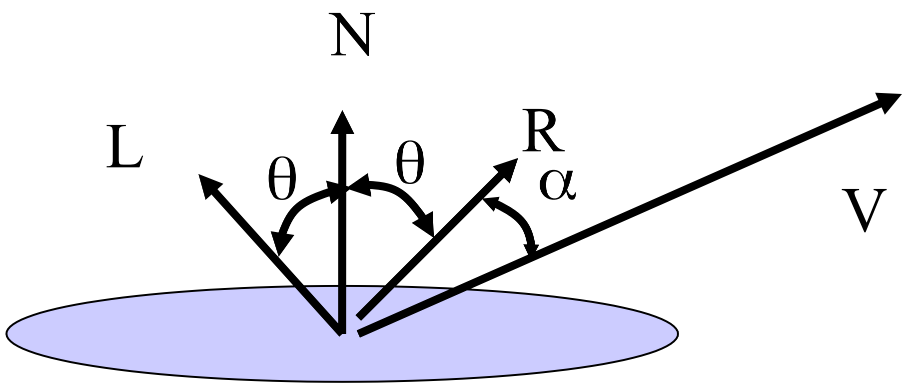
Specular highlights

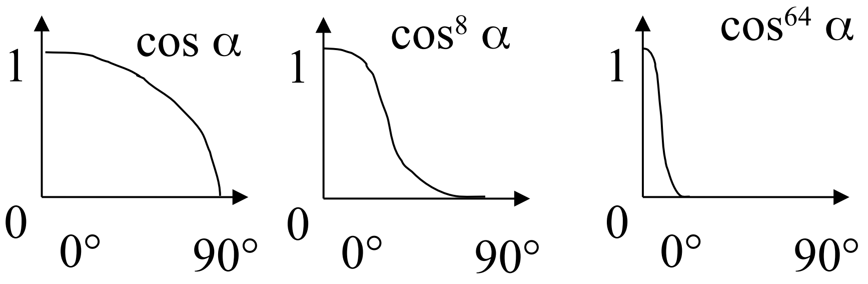
- In real life, most surfaces are glossy, and not matte
  - Think for ex. at an apple
- Gloss is due to the non-plain-ness at the microscopic level of surfaces (microfacet theory) , and do micro reflecting surfaces of the material
- Since their distribution is approximately gaussian, then most mirror like reflected light is reflected in direction of the specular reflection, and some is scattered in other directions



Specular highlights

- Around the direction of the viewer, reflection rays are scattered and generate a highlight
- Empirically, scattering decay from the direction of the viewer can be seen to behave similarly as the power of the cosinus of the angle α





Specular light

- Heuristic model proposed by Phong Bui-Tuong
- Add term for specular highlight to equation

$$I_\lambda = I_{a\lambda} k_a O_{d\lambda} + f_{att} I_{d\lambda} \left[k_d O_{d\lambda} (\overline{N} \cdot \overline{L}) + k_s O_{s\lambda} (\overline{R} \cdot \overline{V})^n \right]$$

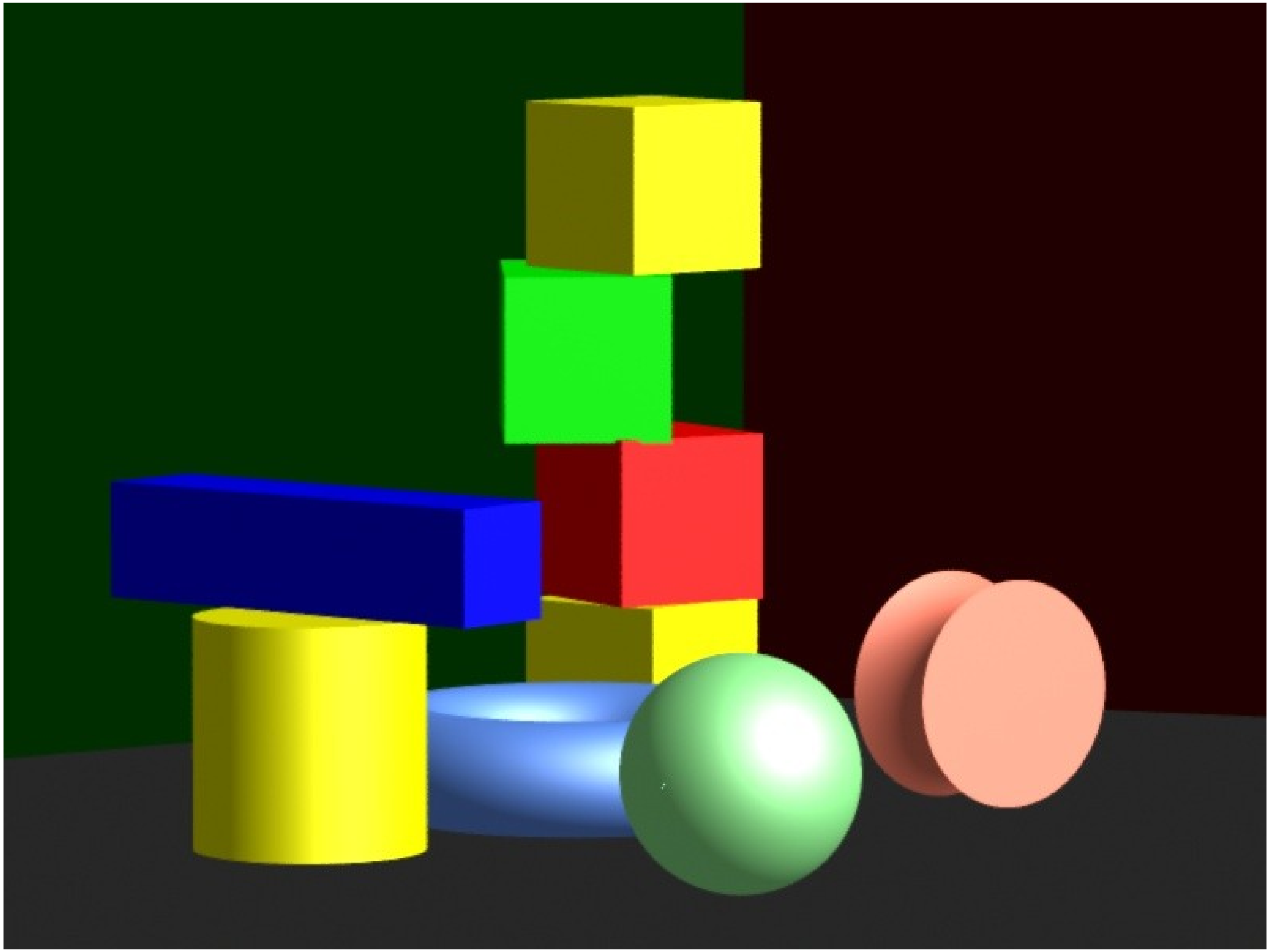
where

- k_s= specular reflection constant of surface
- $(R \cdot V)^n = \cos^n \alpha$

Specular highlights

- Applying Phong illumination allows to obtain quite convincing images
- Note: these illumination models are implemented in hardware nowadays

Specular highlights



Multiple lights

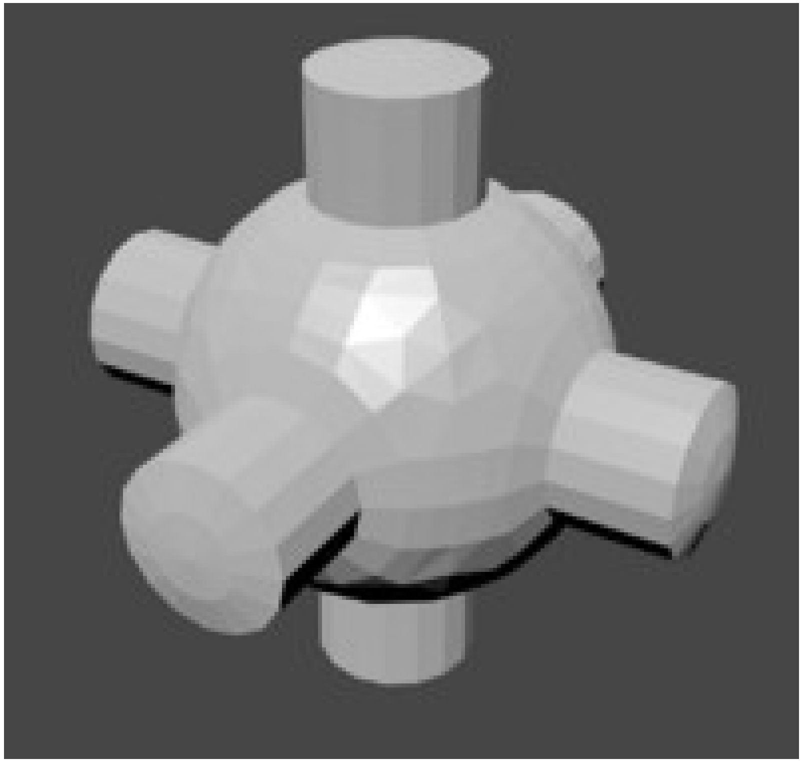
- Adding multiple light sources to the illumination model in an environment is simple:
  - Just add contributions due to the single lights
  - This, of course, doubles the comptations in the case of two lights

