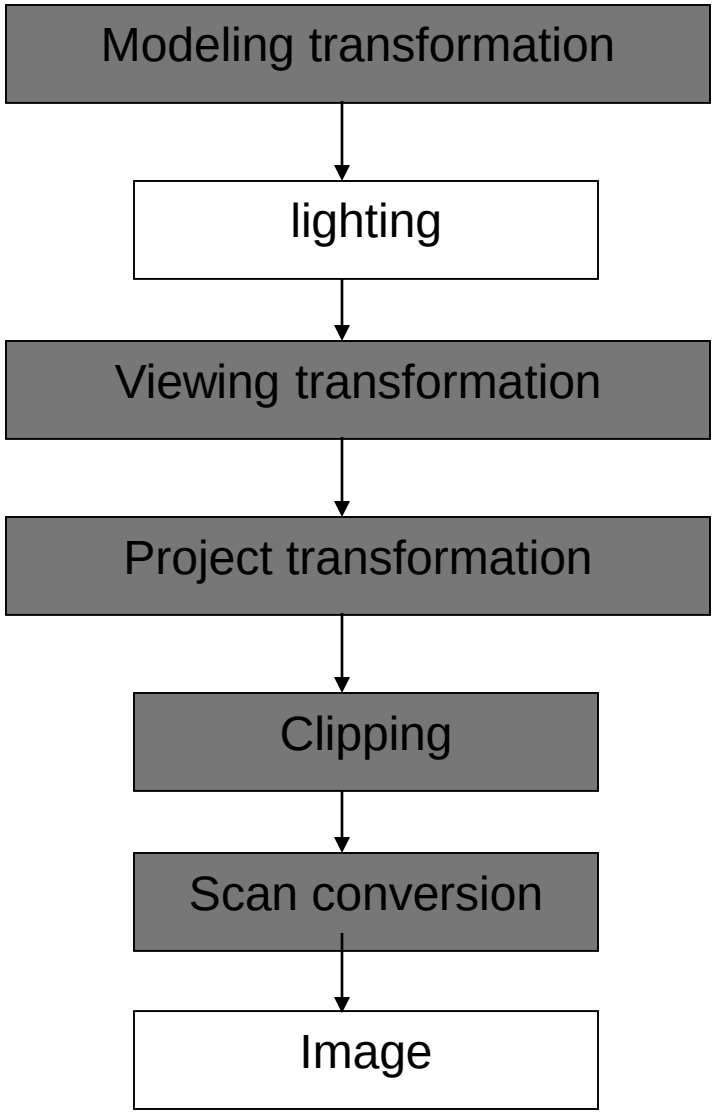
ΗΥ416
ΓΡΑΦΙΚΑ ΥΠΟΛΟΓΙΣΤΩΝ

Μοντέλα Φωτισμού – Απόδοση Επιφανειών και Υφής

Π. ΤΣΟΜΠΑΝΟΠΟΥΛΟΥ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ & ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

Μοντέλα Φωτισμού

3D Rendering pipeline



Transform into 3D world system

Illuminate according to lighting and reflectance

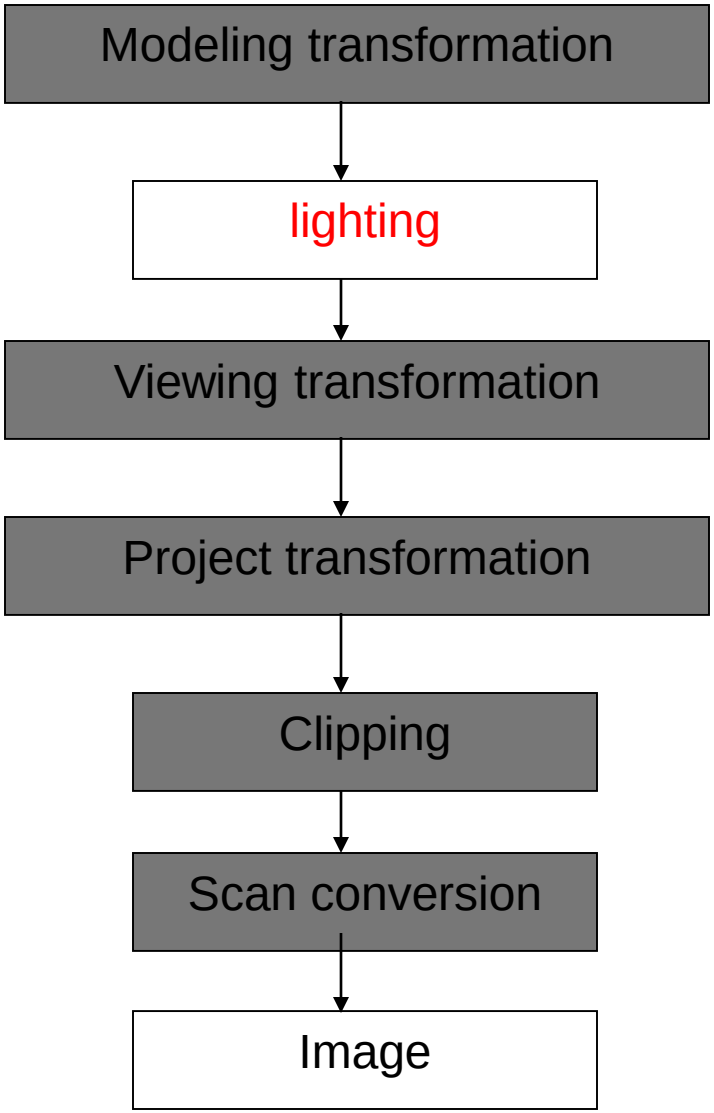
Transform into 3D camera coordinate system

Transform into 2D camera system

Clip primitives outside camera's view

Draw pixels (includes texturing, hidden surface, etc.)

3D Rendering pipeline



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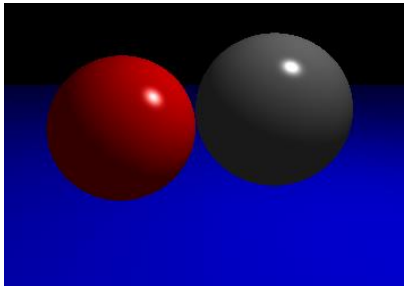
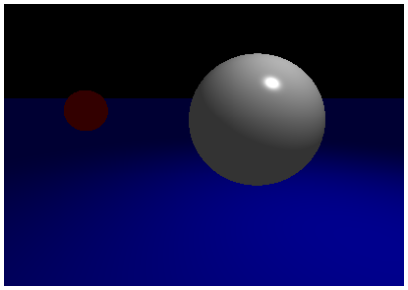
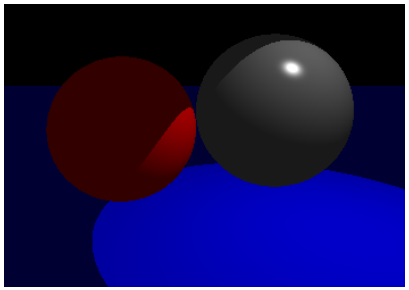
Outline

- Ambient, diffuse and specular light



- Light attenuation & spot lights





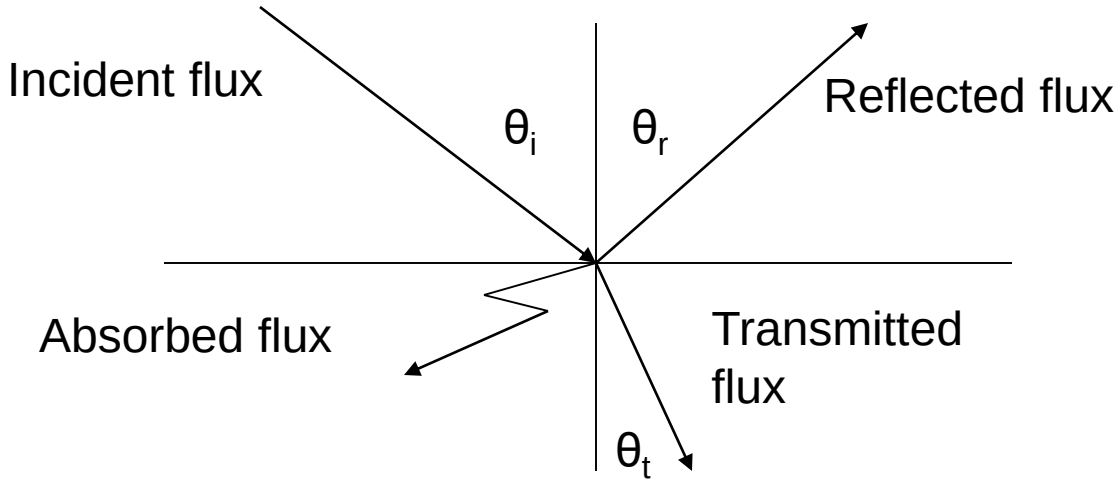
- Readings: HB 10.1, 10.2, 10.3

Illumination Model

- The governing principles for computing the illumination
- A illumination model usually considers:
  - Light attributes (light intensity, color, position, direction, shape)
  - Object surface attributes (color, reflectivity, transparency, etc)
  - Interaction among lights and objects (object orientation)
  - Interaction between objects and eye (viewing dir.)

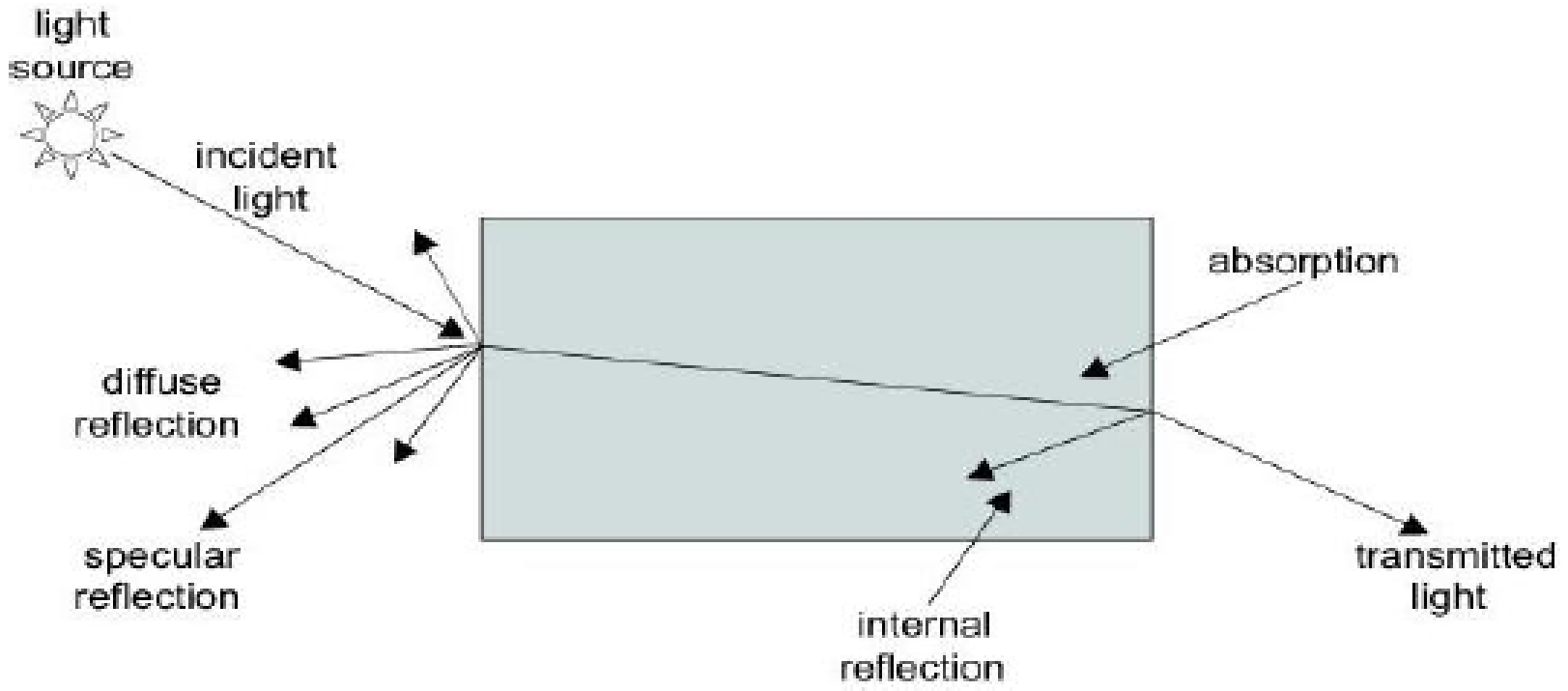
Illumination Models

- Local Illumination
  - Defines single light and single surface interaction
- Global Illumination
  - Defines interchange of lights between all surfaces



Μοντέλα φωτισμού

- Τοπικός φωτισμός (local illumination)
  - Το φως έρχεται στα αντικείμενα κατευθείαν από τις φωτεινές πηγές και ανακλάται στο μάτι
- Γενικός φωτισμός (global illumination)
  - λαμβάνεται υπόψη και το φως που αναπηδά από άλλες επιφάνειες πριν ανακλαστεί από το αντικείμενο στο μάτι μας

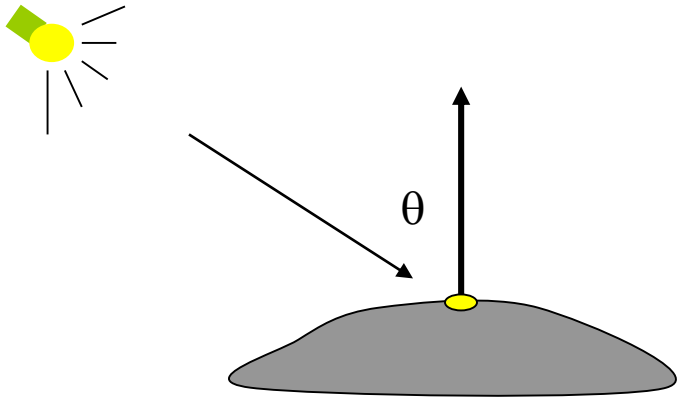


Lighting/Illumination

- Color is a function of how light reflects from surfaces to the eye
- *Global illumination* accounts for light from all sources as it is transmitted throughout the environment
- *Local illumination* only accounts for light that directly hits a surface and is transmitted to the eye

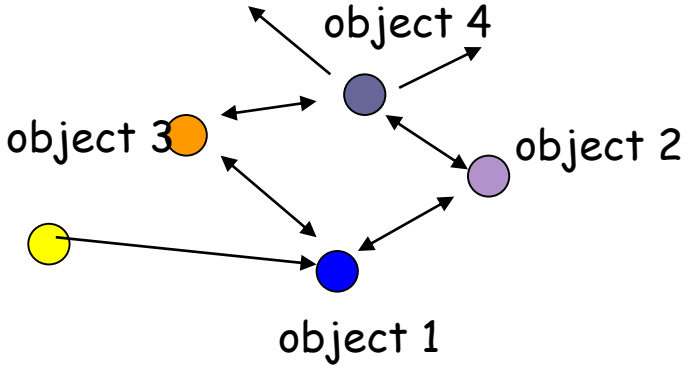
Illumination Calculation

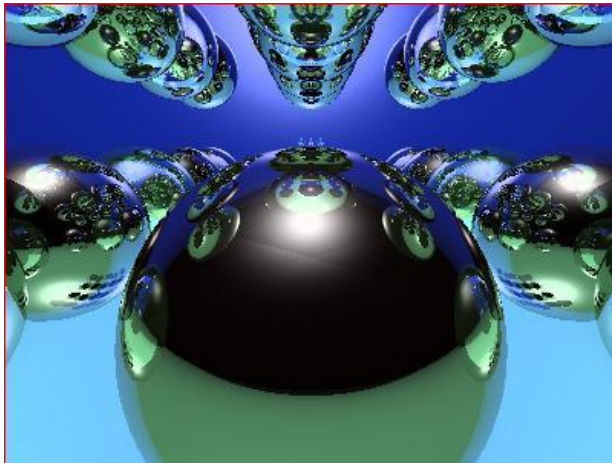
- Local illumination: only consider the light, the observer position, and the object material properties



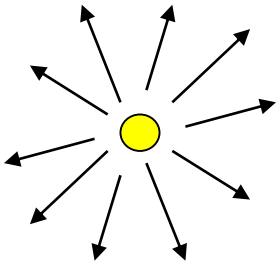
Illumination Models

- Global illumination: take into account the interaction of light from all the surfaces in the scene