Graphics Pipeline: Shading

Pipeline: Application → Geometry → Rasterization

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
Converts into triangles	Shading	Interpolate: lighting+texture
	Clipping	

- Shading concerns simulating the interaction of light with the objects.
- The interaction is ruled by the illumination equation, which describes the resulting colour of the object.
- In its simplest form, one illumination value per triangle is computed
- Otherwise, the wholeshading has to be done



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Graphics Pipeline: Clipping

Pipeline:

Application	Geometry	Rasterization
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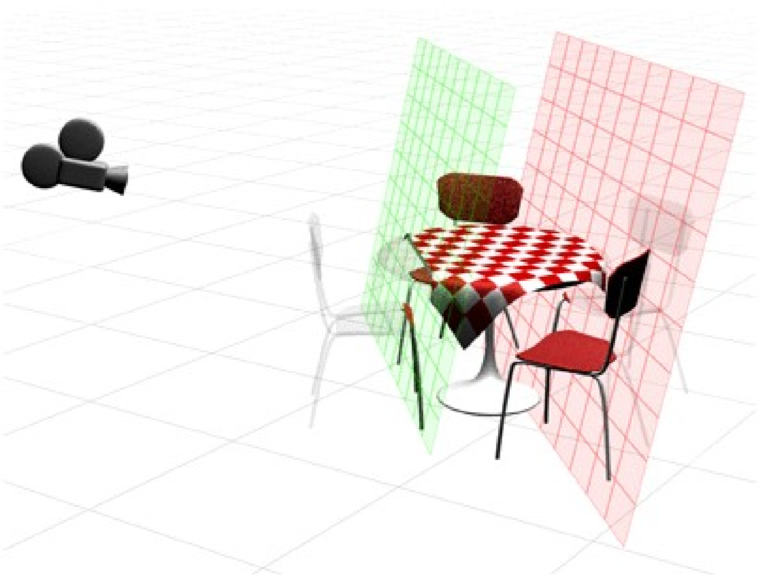
- Clipping “clips” the scene and eliminates the polygons that do not need to be displayed
- There are two clippings being done:
- 3D clipping, eliminating all polygons
  - Farther than the far plane
  - Nearer than the near plane



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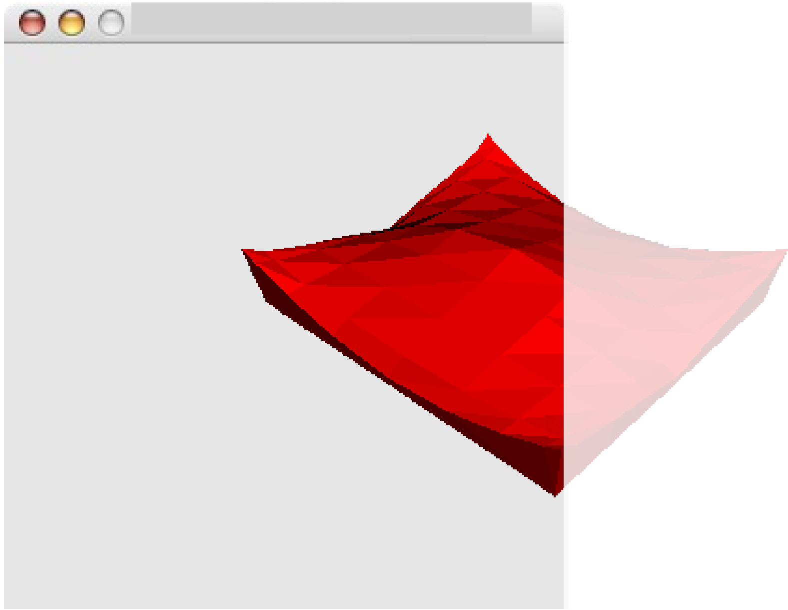
Graphics Pipeline: Clipping

Pipeline:	Application	→	Geometry	→	Rasterization
	Supplies geometric data		Apply transformations		Convert triangles 2 pixels
	Converts into triangles		Shading		Interpolate: lighting+texture
			Clipping		

- 2D clipping, eliminating the polygons and lines I cannot view in the image window and would therefore eat up computing power



Courtesy Stephen Chenney, University of Wisconsin at Madison

Graphics Pipeline: Triangle Rasterization

Pipeline: **Application** → **Geometry** → **Rasterization**

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
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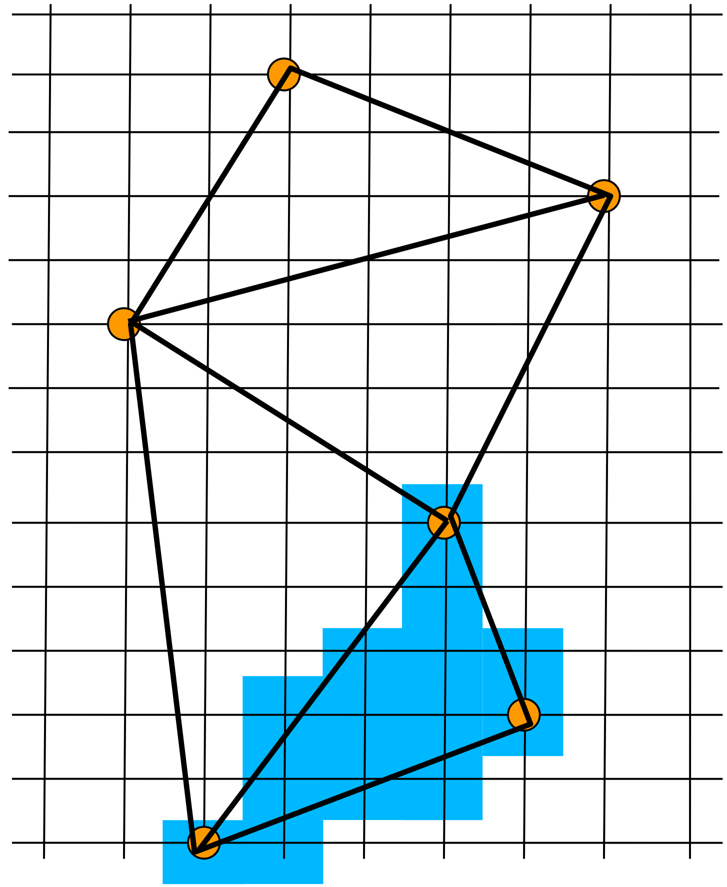
- While nature is continuous, screens are made of pixels:
  - Placed on a square grid
  - Integer coordinates
- Convert the triangles into pixels is a complex operation:
  - Find out which pixels have to be coloured
  - At the same time, draw only triangles which are not covered by other triangles



Graphics Pipeline: Triangle Rasterization

Pipeline:	Application	→	Geometry	→	Rasterization
	Supplies geometric data		Apply transformations		Convert triangles 2 pixels
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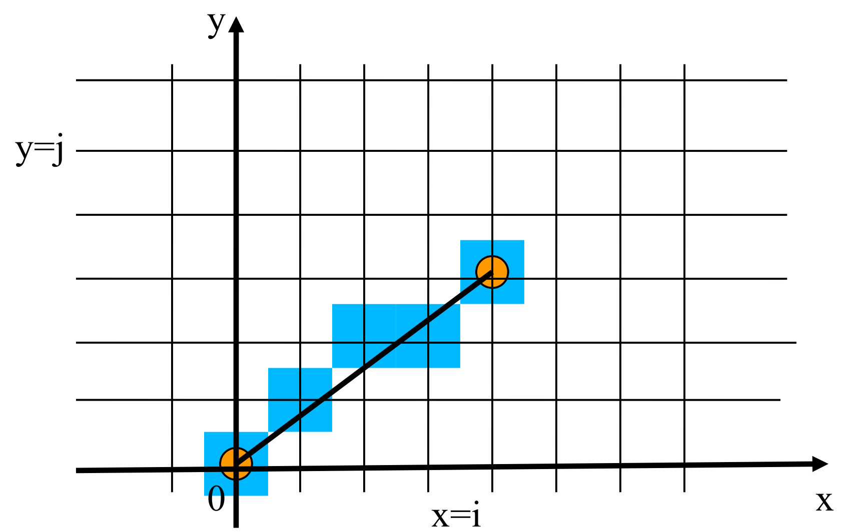
			Clipping		

- First we have to know how to draw a line to draw the borders
- Line through $P_I=(x_I,y_I)$, $P_F=(x_F,y_F)$:

$$y = \frac{y_F - y_I}{x_F - x_I}x + y_I - \frac{y_F - y_I}{x_F - x_I}x_I$$

  or, more simply: $y=mx+q$.
- Let us find the pixels we need to switch on to draw the line
- Let us start from $(0,0)$, I.e. let us suppose that $P_i=(0,0)$ and $P_F=(4,3)$
- I need to find the intersections of the line $y=3/4x$ with the lines $x=j$ between 0 and 4



Graphics Pipeline: Line Rasterization

Pipeline: **Application** → **Geometry** → **Rasterization**

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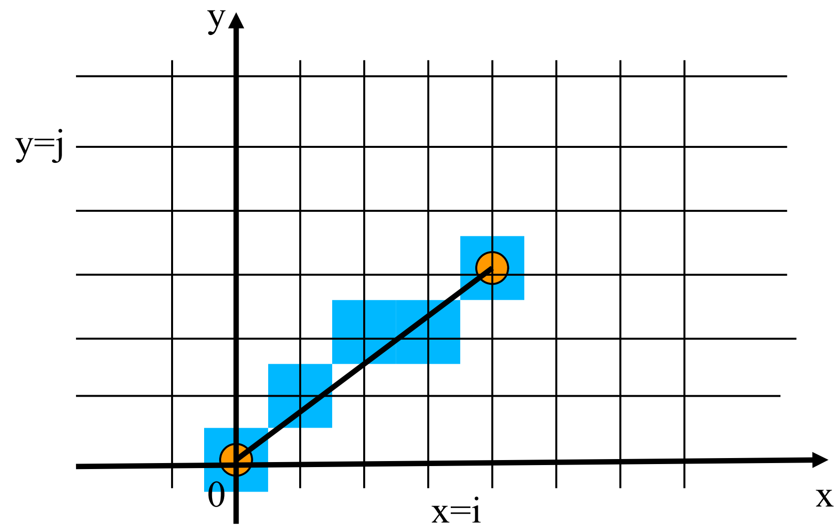
- Let‘s compute: $y=3/4x$

x	y
0	0
1	3/4=0.75 round to 1
2	6/4=1.50 round to 2
3	9/4=2.25 round to 2
4	12/4=3



- So I draw the pixels obtained by rounding the intersections with the vertical straight lines

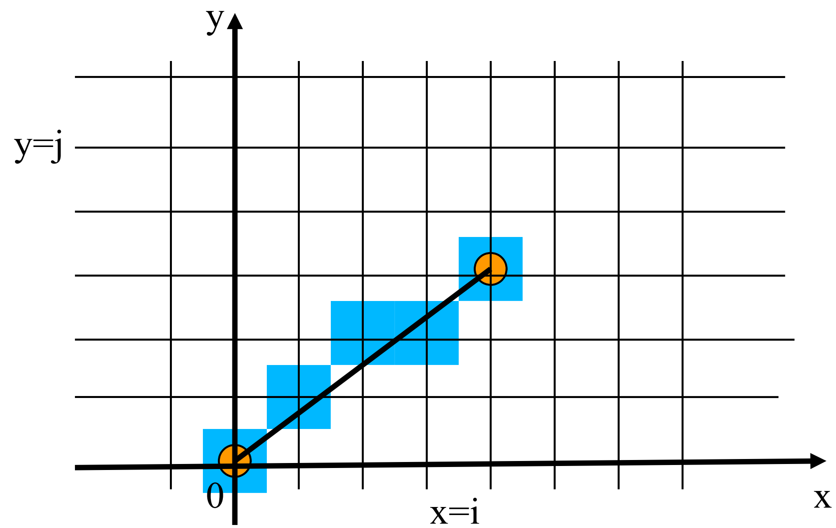
Graphics Pipeline: Line Rasterization

Pipeline: **Application** → **Geometry** → **Rasterization**

- Application
  - Supplies geometric data
  - Converts into triangles
- Geometry
  - Apply transformations
  - Shading
  - Clipping
- Rasterization
  - Convert triangles 2 pixels
  - Interpolate: lighting+texture

- And for a generic line? $y=mx+q$

x	y
0	q
1	m+q
2	2m+q=m+(m+q)
3	3m+q=m+(2m+q)
4	4m+q=m+(3m+q)



$$y = \underbrace{\frac{y_F - y_I}{x_F - x_I}}_{m} x + \underbrace{y_I - \frac{y_F - y_I}{x_F - x_I} x_I}_{q}$$

- Hey!
  Each time I add m!!!
- This is exactly what we do to draw lines: add m each step till endpoint is reached

Graphics Pipeline: Triangle Rasterization

Pipeline: **Application** → **Geometry** → **Rasterization**

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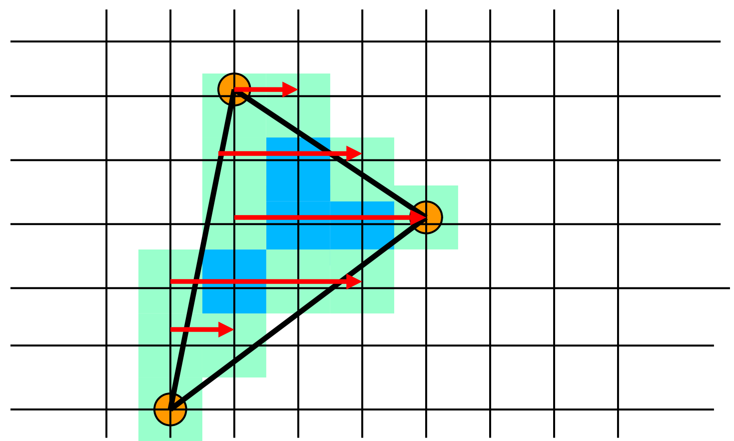
- And for triangles? How do I rasterize them?
  - First draw borders
  - Then fill one scanline at the time between border points
  - For example, from top to bottom, until triangle is finished

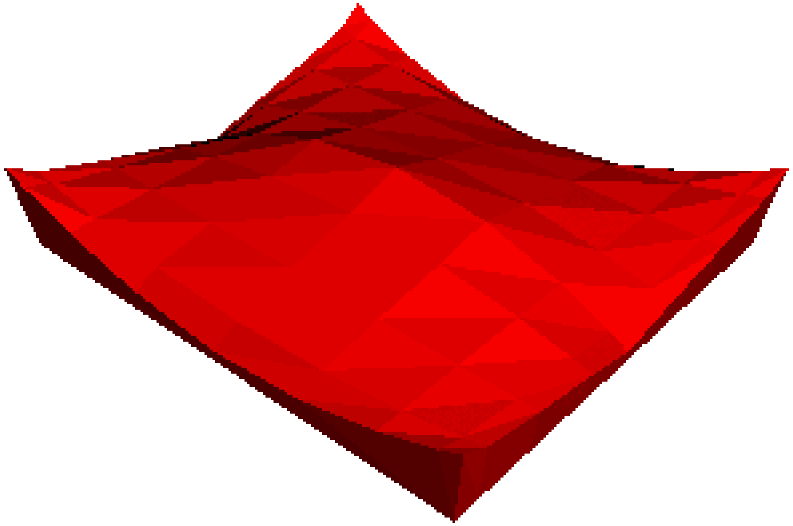


Flat shading

- And which colour do I draw the polygons with?
- We saw the problem of flat shading: you saw the faces!