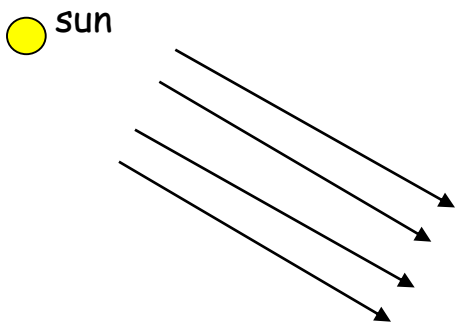




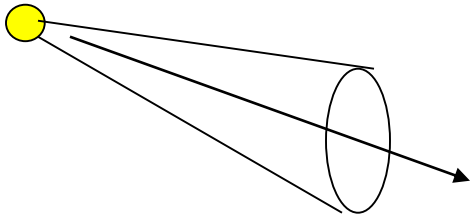
Basic Light Sources



Point light



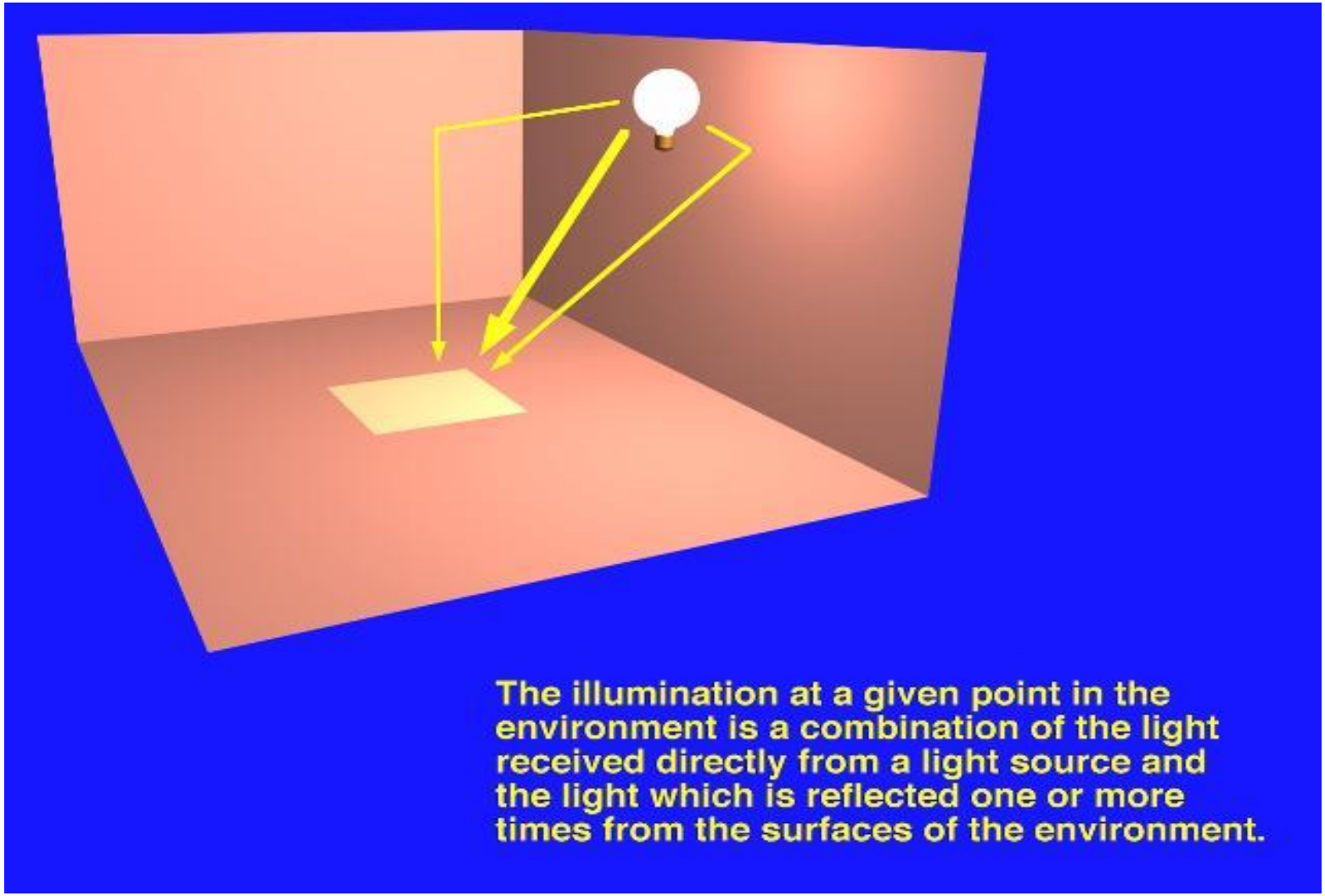
Directional light



Spot light

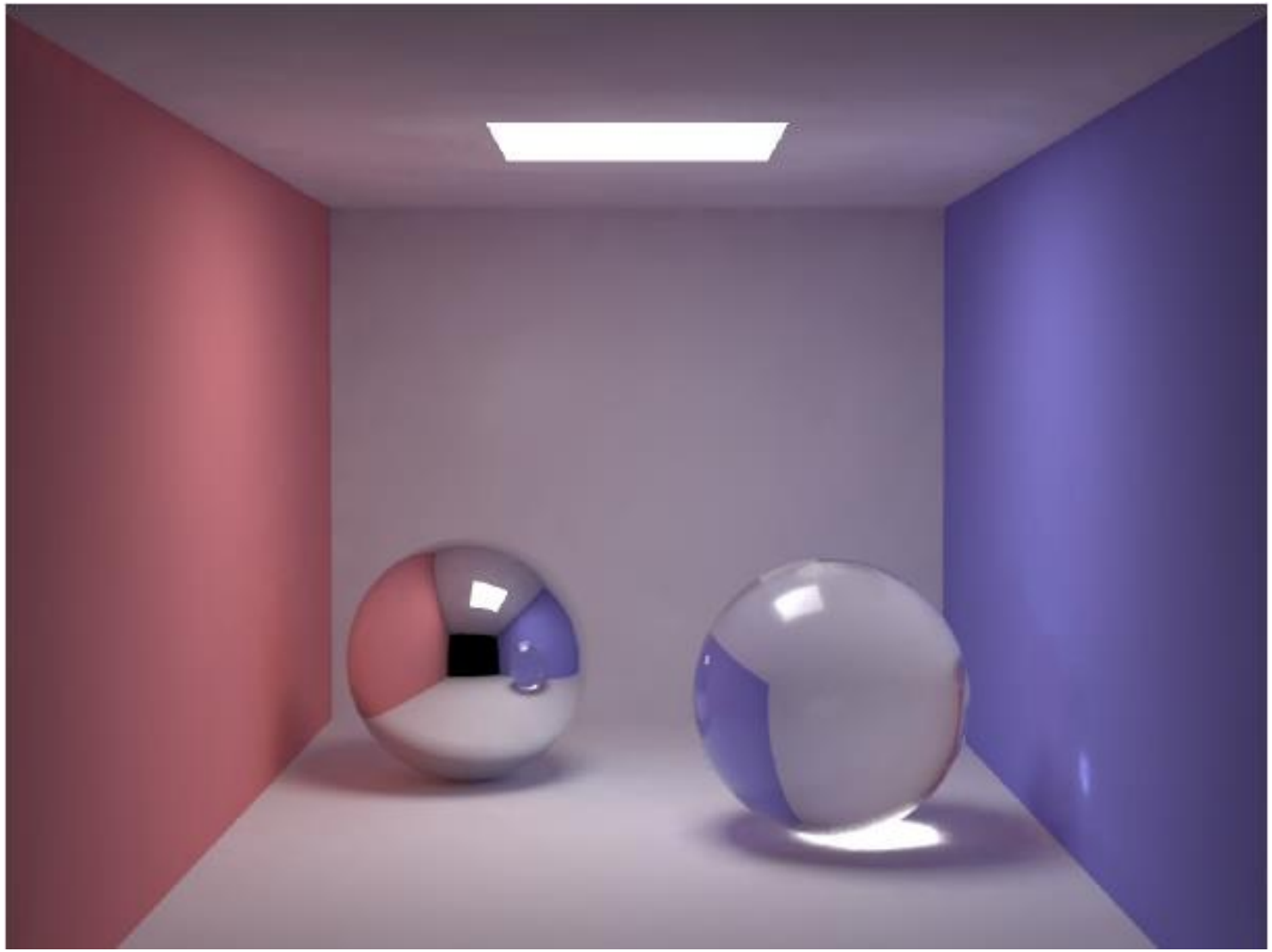
Light intensity can be independent or dependent of the distance between object and the light source

Direct and Indirect Light



Global Illumination I

Global Illumination II



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Φυσική Ανάκλαση

- Κυκλική γωνία = l (μήκος τόξου)/r (ακτίνα)
- Στερεά γωνία – Ω = α (επιφάνεια σφαίρας)/r^2 steradinas
- Φωτεινή ισχύς (flux) – Φ- ταχύτητα εκπομπής - watt - 1 watt = joule/sec
- Ένταση φωτεινής πηγής (radian intensity) – R = dΦ/dΩ
- Φωτεινή ροή (radiance) I=dR/(dA.cosθ)=dR/(dA.N.L)
- Ένταση σημείου επιφάνειας Ei=Ii (ένταση σημείου).cosθi.dΩi
- Συνάρτηση ανάκλασης BRDF (bidirectional reflectance distribution function) = Ir (ανακλώμενη ένταση στην κατεύθυνση της παρατήρησης)/Er (προσπίπτουσα ροή από άλλη κατεύθυνση)
- ΠΡΟΣΠΙΠΤΟΝ ΦΩΣ = ΑΝΑΚΛΩΜΕΝΟ ΦΩΣ + ΔΙΑΧΕΟΜΕΝΟ ΦΩΣ + ΑΠΟΡΡΟΦΟΥΜΕΝΟ ΦΩΣ + ΜΕΤΑΔΙΔΟΜΕΝΟ ΦΩΣ
- Incident light = reflected light + scattered light + absorbed light + transmitted light
- BRDF=κατευθυνόμενη ανάκλαση (specular reflection) + διάχυτη κατευθυνόμενη ανάκλαση (directional diffuse) + ιδανική διάχυτη ανάκλαση (ideal diffuse)

Reflection Models

- Definition: Reflection is the process by which light incident on a surface interacts with the surface such that it leaves on the incident side without change in frequency.

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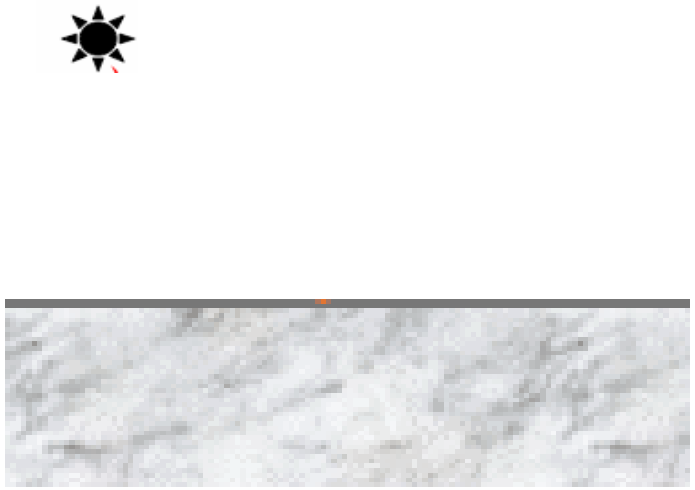

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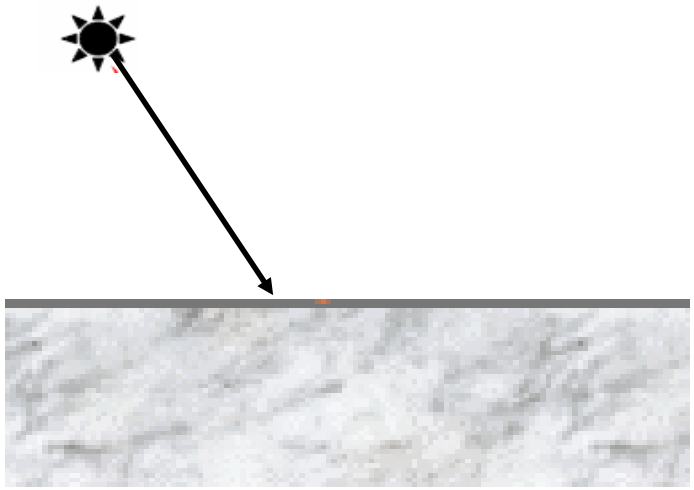

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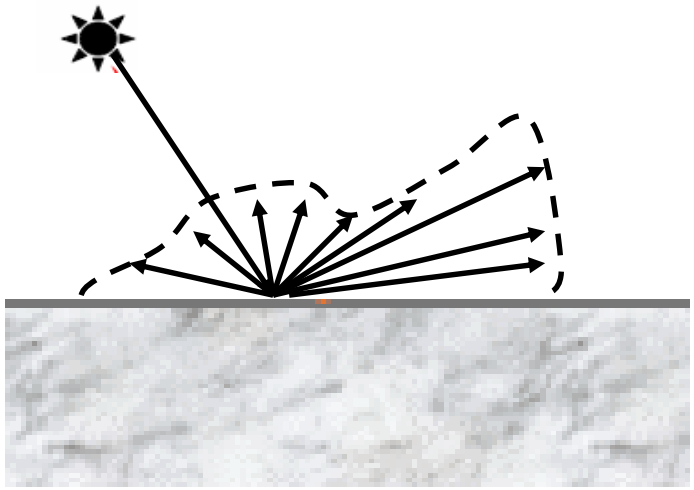
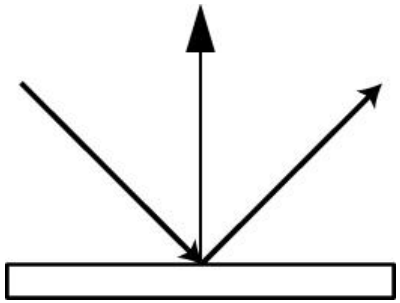
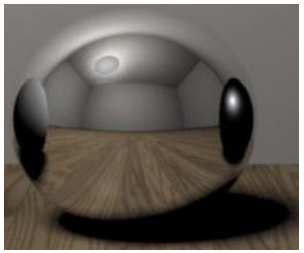


Types of Reflection Functions

- Ideal Specular
  - Reflection Law
  - Mirror





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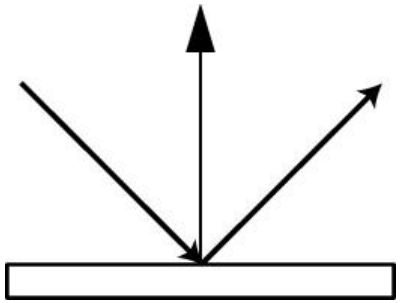
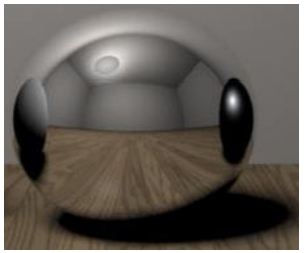
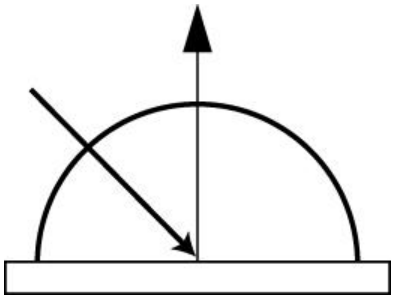
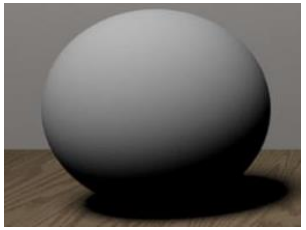




- Ideal Diffuse
  - Lambert's Law
  - Matte





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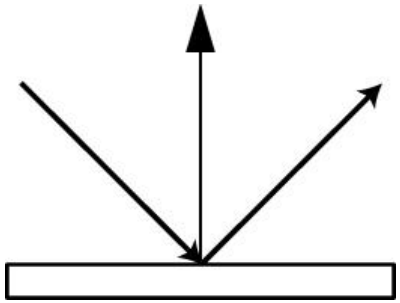