- For each polygon in the mesh, compute illumination equation
- Render the whole polygon with the obtained colour

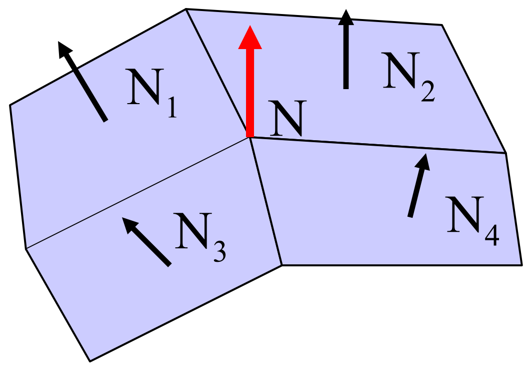
- Results are already good for giving an idea of the shape
- However, all polygonal facets are seeable, and this is mostly unwanted
- We will come back to this later, and learn the tricks used to avoid visible facets

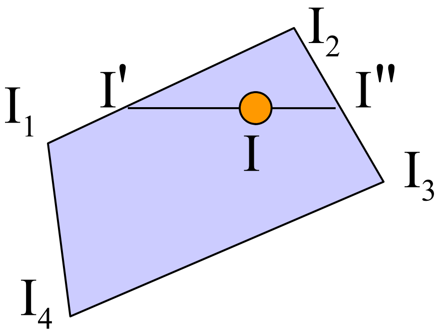


Courtesy Stephen Chenney, University of Wisconsin at Madison

Gouraud shading

- To avoid this problem, Gouraud in 1971 proposed a method to smooth polygonal surface rendering
- The idea is to
  - compute normal vectors at vertices of each polygon (average adjacent polygon normals $N=N_1+N_2+N_3+N_4$)
  - compute illumination at vertices
  - linearly interpolate colour values along the edges of the polygons
  - linearly interpolate colour values between edges to find out colour at a given point
- Bilinear interpolation





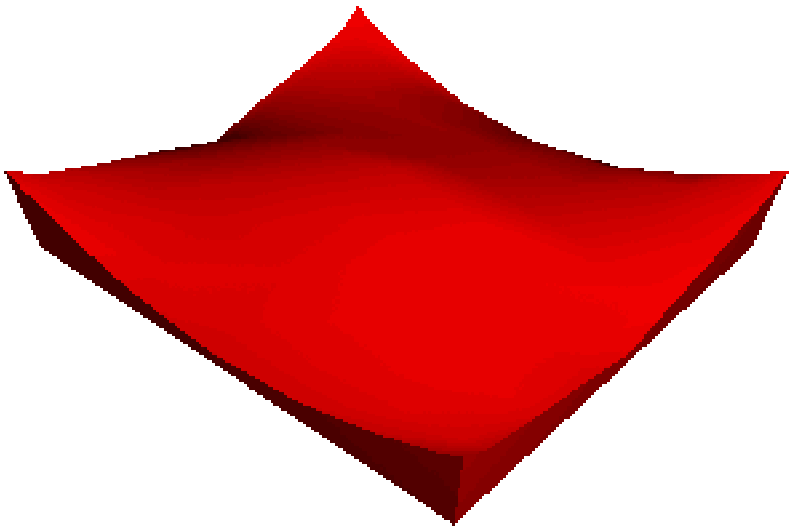
$I' = tI_2 + (1-t)I_1$

$I'' = tI_2 + (1-t)I_3$

$I = tI' + (1-t)I''$

Gouraud shading

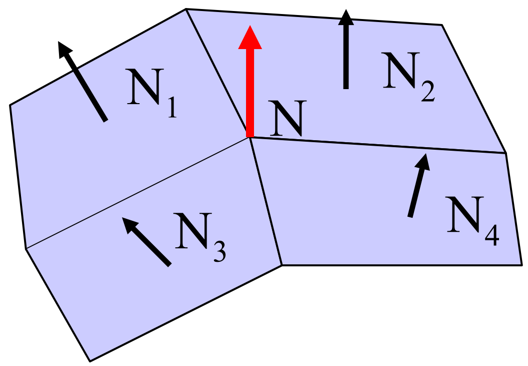
Courtesy Stephen Chenney,
University of Wisconsin at Madison

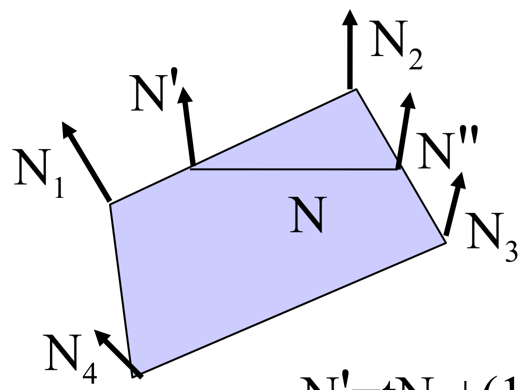


- Gouraud shading gives smooth surfaces
- Sometimes highlights are missed

Phong shading

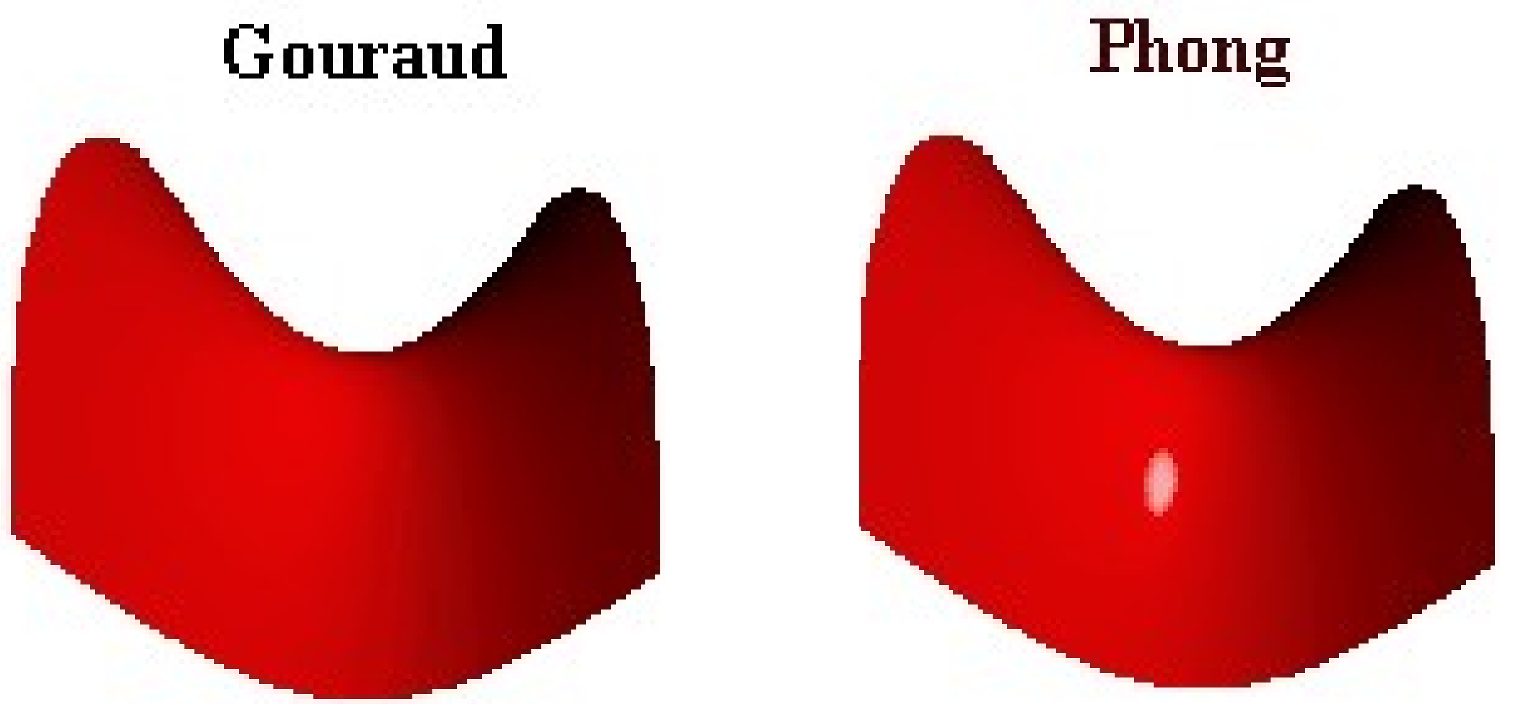
- Phong proposed an improvement to Gouraud‘s idea
- Phong interpolates between normals and not between colour to find the normal at a point inside the polygon
- Note that both interpolations (Phong, Gouraud) have three components to compute
- Only once known the interpolation normal at the point, illumination is computed at each point
- Much more computationally intensive than Gouraud