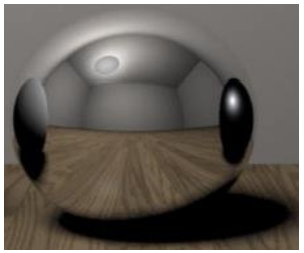

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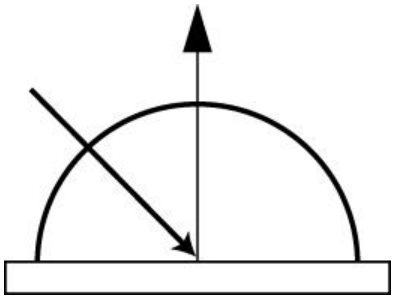
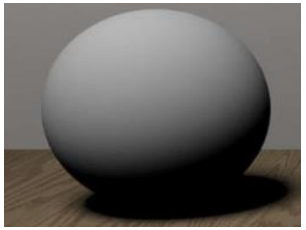
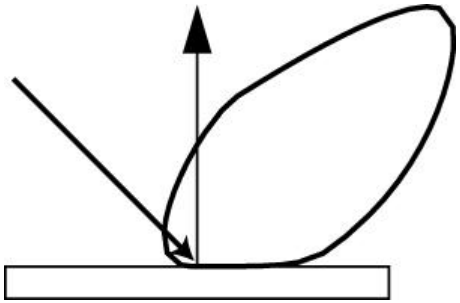
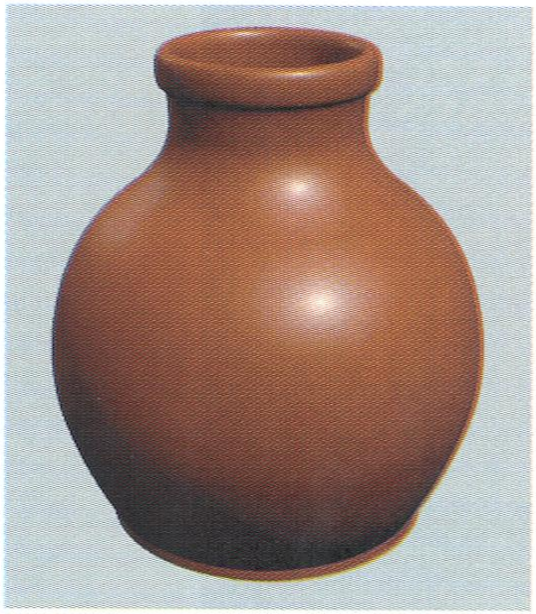




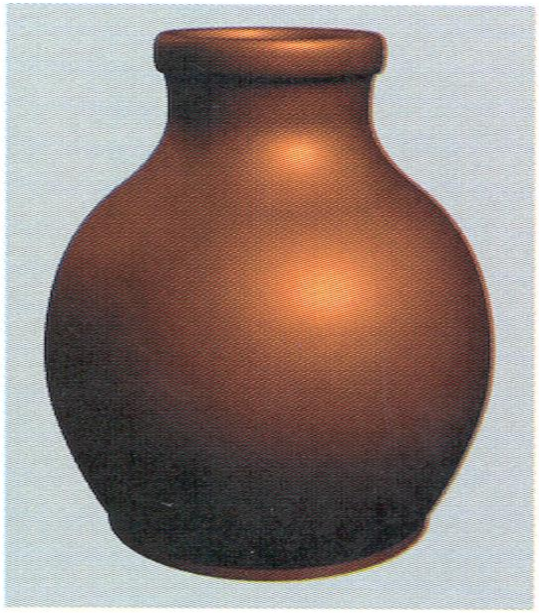
- Specular
  - Glossy
  - Directional diffuse



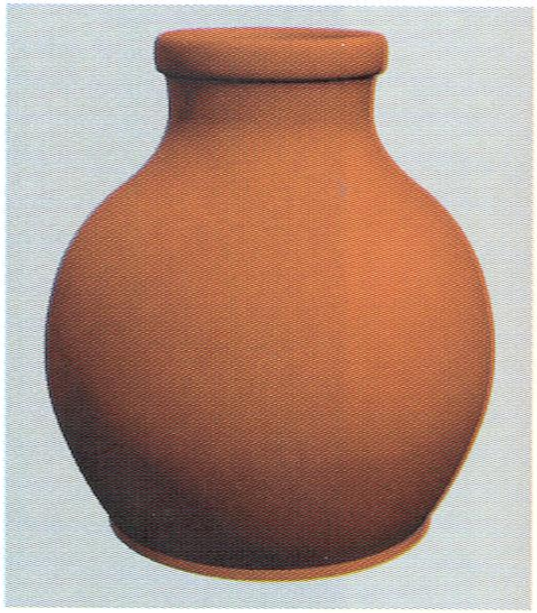
Materials



Plastic



Metal



Matte

From Apodaca and Gritz, *Advanced RenderMan*

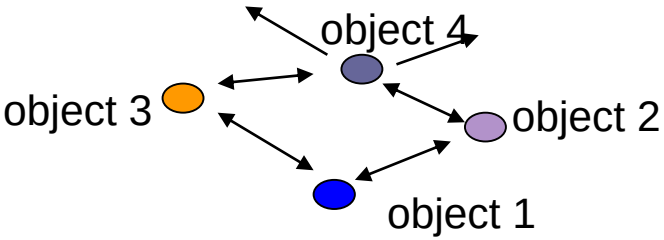
Illumination Model

- Ambient Light (έμμεσος)
  - Uniform light caused by secondary reflections
- Diffuse Light (διάχυτος)
  - Light scattered equally in all directions
- Specular Light (κατευθυνόμενος)
  - Highlights on shiny surfaces

- Final illumination of a point (vertex) =
  ambient + diffuse + specular

Ambient light contribution

- Ambient light (background light): the light that is scattered by the environment
- A very simple approximation of global illumination



- Independent of the light position, object orientation, observer's position or orientation – ambient light has no direction

Ambient Light

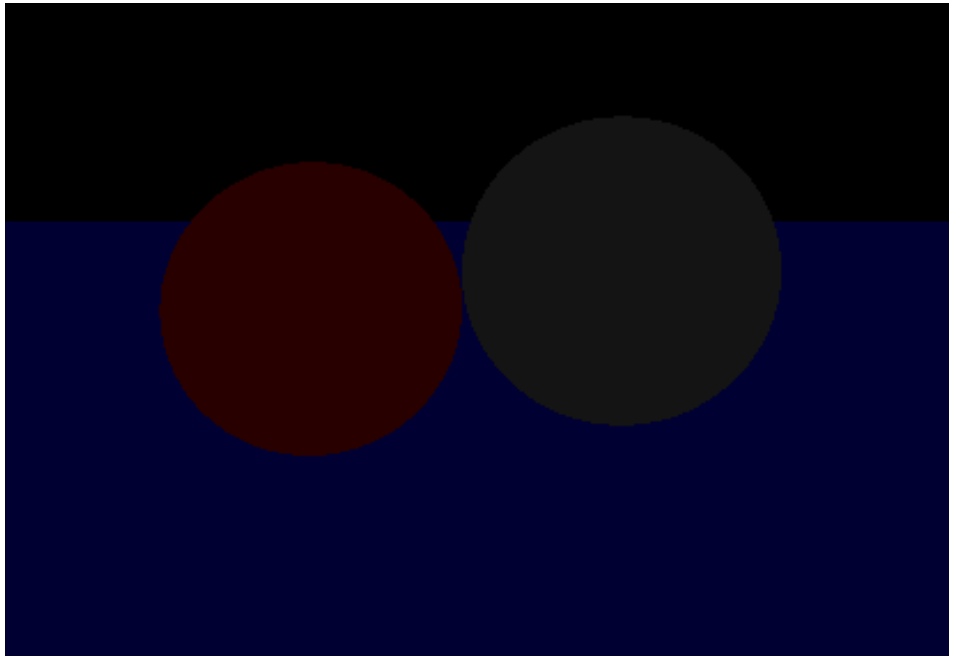
- Each light source has an ambient light contribution (*A* =intensity of ambient light)
- Different objects can reflect different amounts of ambient (different ambient reflection coefficient Ka, 0 <= Ka <= 1)
- So the amount of ambient light that can be seen from an object is:

$$I = k_a A$$

- 3 equations! (Red, Green, Blue)
- Accounts for indirect illumination
- Determines color of shadows

Total Illumination (ambient)

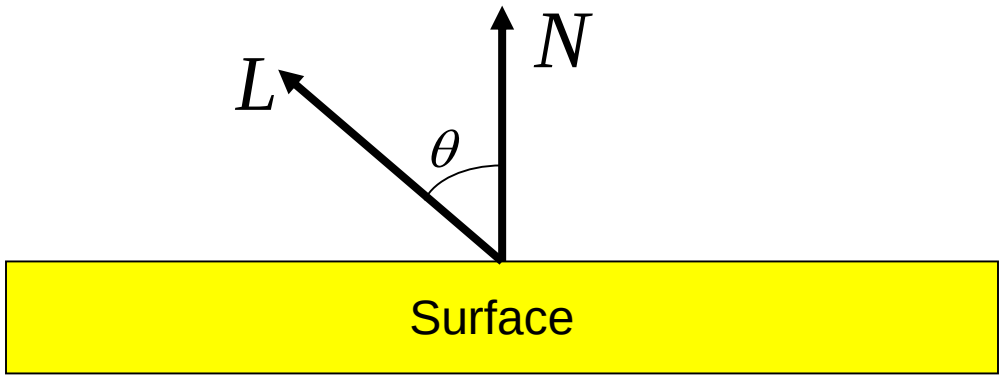
$$I = k_a A$$



Ambient lighting example

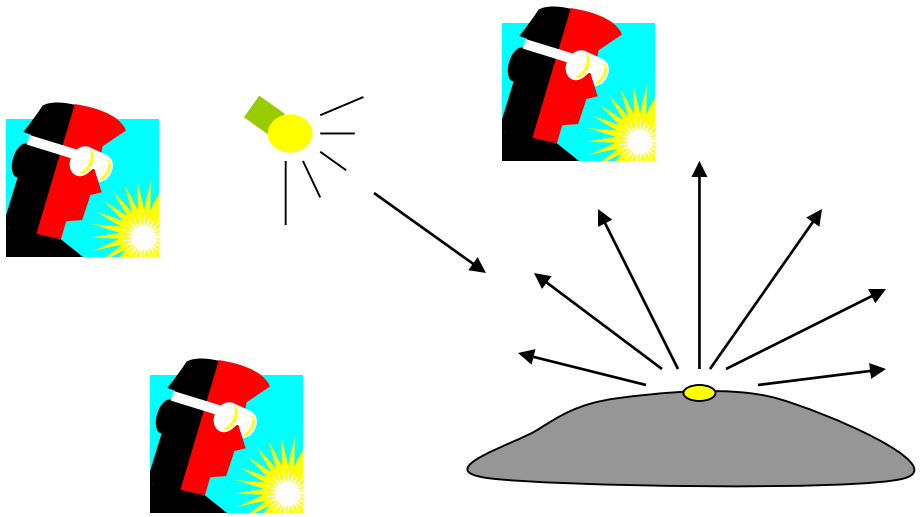
Diffuse Light

- Assumes that light is reflected equally in all directions
- Handles both local and infinite light sources
  - Infinite distance: *L* doesn't change
  - Finite distance: must calculate L for each point on surface



Diffuse light contribution

- Diffuse light: The illumination that a surface receives from a light source and reflects equally in all direction

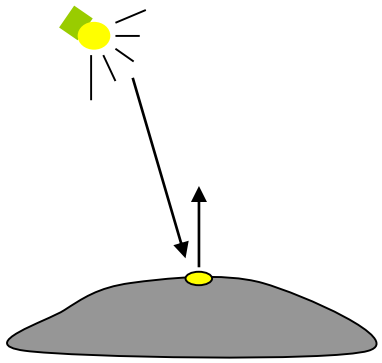


It does not matter where the eye is

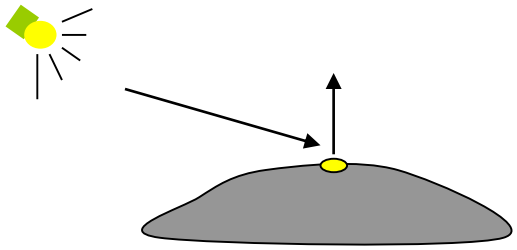
Diffuse lighting example

Diffuse light calculation

- Need to decide how much light the object point receive from the light source – based on Lambert's Law

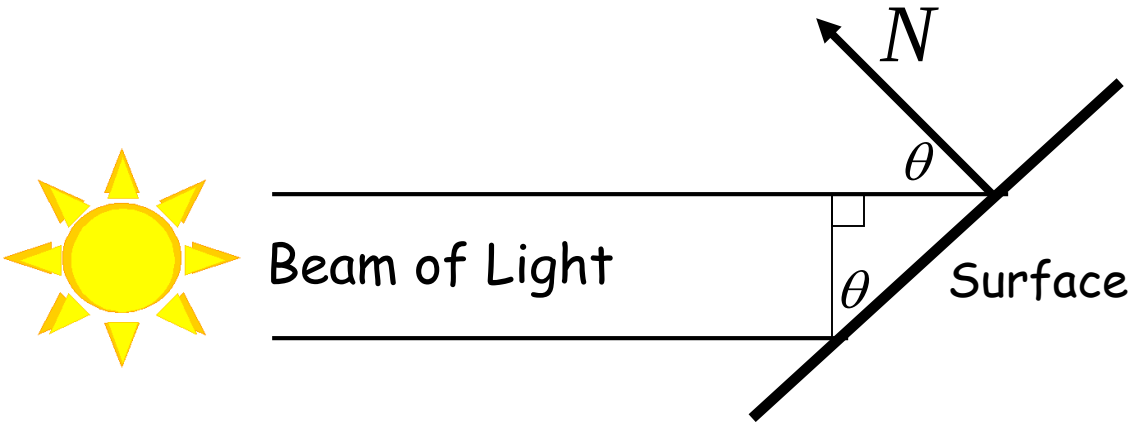


Receive more light



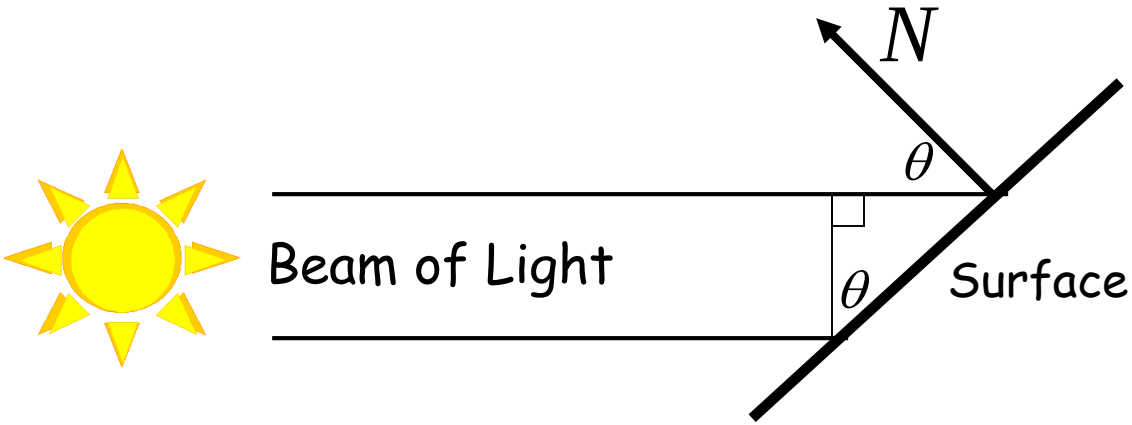
Receive less light

Lambert's Law



$$I = \frac{Light}{Area} = \frac{Beam\ Width \times I_{source}}{Surface\ Area}$$

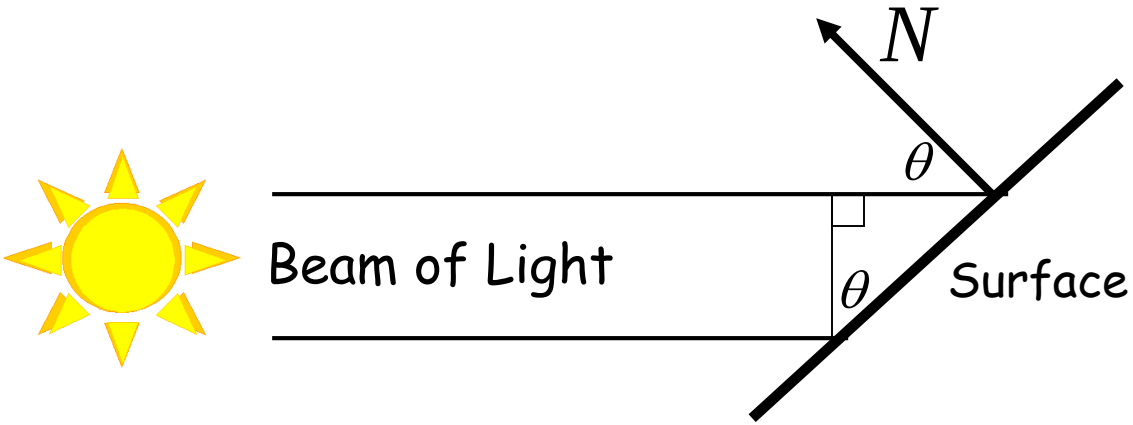
Lambert's Law



$$I = \frac{Light}{Area} = \frac{Beam\ Width \times I_{source}}{Surface\ Area}$$

$$\frac{Beam\ Width}{Surface\ Area} = \cos(\theta)$$

Lambert's Law



$$I = \frac{Light}{Area} = \frac{Beam\ Width \times I_{source}}{Surface\ Area} = I_{source}(L \cdot N)$$