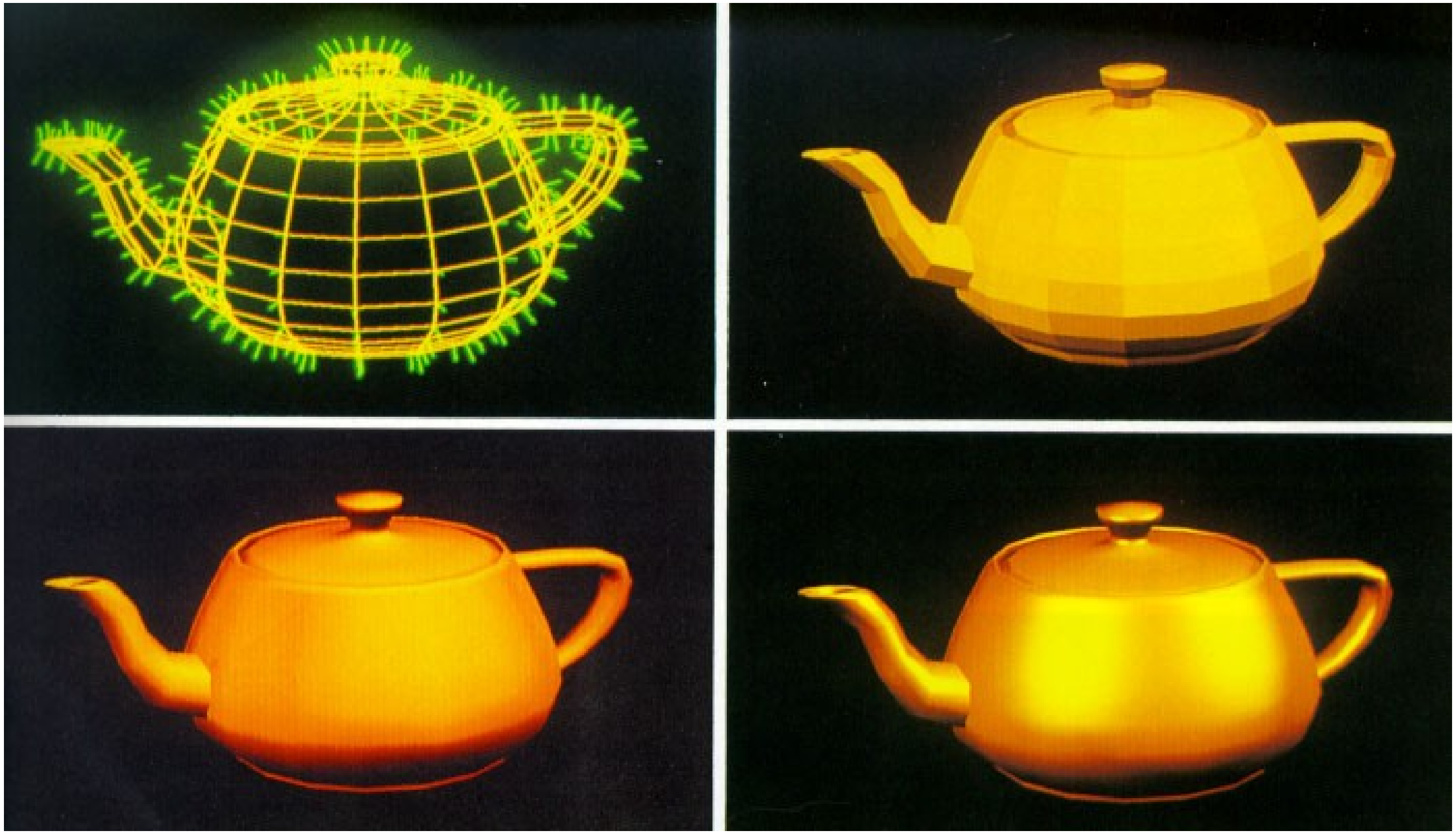
$$N' = tN_2 + (1-t)N_1$$
$$N'' = tN_2 + (1-t)N_3$$
$$N = tN' + (1-t)N''$$

Comparing shading methods



Courtesy Stephen Chenney,
University of Wisconsin at Madison

Comparing shading methods



Graphics Pipeline: Z-buffering

Pipeline: Application → Geometry → Rasterization

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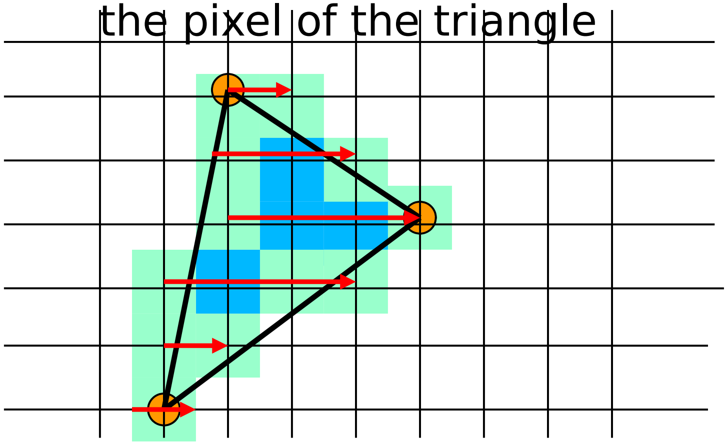
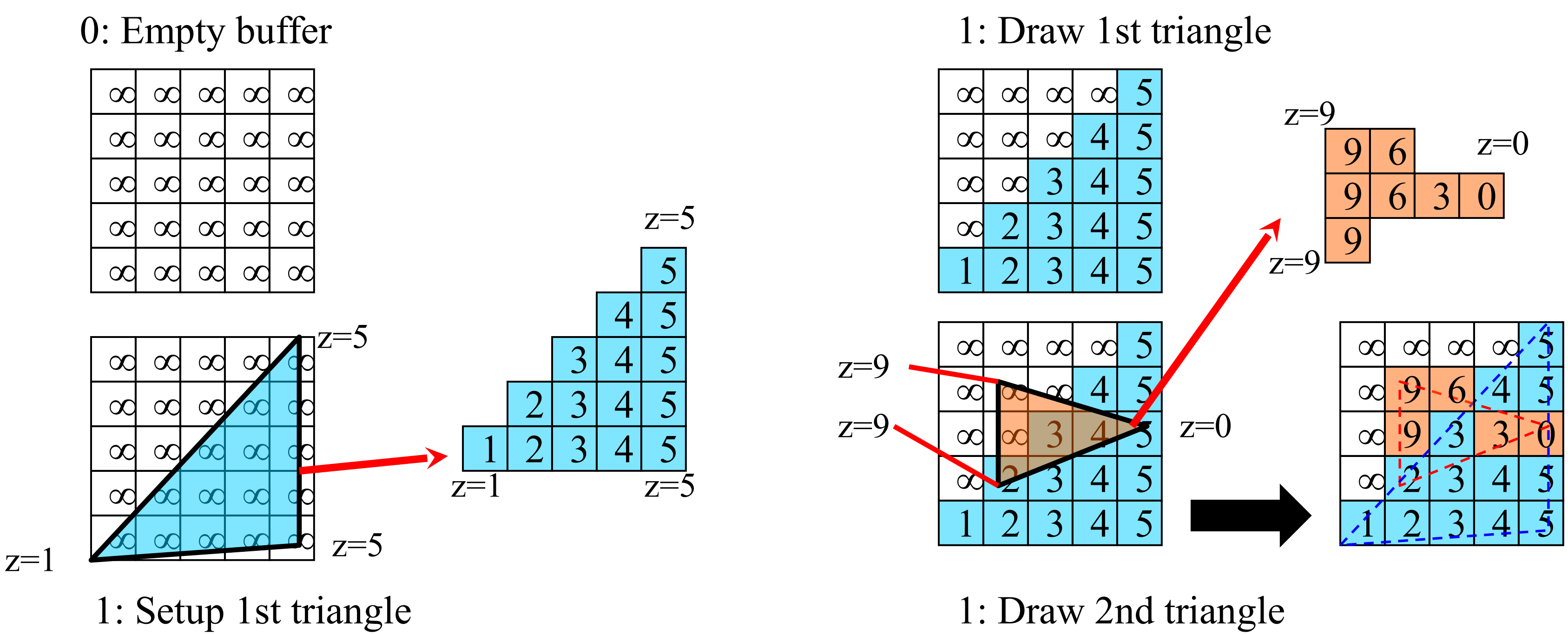
- Wait! Some triangles might cover others: *hidden surface removal*.
- How do I know which ones to draw?
- Simple: I compute the depth (=z value) of each pixel I am about to draw
- At the start, I enter infinite in a buffer (= table as big as screen) at each position of the table
- When I am about to write a pixel, I look the z value of what I am drawing is smaller of the current value at the table
  - If it is, then I write the current pixel in the image and update the value of the "parallel" table to the z value of the pixel
  - If not, I leave the table untouched and do NOT write the pixel of the triangle



Graphics Pipeline: Z-buffering

Pipeline: **Application** → **Geometry** → **Rasterization**

- **Application**
  - Supplies geometric data
  - Converts into triangles
- **Geometry**
  - Apply transformations
  - Shading
  - Clipping
- **Rasterization**
  - Convert triangles 2 pixels
  - Interpolate: lighting+texture

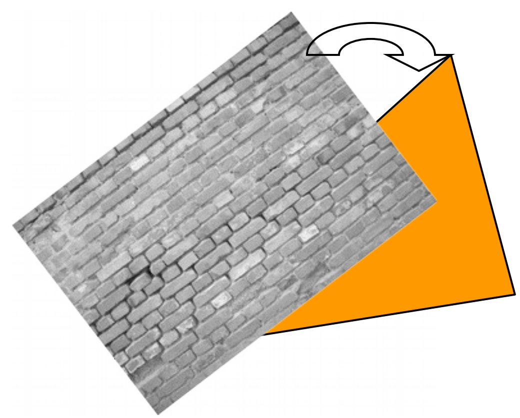


Graphics Pipeline: Textures

Pipeline:

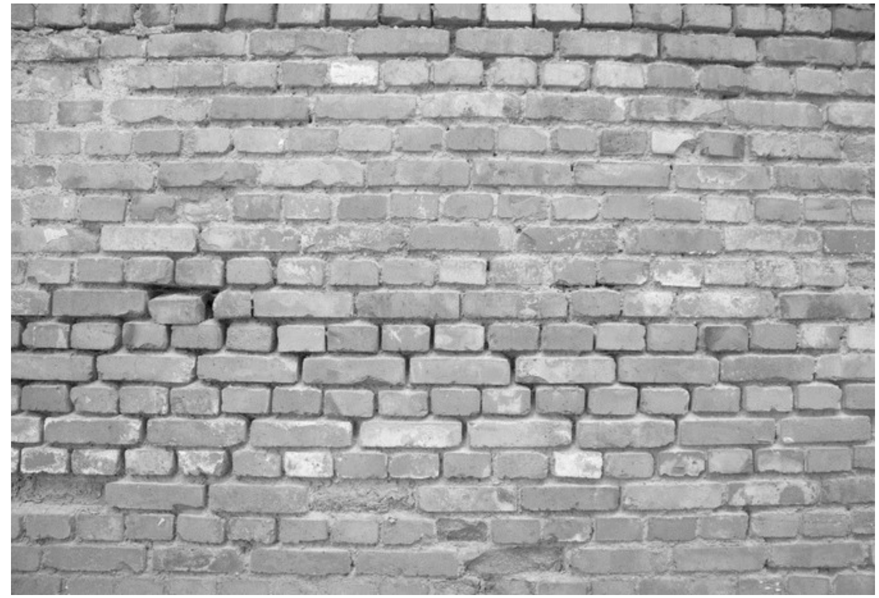
Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
Converts into triangles	Shading	Interpolate: lighting+texture
	Clipping	

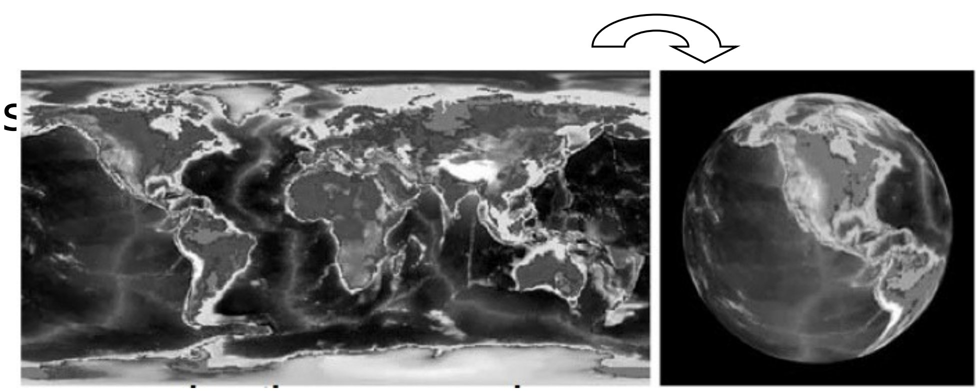
- So I compute lighting equation almost at every pixel to interpolate it with Phong shading
- This for drawing solid triangles: at each point, I take basic colours and compute illumination either by using Gouraud or Phong to obtain the colour
- And what if I want more interesting looking objects?
- I could glue wrapping paper on them!
- But how? With textures!



Textures

- Reality shows much more richness of surface detail than the one obtainable through local illumination: look at the wall!!
- One could model the surface with detailed geometry
- However, this would increase greatly the complexity of the model.
- A better appproach is therefore to „paint“ detail on simple geometry
- The image, called *texture*, is „glued“ to a simple geometry to obtain detail
- First approaches due to Catmull (74) and Blinn & Newell (76)





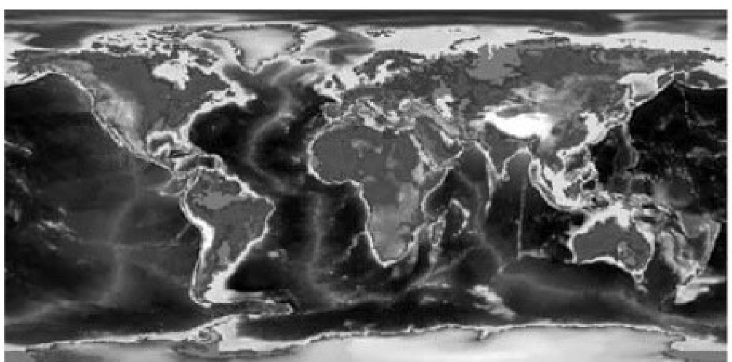
Textures

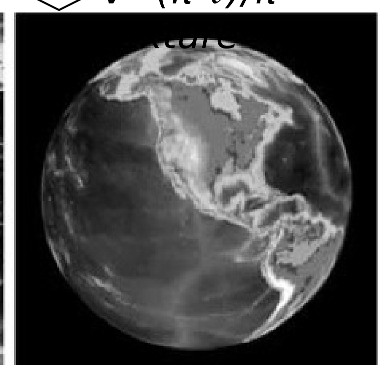
- There are basically two ways of texture mapping:
  - 2D
  - 3D
- Let us look first at 2D textures
- Image data (surface pixel colors) is stored in a 2D image, the pixels of which are called *texels*
- Let's assume the coordinates of the image are called *u*,*v* and that *u* and *v* vary in the interval [0,1]

- To compute what colour is reflected by the sphere, one must find a correspondence between sphere and the texture space
- Parametric sphere:

$$x=x_c+R\cos\psi\sin\vartheta$$
$$y=y_c+R\sin\psi\sin\vartheta$$
$$z=z_c+R\cos\pi$$

- $\vartheta=(z-z_c)/R$ longitude
  $\psi=artan((y-y_c)/(x-x_c))$ +latitude
- $u=\psi/2\pi$
  $v=(\pi-\vartheta)/\pi$ *to*
  xture

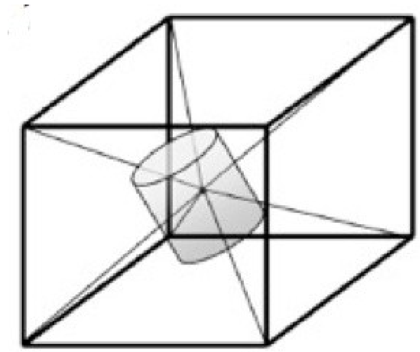


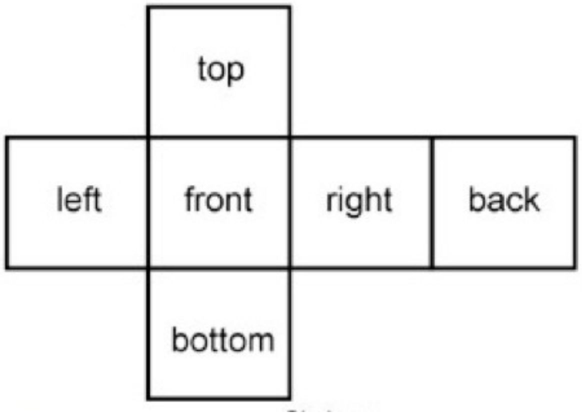


- Similarly, for other simple maps
  - Cube
  - Cylinder
  - Plane

Textures

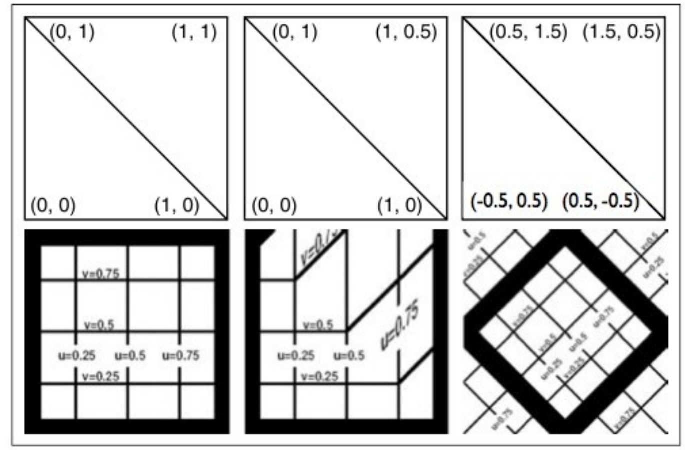
- There are different ways of applying textures for complicated objects:
  - Surround object to be textured with a simple object: cube, sphere, cilinder
  - Choose a center for the object
  - Texture the cube (invisibly)
  - When one draws pixel of the object, project this pixel to the cube, and pick the cube texture color