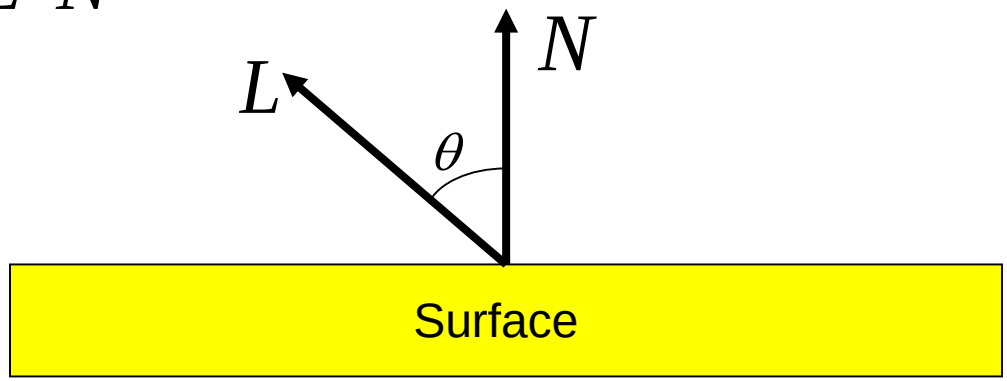
$$\frac{Beam\ Width}{Surface\ Area} = \cos(\theta)$$

Diffuse Light

$$I = C k_d \cos(\theta) = C k_d (L \cdot N)$$

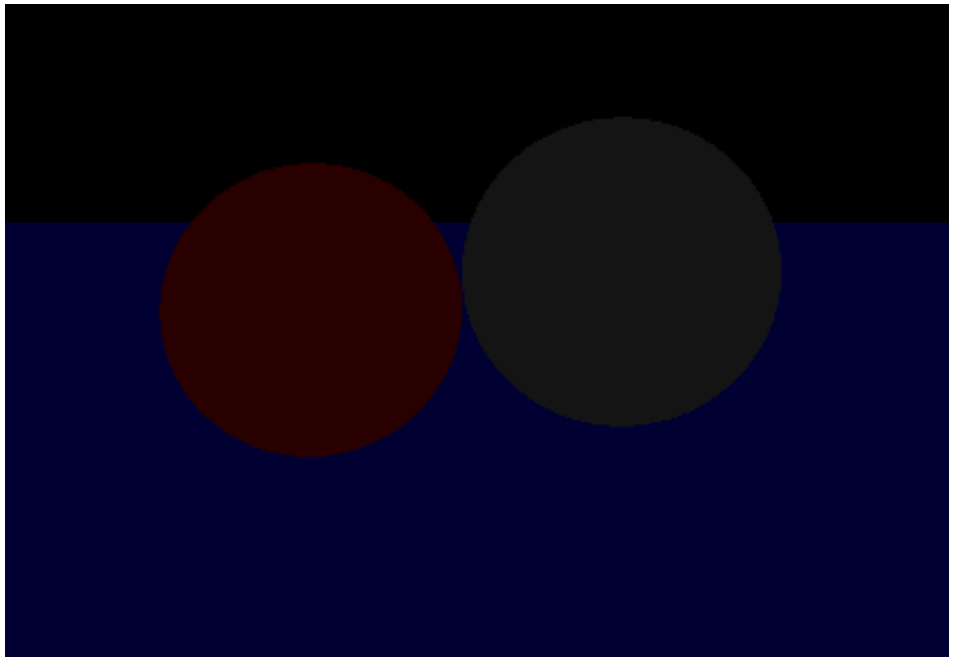
- C = intensity of point light source
- k_d = diffuse reflection coefficient of the particular object
- θ = angle between normal and direction to light

$$\cos(\theta) = L \cdot N$$



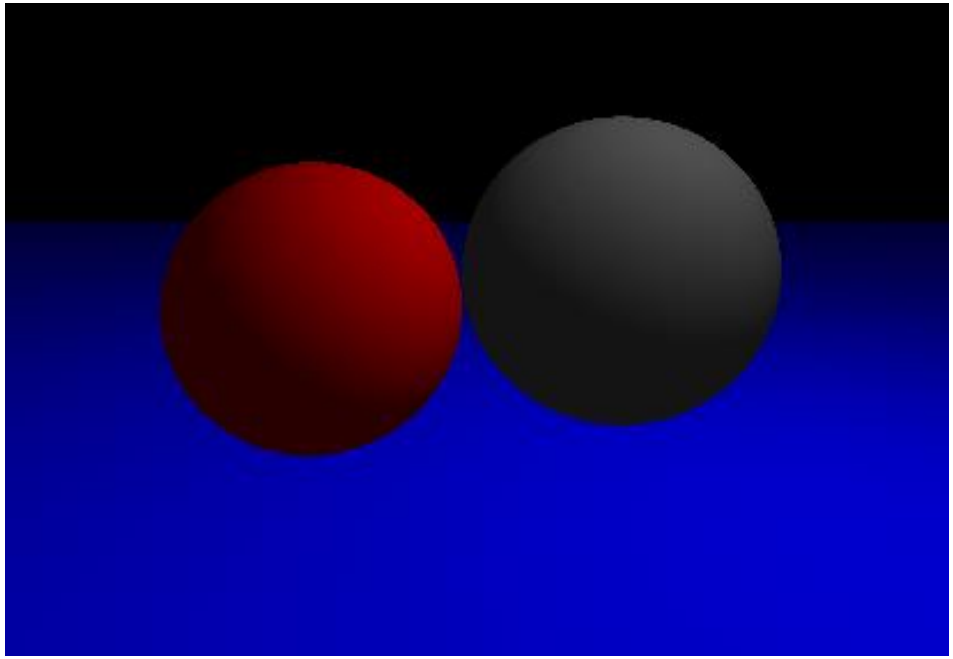
Total Illumination (ambient)

$$I = k_a A$$

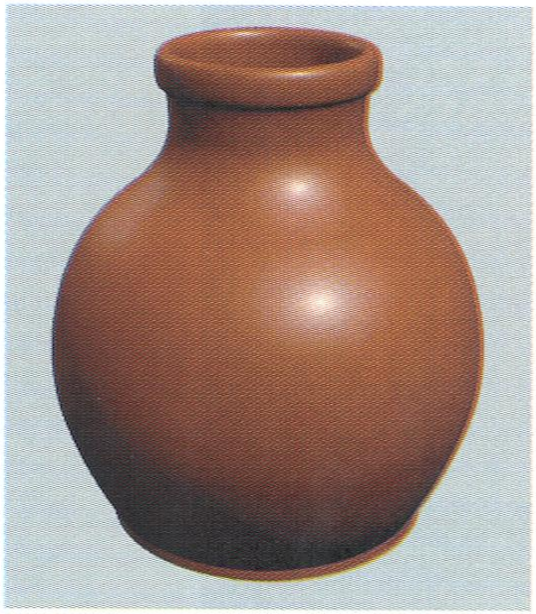


Total Illumination (ambient + diffusion)

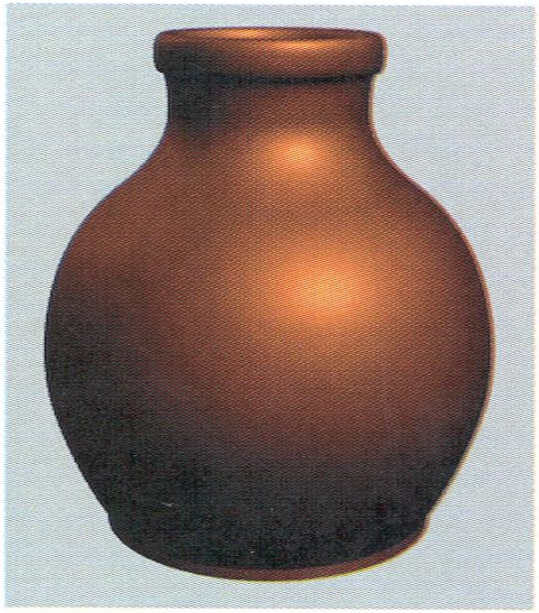
$$I = k_a A + k_d C(L \cdot N)$$



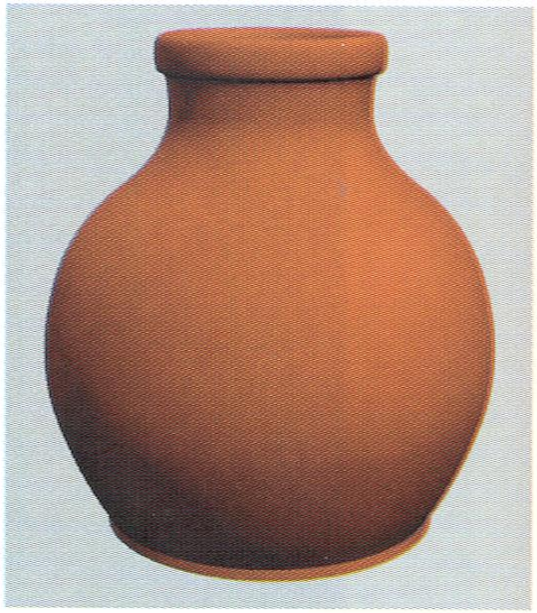
Materials



Plastic



Metal

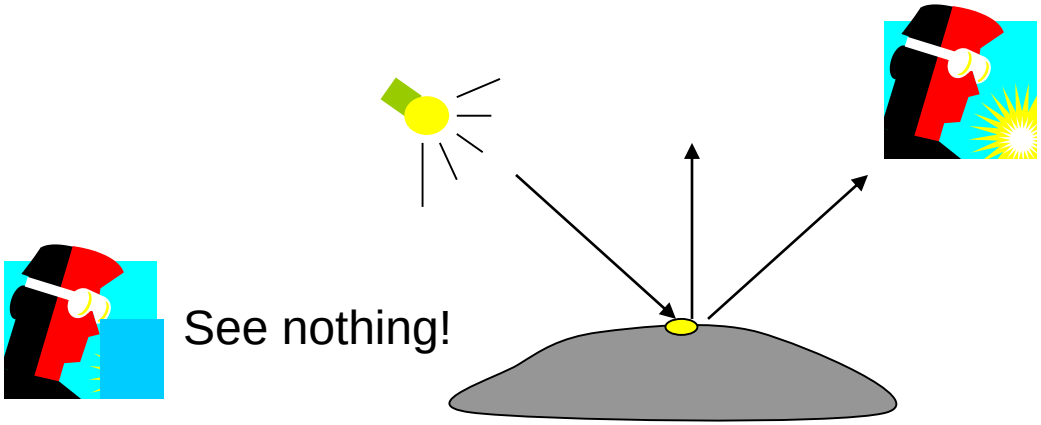


Matte

From Apodaca and Gritz, *Advanced RenderMan*

Specular light contribution

- The bright spot on the object
- The result of total reflection of the incident light in a concentrate region

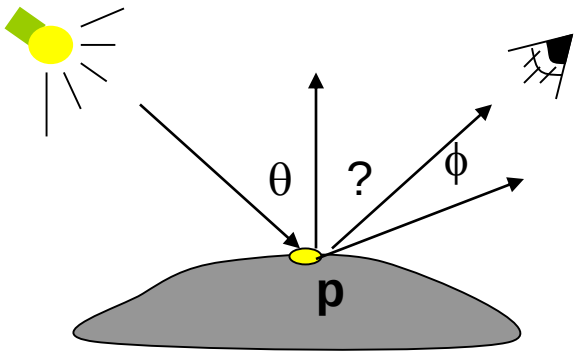


Specular light example

Specular light calculation

- How much reflection you can see depends on where you are

The only position the eye can see specular from P if the object has an ideal reflection surface

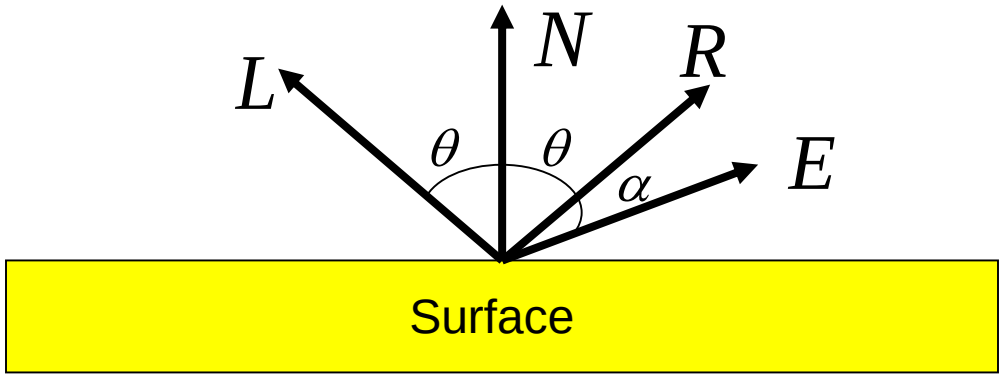


But for a non-perfect surface you will still see specular highlight when you move a little bit away from the idea reflection direction

When φ is small, you see more specular highlight

Specular Light

- Perfect, mirror-like reflection of light from surface
- Forms highlights on shiny objects (metal, plastic)



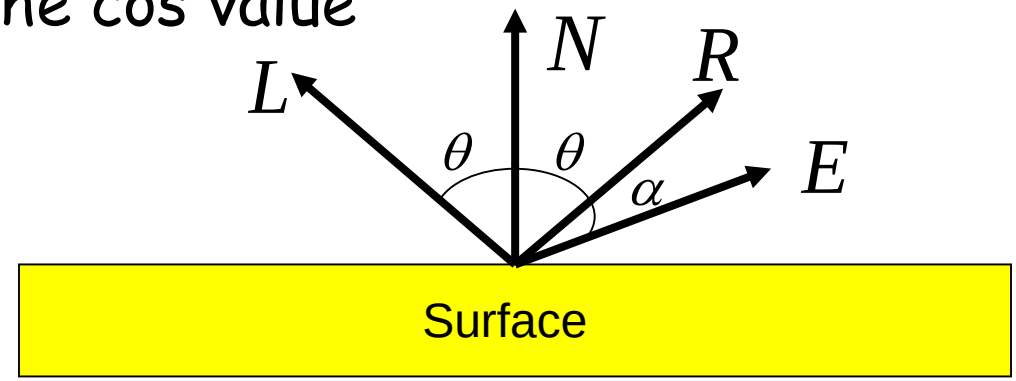
Specular Light

$$I = C k_s \cos^n(\alpha) = C k_s (R \cdot E)^n$$

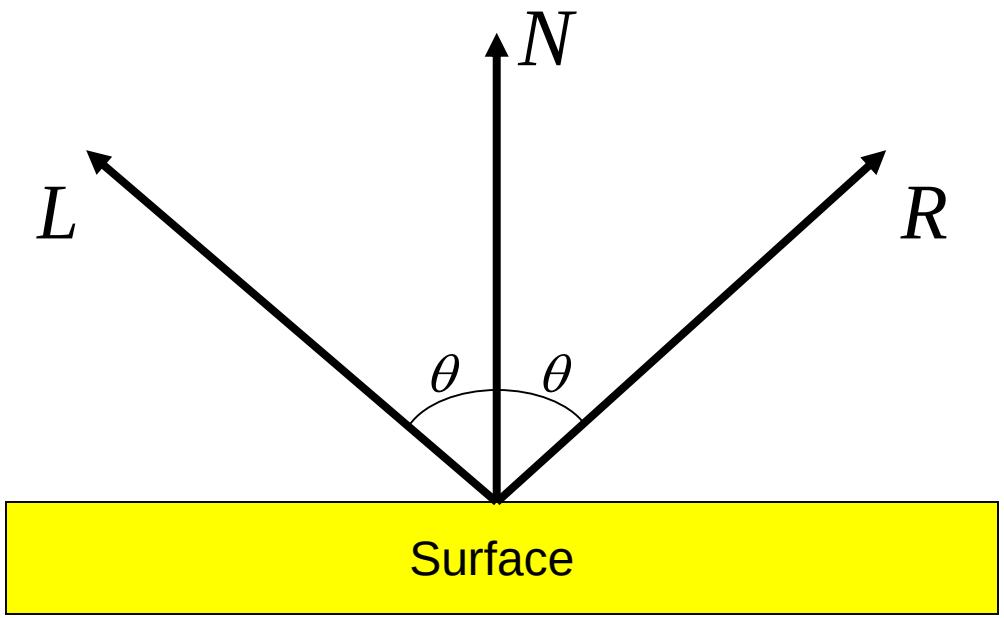
- C = intensity of point light source
- k_s = specular reflection coefficient
- α = angle between reflected vector (R) and eye (E)

$$\cos(\alpha) = R \cdot E$$

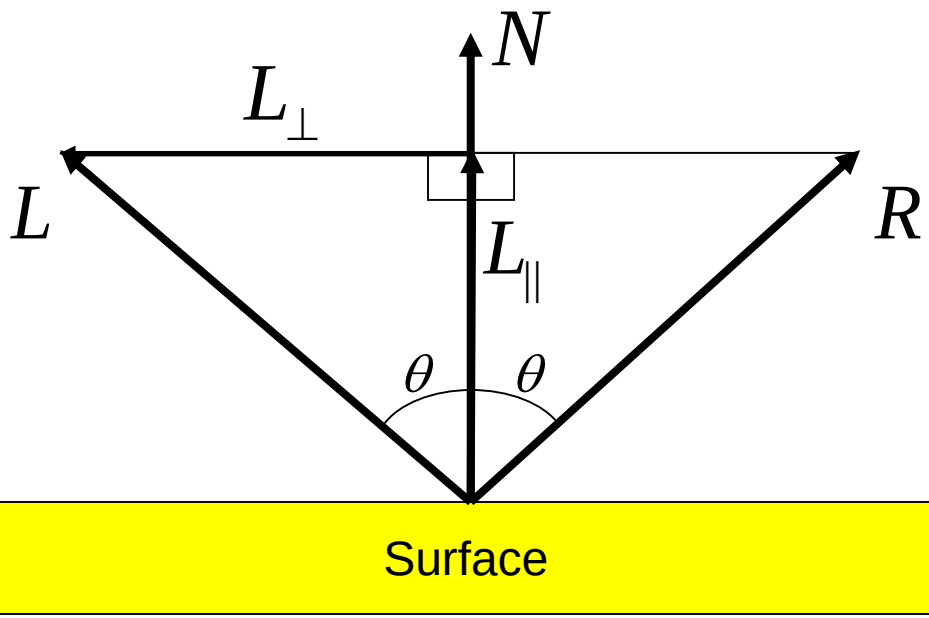
- n = specular coefficient - the larger is n, the smaller is the cos value



Finding the Reflected Vector



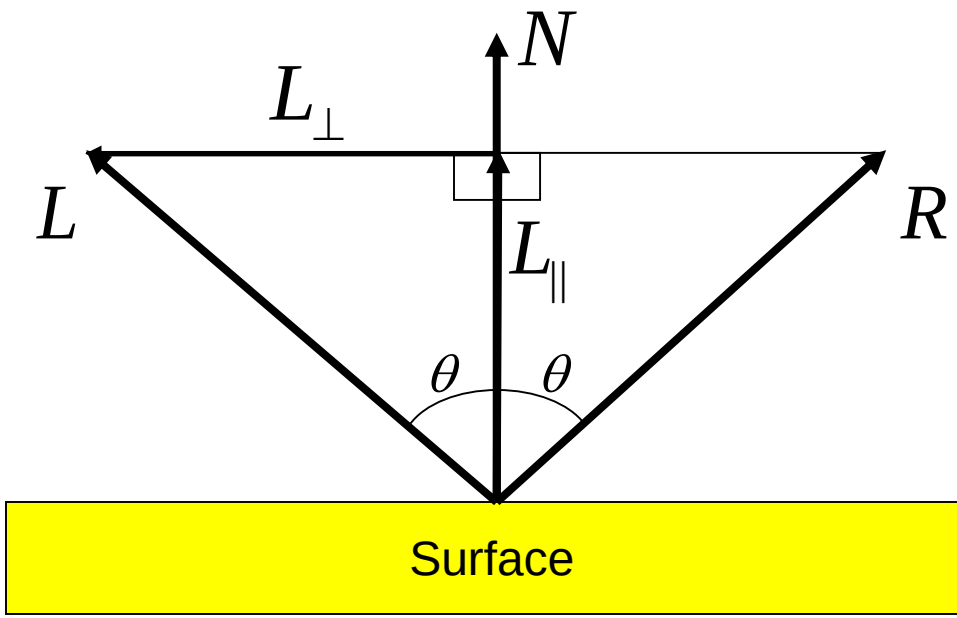
Finding the Reflected Vector



Finding the Reflected Vector

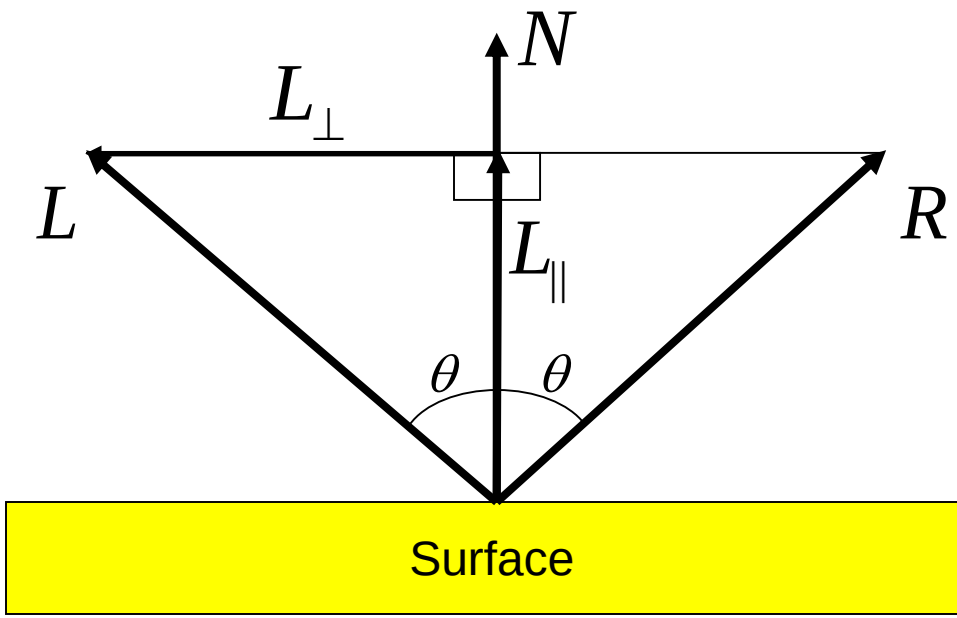
$$L_{\parallel} = N\cos(\theta) = N(L \cdot N)$$

$$L_{\perp} = L - L_{\parallel}$$



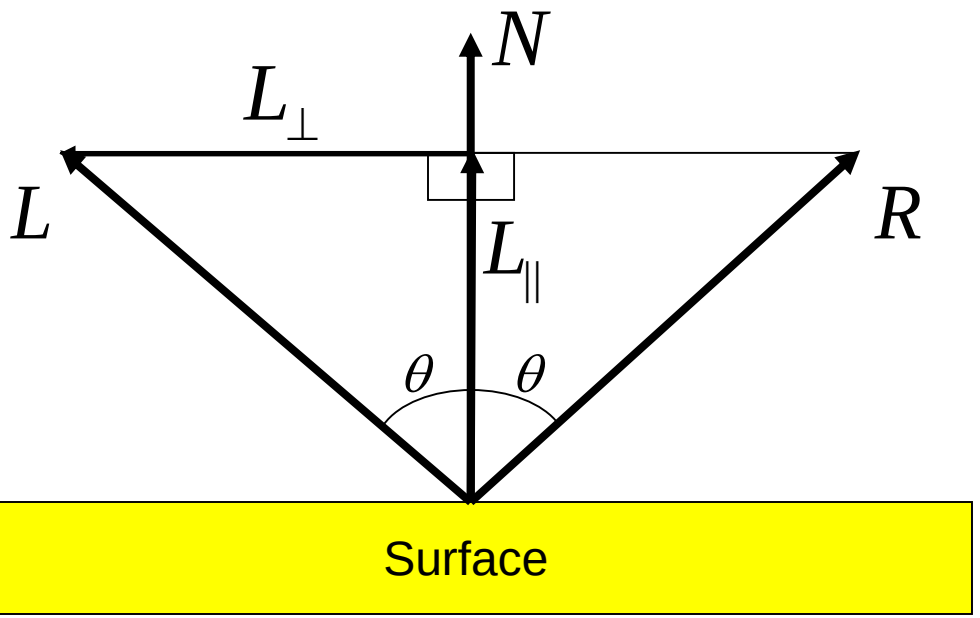
Finding the Reflected Vector

$$R = L_{\parallel} - L_{\perp}$$



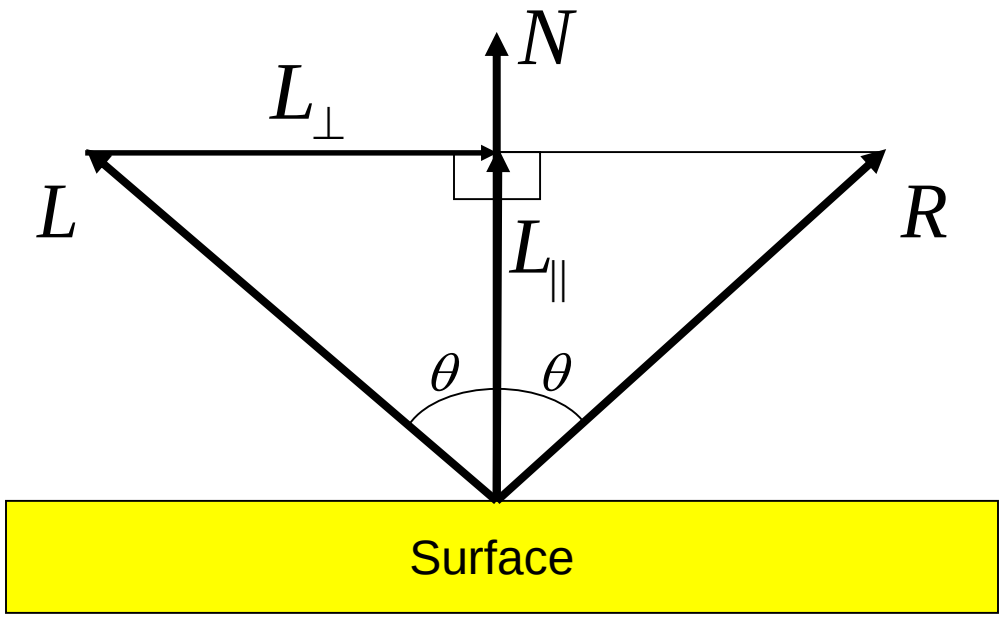
Finding the Reflected Vector

$$R = L_{\parallel} - L_{\perp} = 2L_{\parallel} - L$$



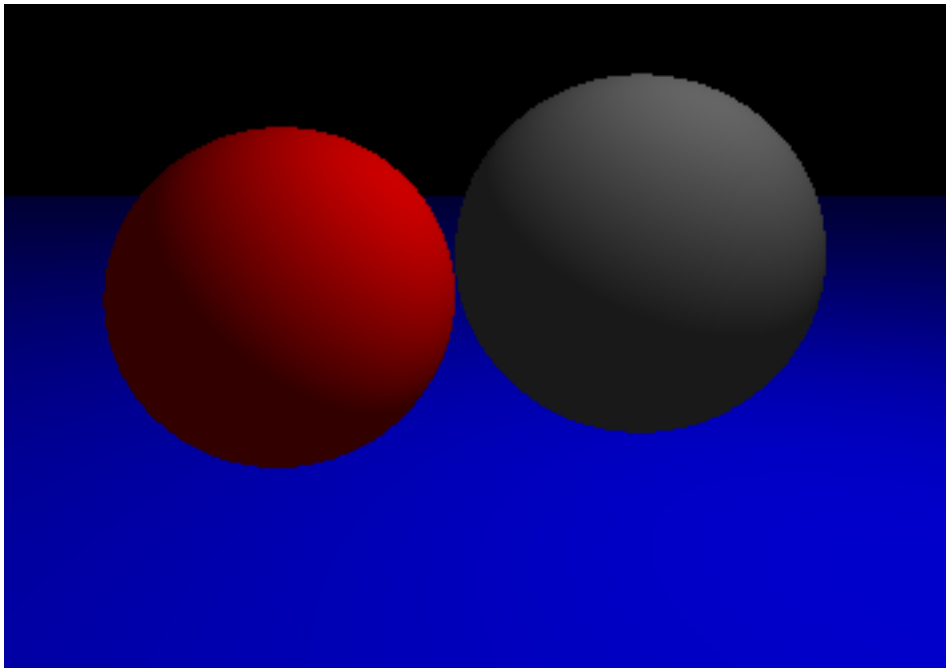
Finding the Reflected Vector

$$R = 2(L \cdot N)N - L$$



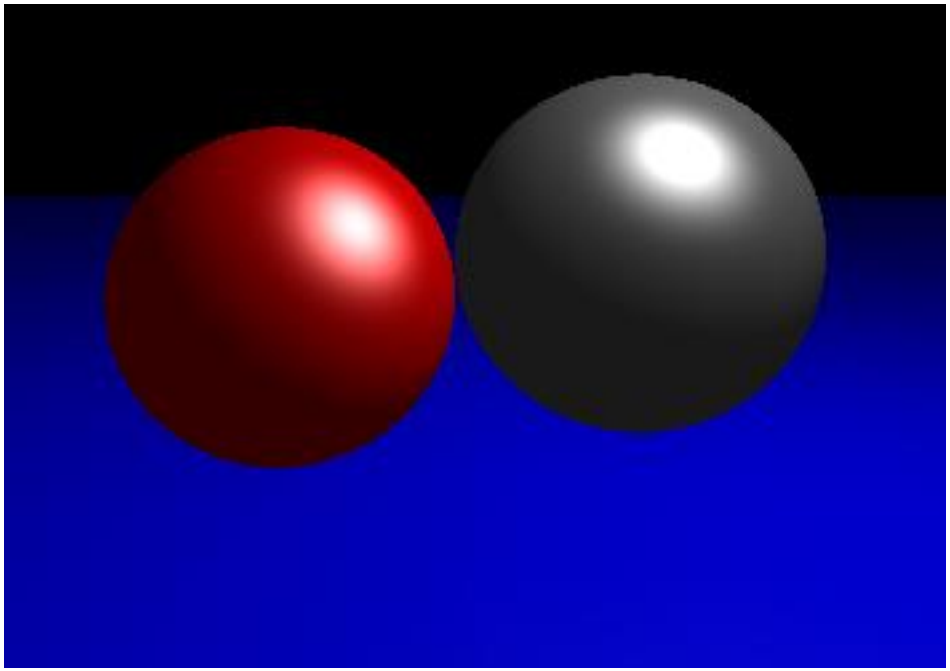
Total Illumination (ambient+diffusion)

$$I = k_a A + k_d C(L \cdot N)$$



Total Illumination (ambient+diffusion+specular)