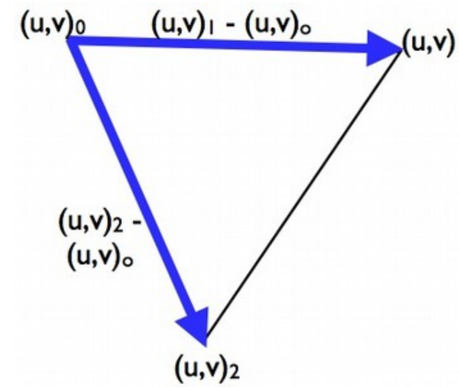


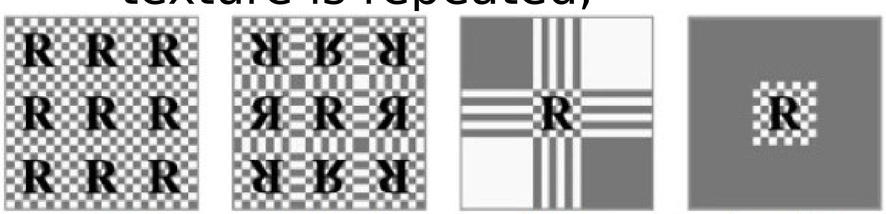


Textures

- And what if my object is in mesh form?
- Determine texture coordinate for each vertex of the mesh (by projection as before)
- Bilinear interpolation between vertices
  - For triangles, use baricentric coordinates (same as done for normals)
- If texture coordinates are beyond the image, then texture is repeated,





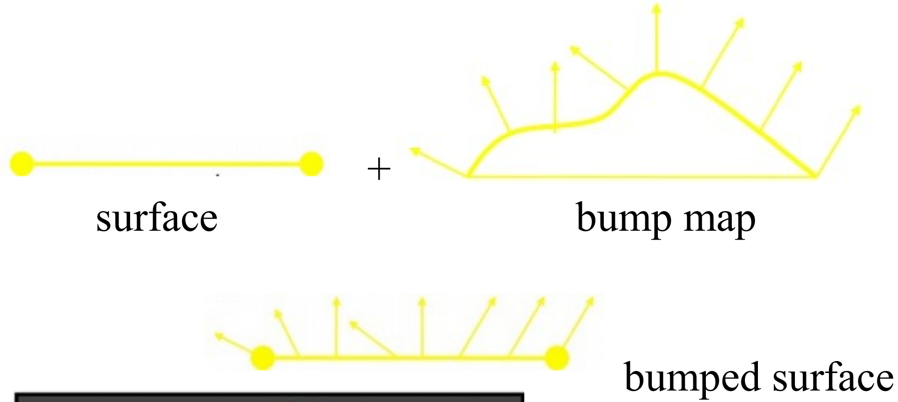


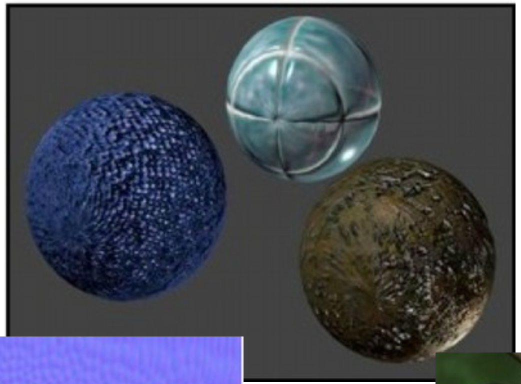
repeat mirror clamp border

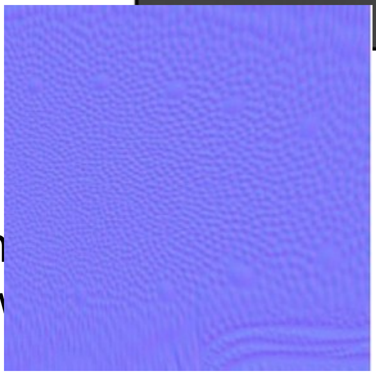
$$u(\beta,\gamma) = u_0 + \beta(u_1 - u_0) + \gamma(u_2 - u_0)$$
$$v(\beta,\gamma) = v_0 + \beta(v_1 - v_0) + \gamma(v_2 - v_0)$$

Bump maps

- Textures help with the color of the pixels to be drawn
- However, the resulting objects still look flat
- To improve this, one can store in a texture (bump map) normal variations, and use it for lighting computations while rendering
- This achieves a bumpy surface, because the varying normals change th shading computations
- However, when bump mapped polygons are seen from a flat angle they show their flatness

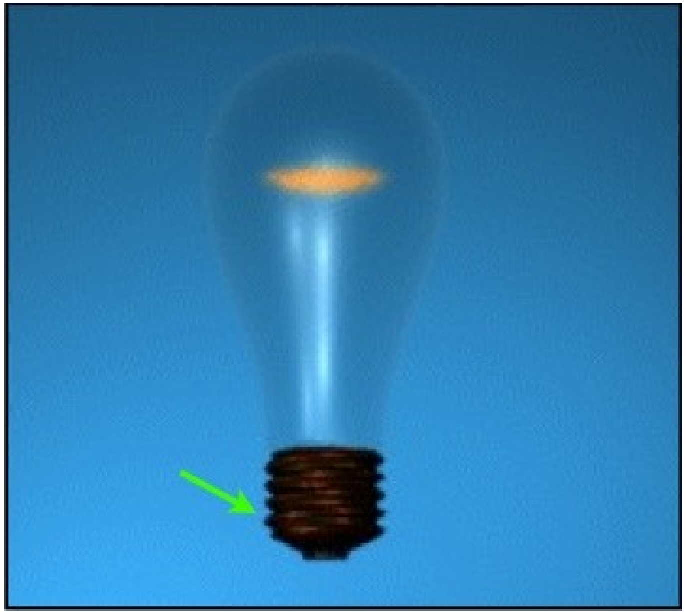


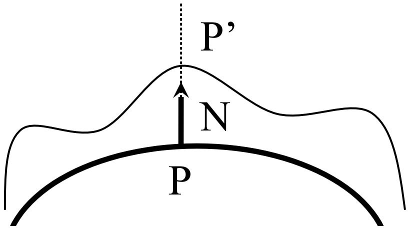




Displacement maps

- Bump maps do not modify geometry height, which does not look good from the profile
- A way to correct this is to interpret an additional black and white texture as displacement offsets along the normal
- This is called a displacement map
- Since the displacement map “modifies” the surface to add detail to it, usual lighting computations can be done in the result