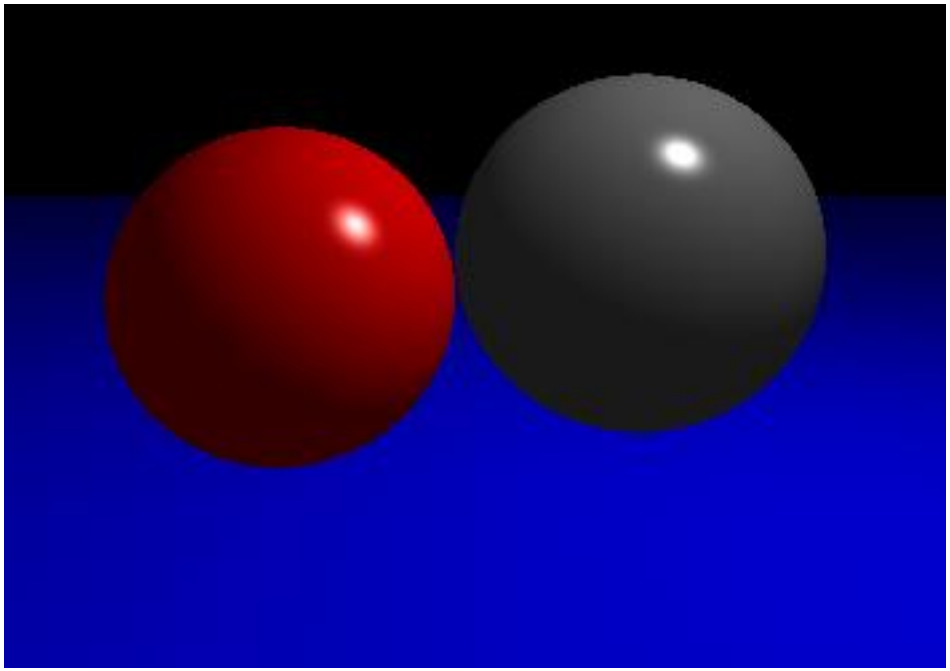
$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$



$n = 5$

Total Illumination (ambient+diffusion+specular)

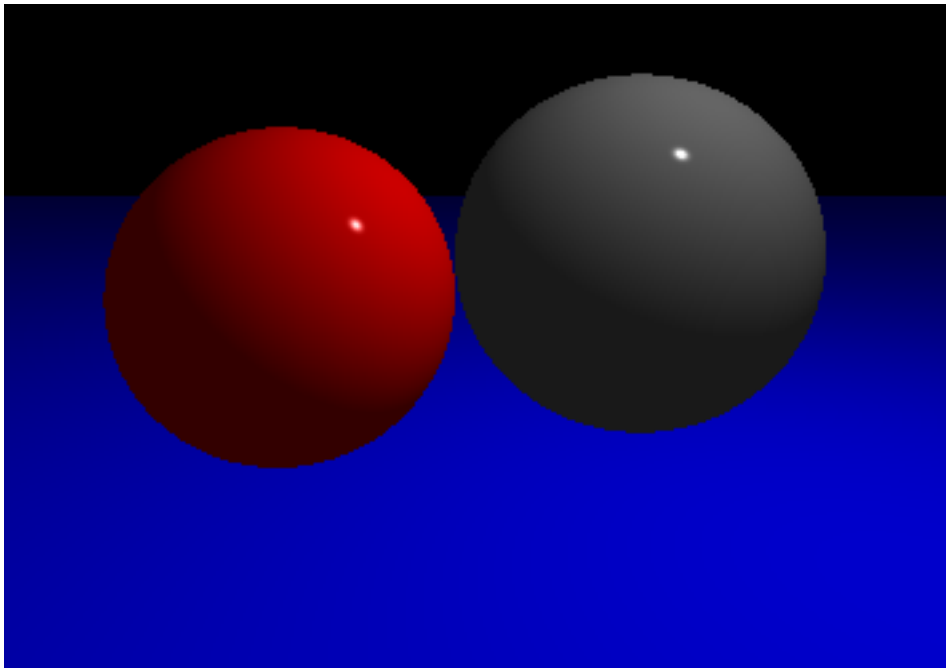
$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$



$$n = 50$$

Total Illumination (ambient+diffusion+specular)

$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$



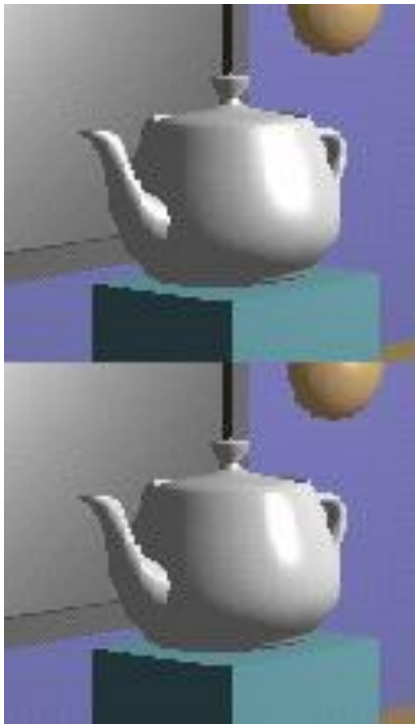
$$n = 500$$

Specular light calculation

- The effect of 'n'

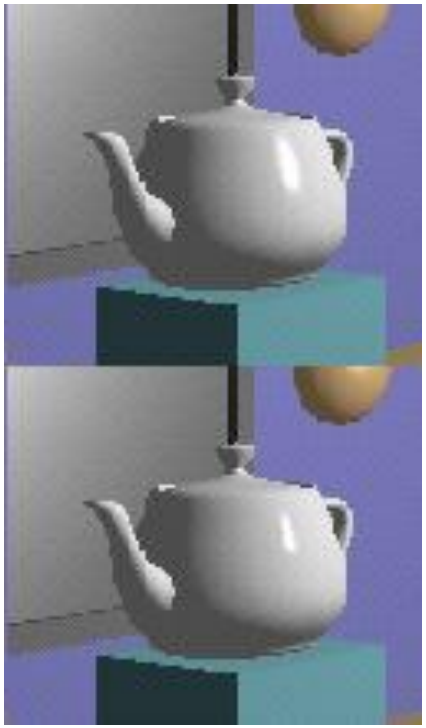
n = 10

n = 30



n = 90

n = 270

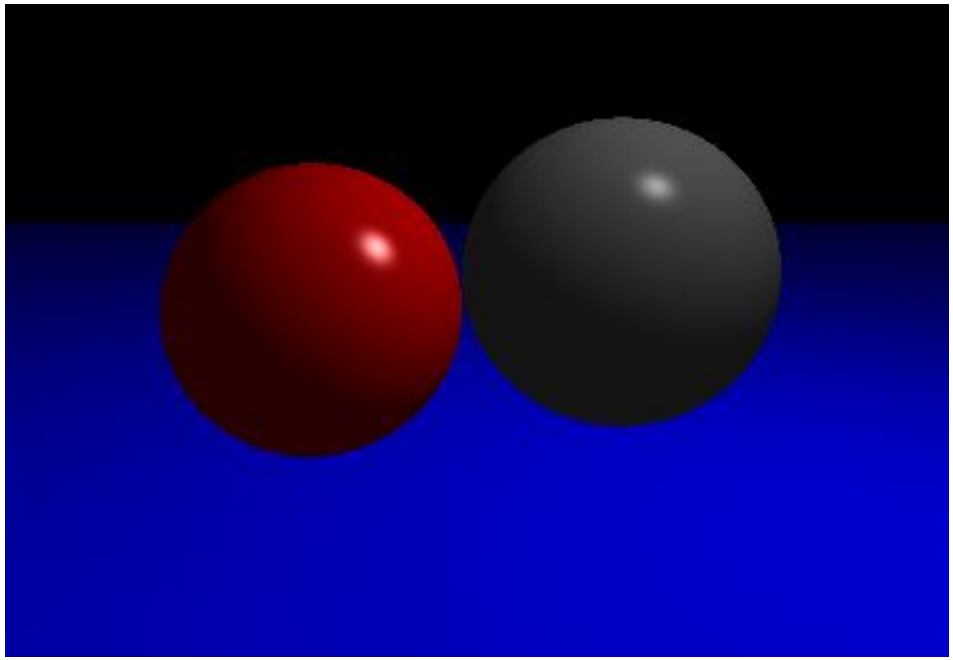


Multiple Light Sources

- Only one ambient term no matter how many lights
- Light is additive; add contribution of multiple lights (diffuse/specular components)

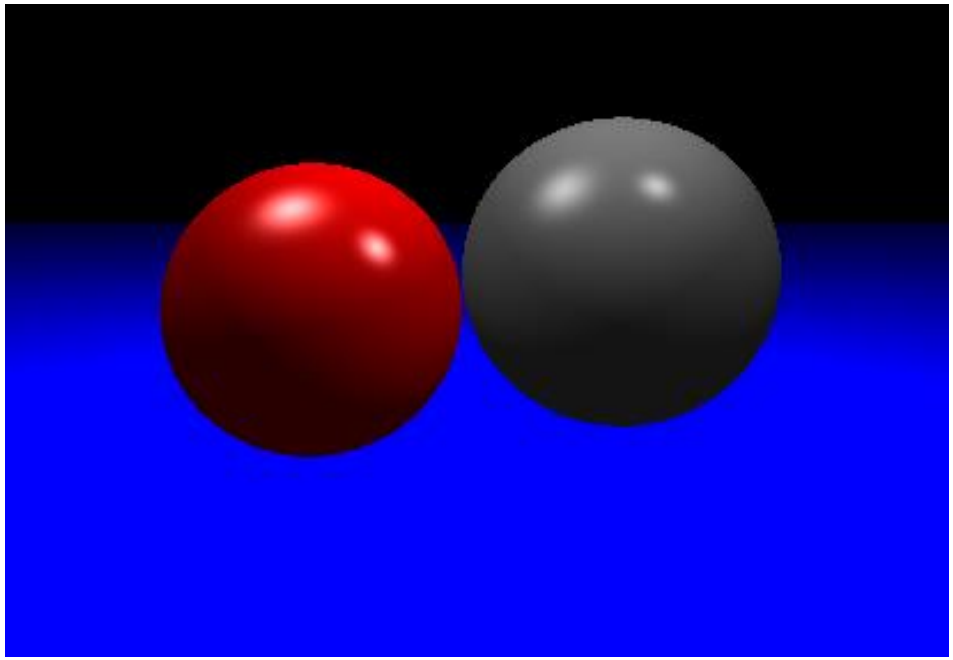
Total Illumination – single light source

$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$



Total Illumination – multiple light sources

$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right)$$



Other Lights

- Attenuation caused by fog, smoke

- Spot lights

Attenuation

- Decrease intensity with distance from light

- d = distance to light
- r = radius of attenuation for light

$$att(d,r) = \max(0, 1 - d/r)$$

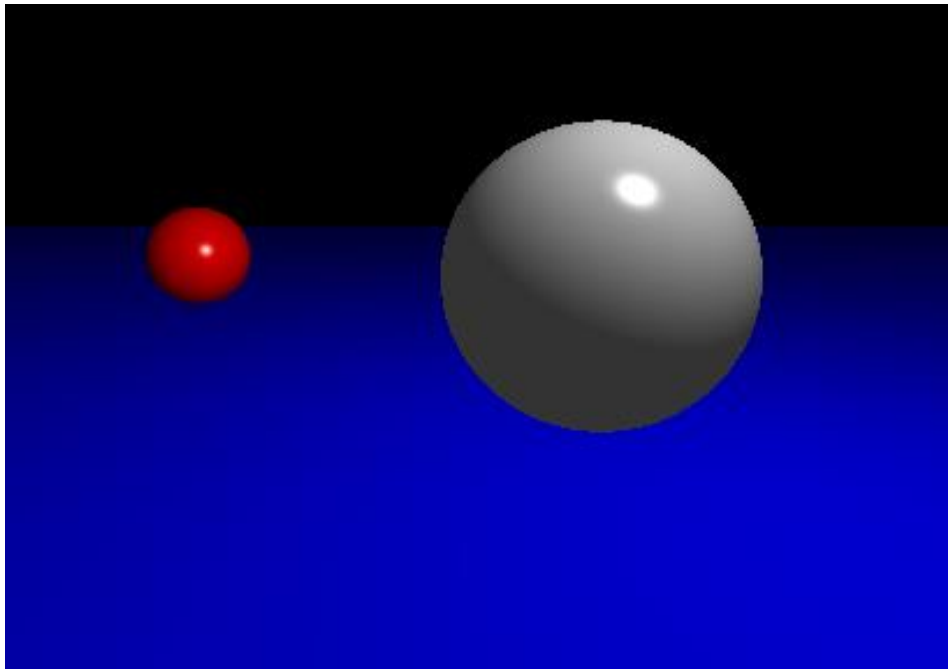
$$att(d,r) = \max(0, 1 - d^2/r^2)$$

$$att(d,r) = \max\left(0, \left(1 - d^2/r^2\right)^2\right)$$

$$att(d,r) = e^{-d^2/r^2}$$

Attenuation

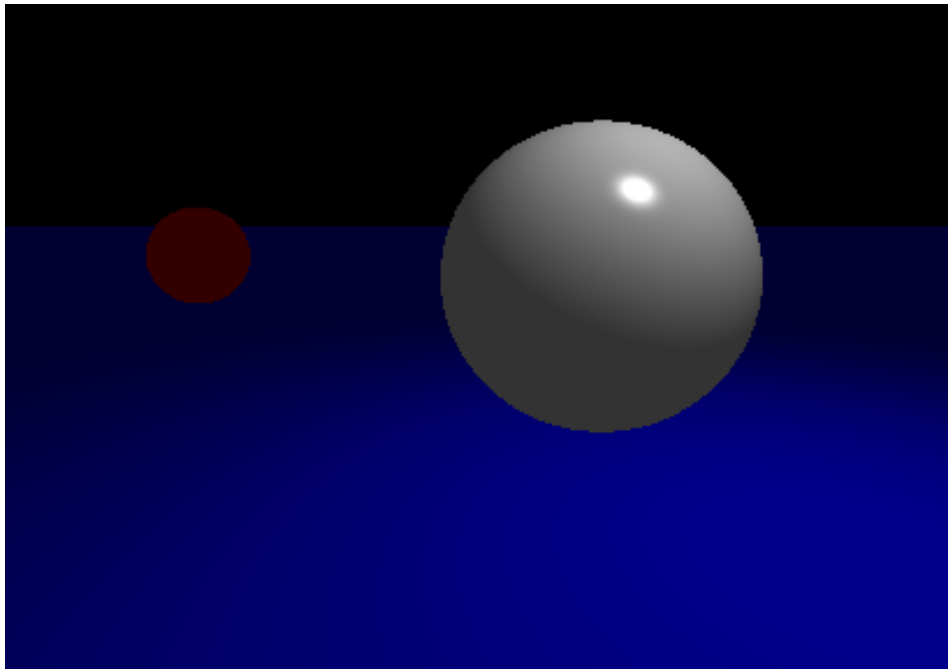
$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right) att(d, r_i)$$



No attenuation

Attenuation

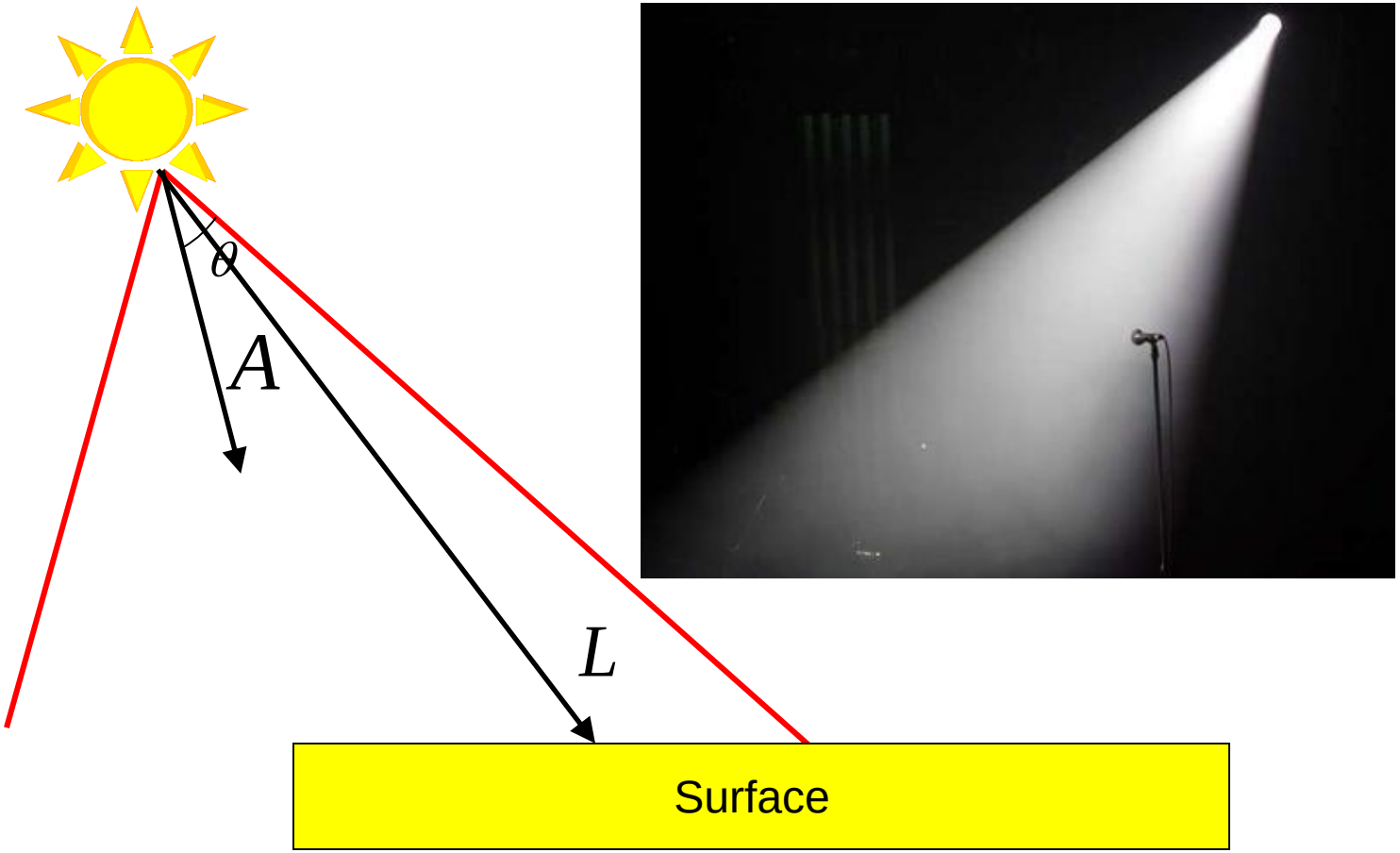
$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right) att(d, r_i)$$



with attenuation

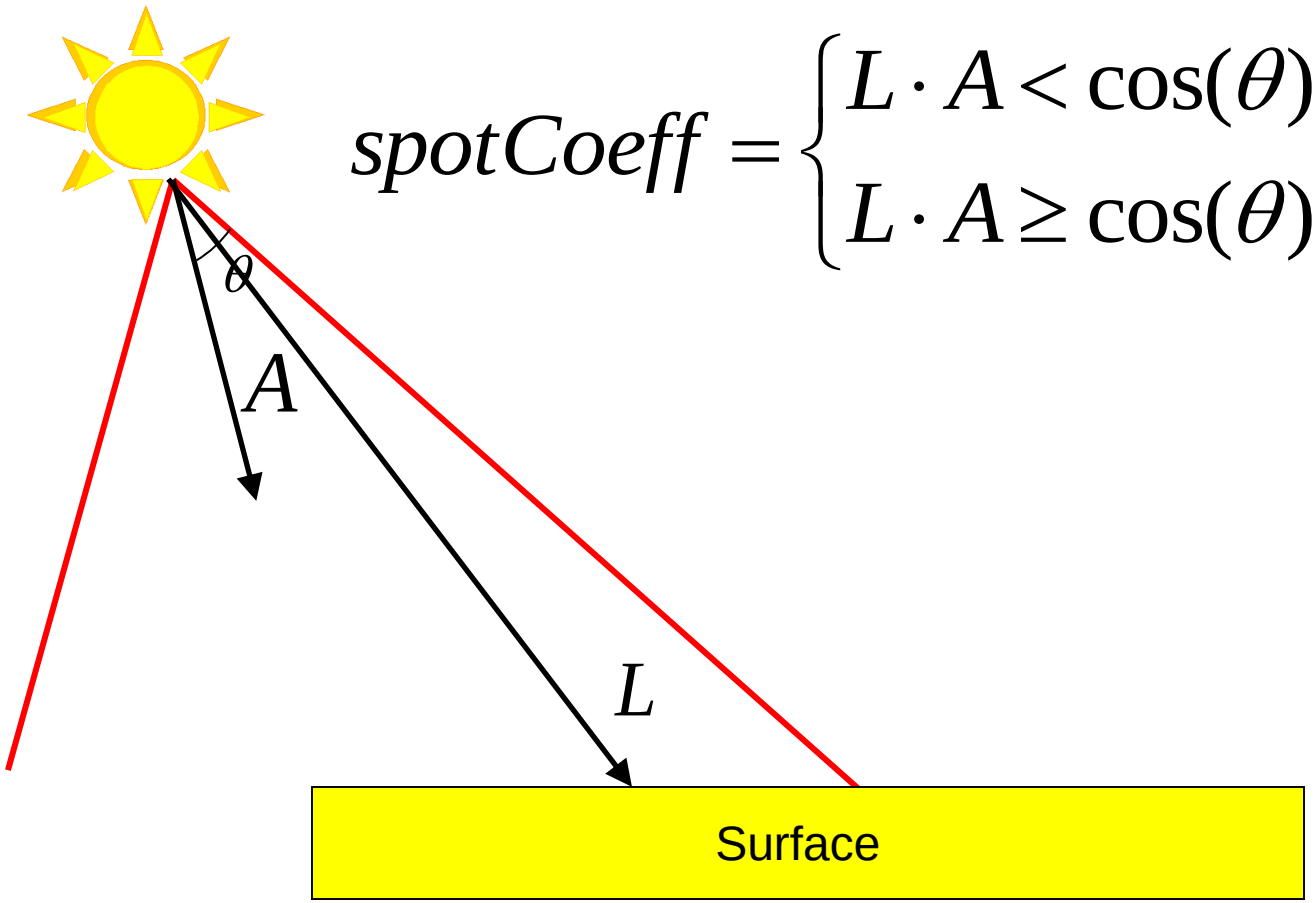
Spot Lights

- Eliminate light contribution outside of a cone



Spot Lights

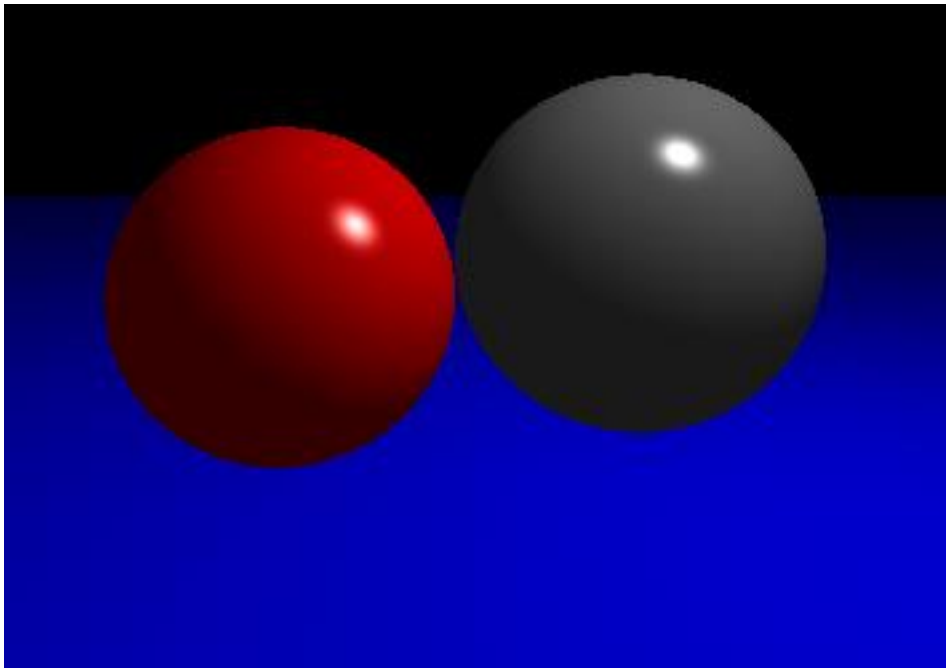
- Eliminate light contribution outside of a cone



$$spotCoeff = \begin{cases} L \cdot A < \cos(\theta), & 0 \\ L \cdot A \geq \cos(\theta), & (L \cdot A)^{\alpha} \end{cases}$$

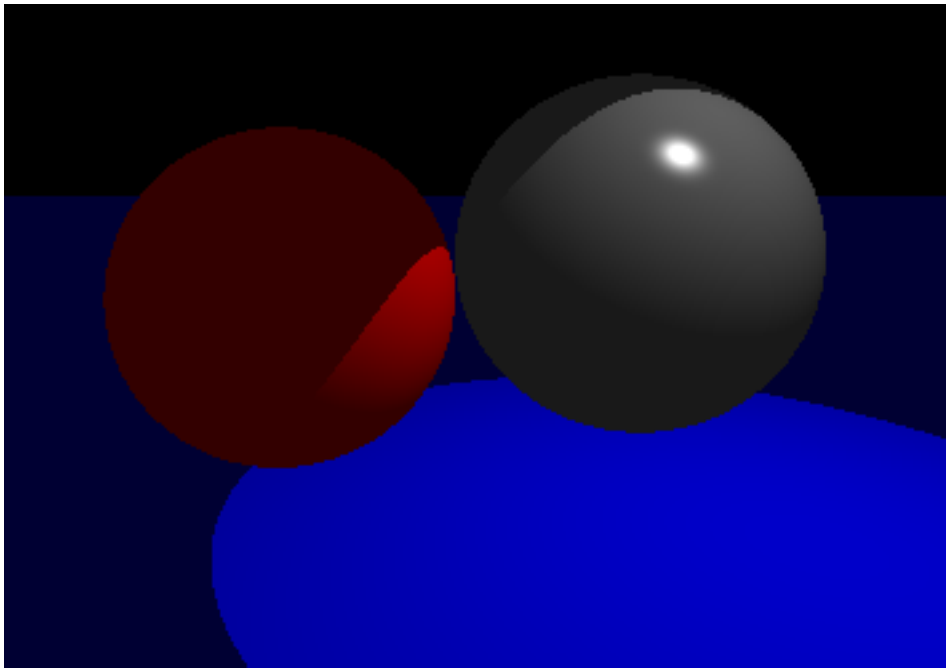
Attenuation

$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right) spotCoeff_i$$



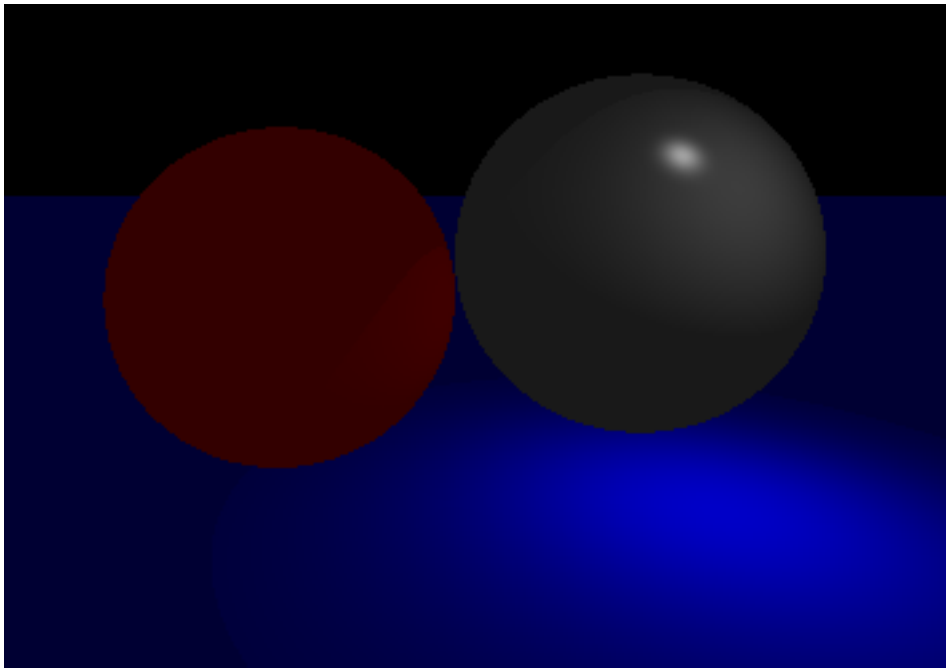
Spot Lights

$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right) spotCoeff_i$$



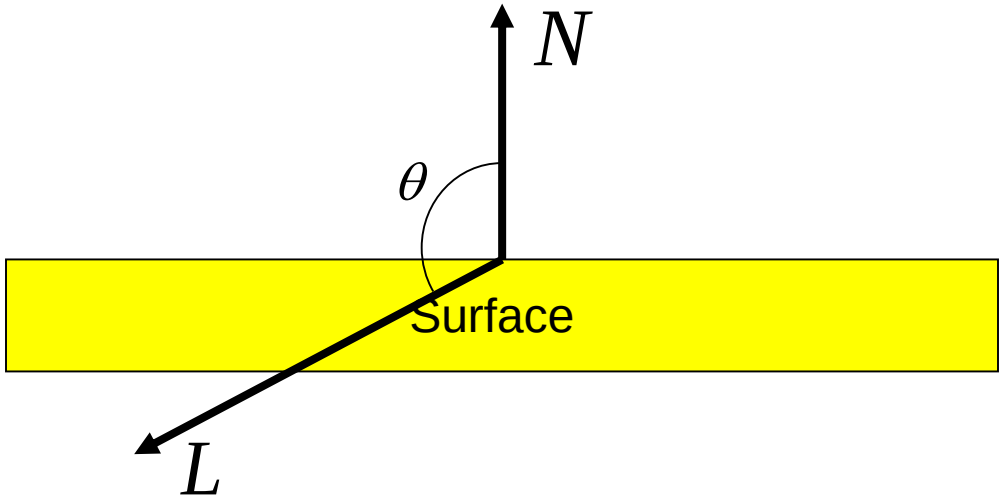
Spot Lights

$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right) spotCoeff_i$$



Implementation Considerations

$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$



Implementation Considerations

$$I = k_a A + \sum_i C_i \left(k_d (L_i \cdot N) + k_s (R_i \cdot E)^n \right)$$

- Typically choose $k_a + k_d + k_s \leq 1$
- Clamp each color component to [0,1]

Opengl Functions

- See section 10.20
- how to set up light sources (light source pos
  - light source position and type
  - light source colors
  - radial-intensity attenuation
  - spotlights
- how to specify global lighting parameters
- how to specify surface properties

Απόδοση Επιφανειών και Υφής

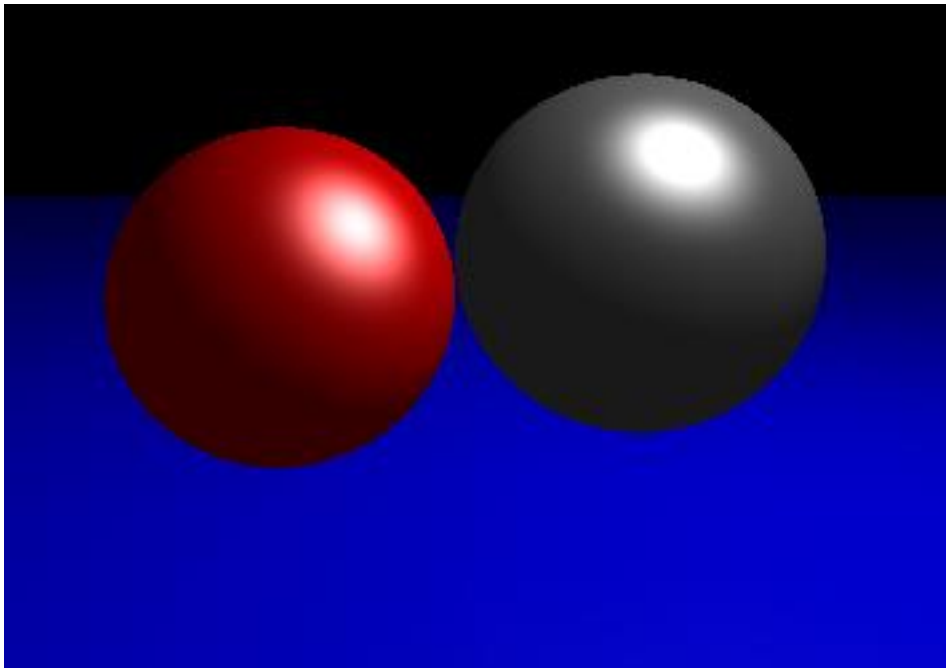
Outline

- Shading

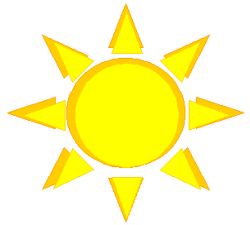
- Texture mapping & others
- Readings: HB 10-10, 10-17, 10-18