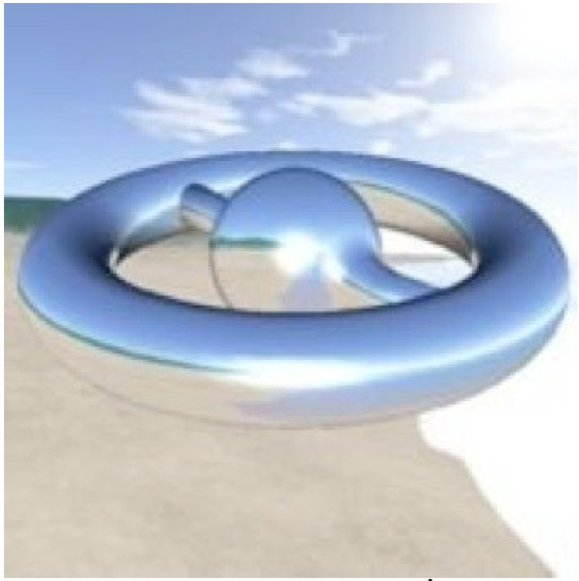


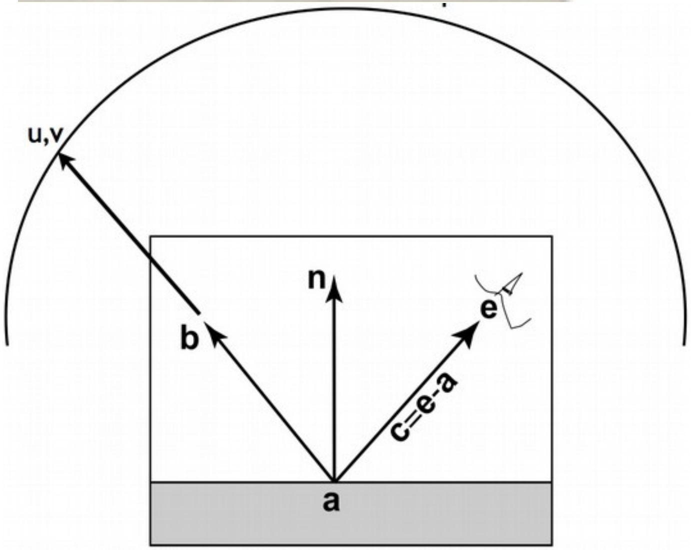


Surface + displacement

Environment maps

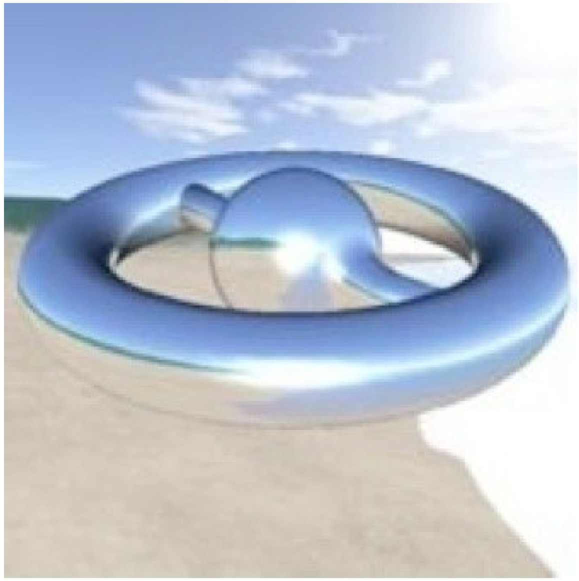
- There are many ways to use textures to obtain special effects in a picture
- *Environment maps* are used to simulate reflections on objects
- In this case, the world is surrounded by a closed surface having a texture
- The colour at the pixel to be rendered is looked up on the texture according to the reflection ray



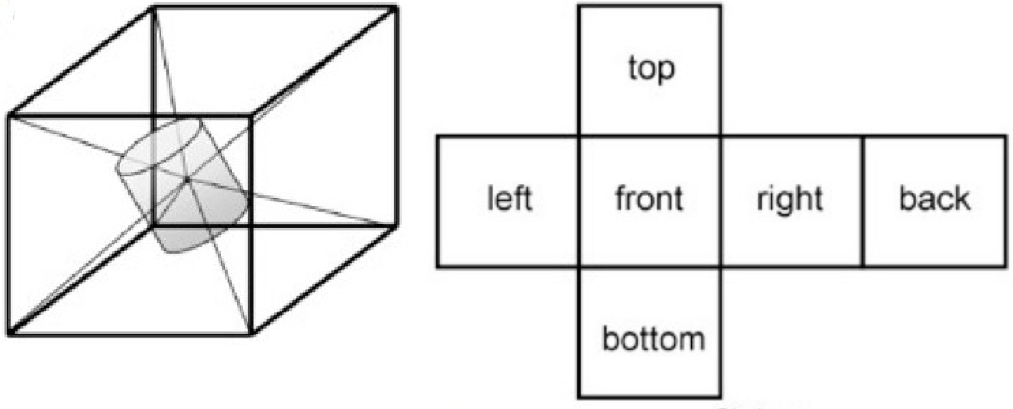


Environment maps

- There are two different ways of surrounding the world with a surface
- With a sphere: *spherical maps*

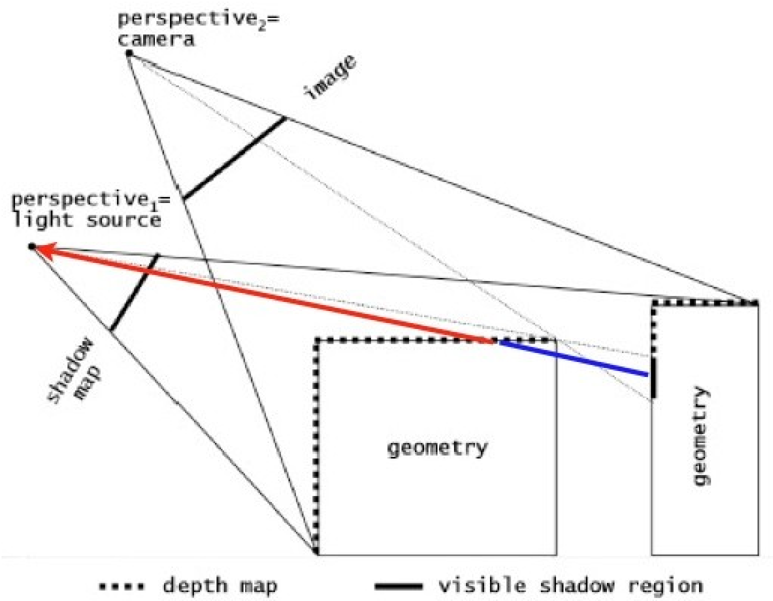


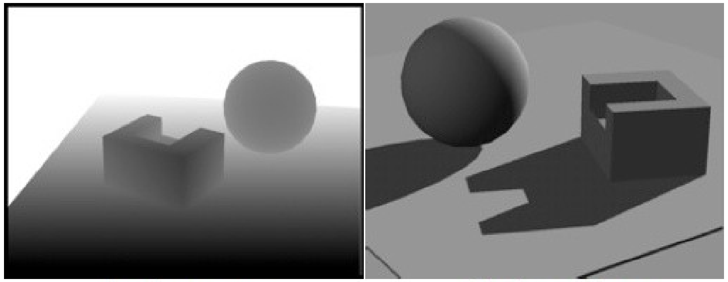
- With a cube: *cube maps*



Shadow maps

- Through textures I can also do shadows
- In this case, you set perspective$_1$ at the light source, and image$_1$ contains z-buffer values of the scene from the light source
- When rendering the scene, at each pixel one is rendering one looks if its distance from the light source is smaller or bigger than the z-buffer from the light source
- In case it is bigger, then this point is in the shadow of something else



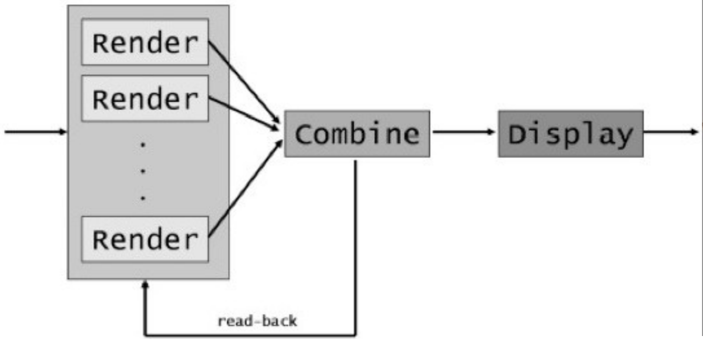


shadow map
1st pass

final rendering
2nd pass

Multi-pass rendering

- To achieve more complex rendering effects, different texture rendering passes are rendered to a texture and not displayed
- This allows the layering of different effects, by blending the results of different rendering passes
- This is called multi-pass rendering



Graphics Pipeline: Wrap up

Pipeline:

Application	Geometry	Rasterization
Supplies geometric data	Apply transformations	Convert triangles 2 pixels
Converts into triangles	Shading	Interpolate: lighting+texture
	Clipping	

- What we can do:
  - Represent a fine variety of objects with detailed and rich surfaces
  - Represent convincing illumination of objects
  - “fake” reflections and shadows
- What we have presented here, is state of the art gaming technology

- What we cannot do well:
  - Reflection
  - Refraction
  - Surface colour bleeding

End

+++ Ende - The end - Finis - Fin - Fine +++ Ende - The end - Finis - Fin - Fine +++