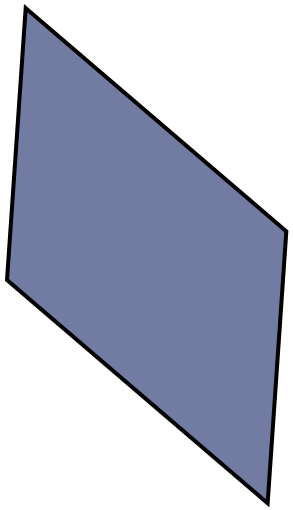
Total Illumination

$$I = k_a A + C\left(k_d (L \cdot N) + k_s (R \cdot E)^n\right)$$

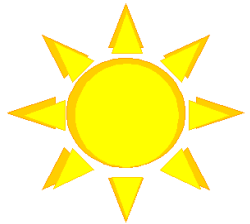


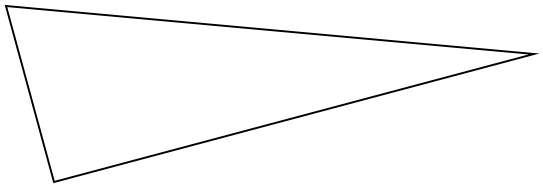
Problem

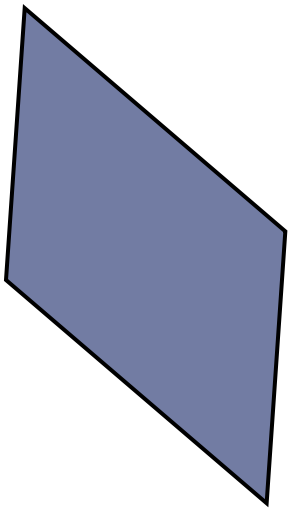




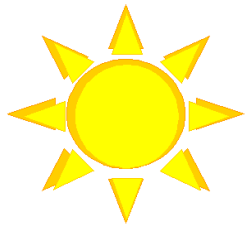
Problem

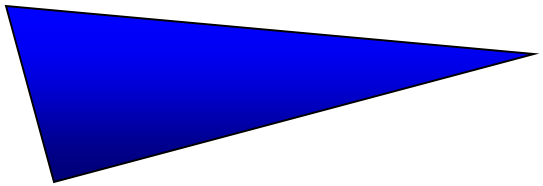


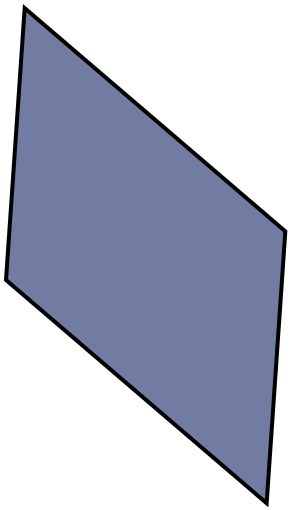




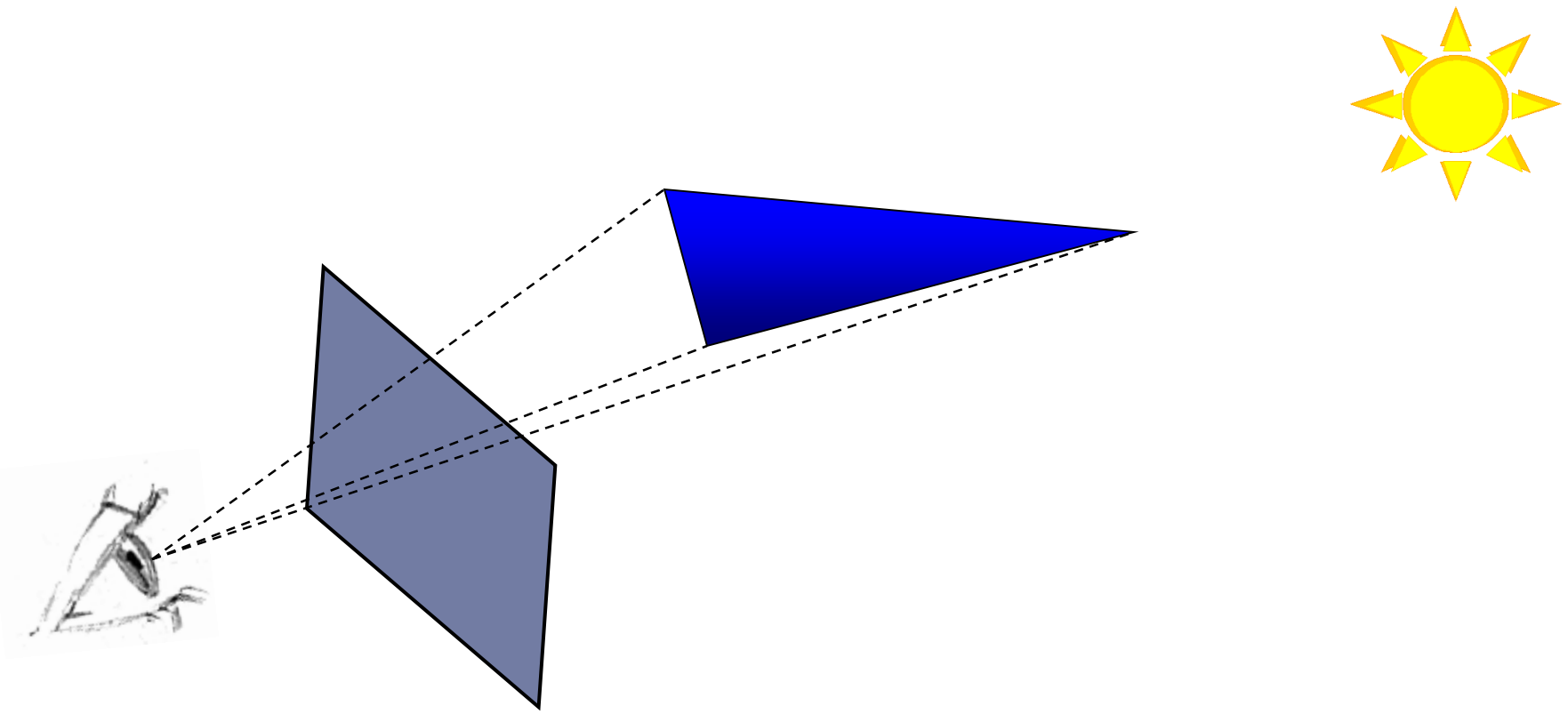
Problem



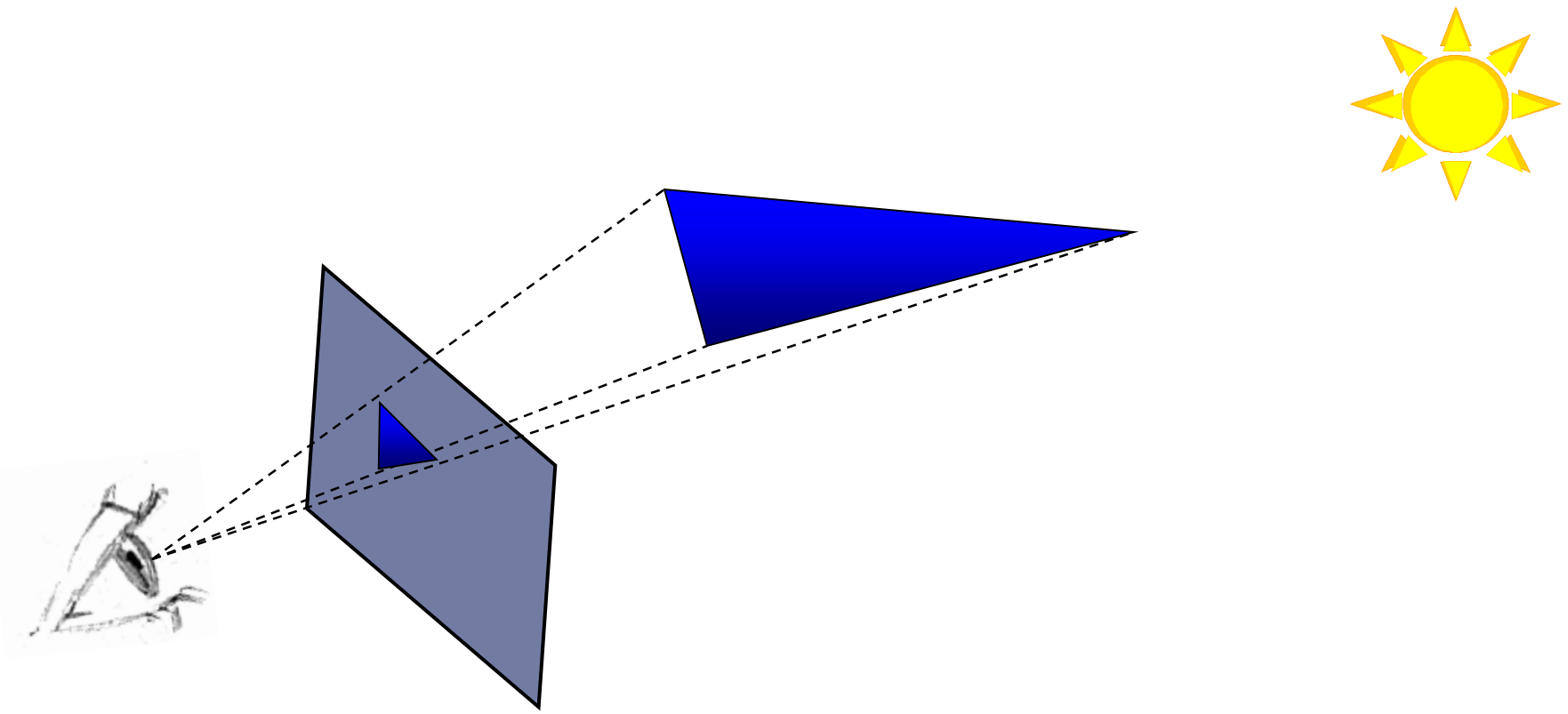




Problem



Problem



Shading Algorithms

- Flat Shading
- Gouraud Shading
- Phong Shading

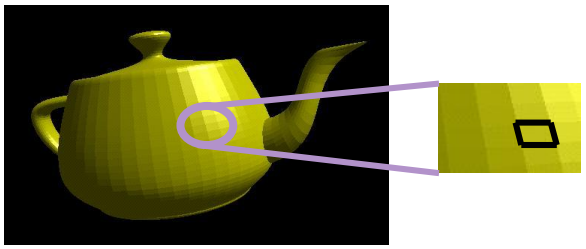
Flat Shading

- Apply same color across entire polygon
- Calculate color once per polygon
  - Typically use center of polygon

- Fast, but not very desirable for smooth shapes

Flat shading

- Only use one vertex (usually the first one) normal and material property to compute the color for the polygon
- Benefit: fast to compute
- It is used when:
  - The polygon is small enough
  - The light source is far away (why?)
  - The eye is very far away (why?)
- OpenGL command: glShadeModel(GL_FLAT)

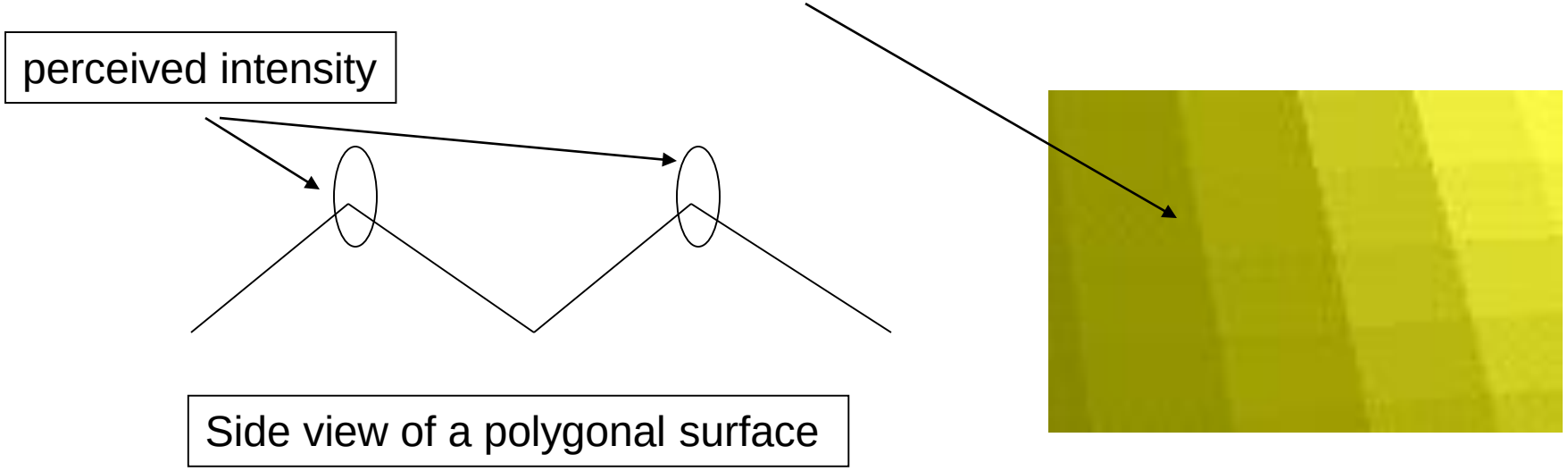


Flat Shading

Image taken from http://www.cs.cmu.edu/~ph/nyit/

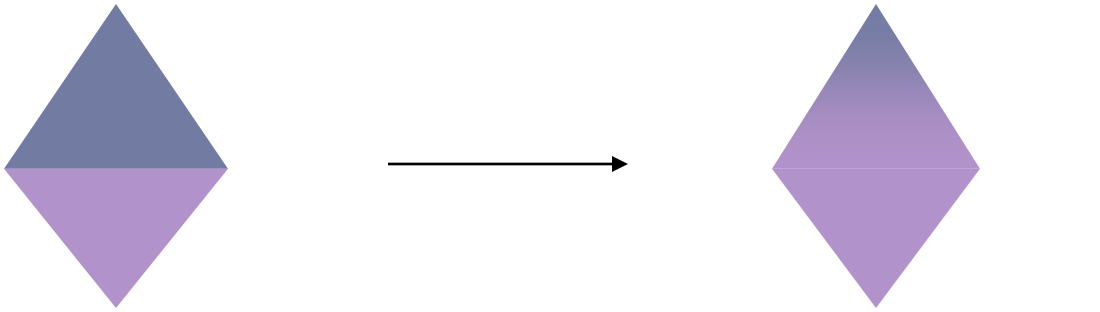
Mach Band Effect

- Flat shading suffers from "mach band effect"
- Mach band effect – human eyes accentuate the discontinuity at the boundary



Smooth shading

- Fix the mach band effect – remove edge discontinuity
- Compute lighting for more points on each face

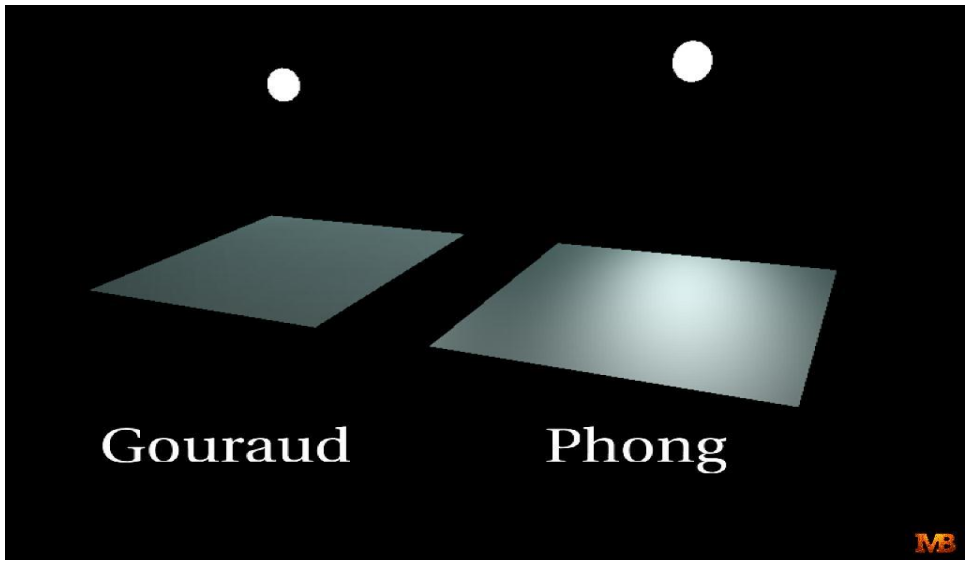


Flat shading

smooth shading

Smooth shading

- Two popular methods:
  - Gouraud shading (used by OpenGL)
  - Phong shading (better specular highlight, not supported by OpenGL)

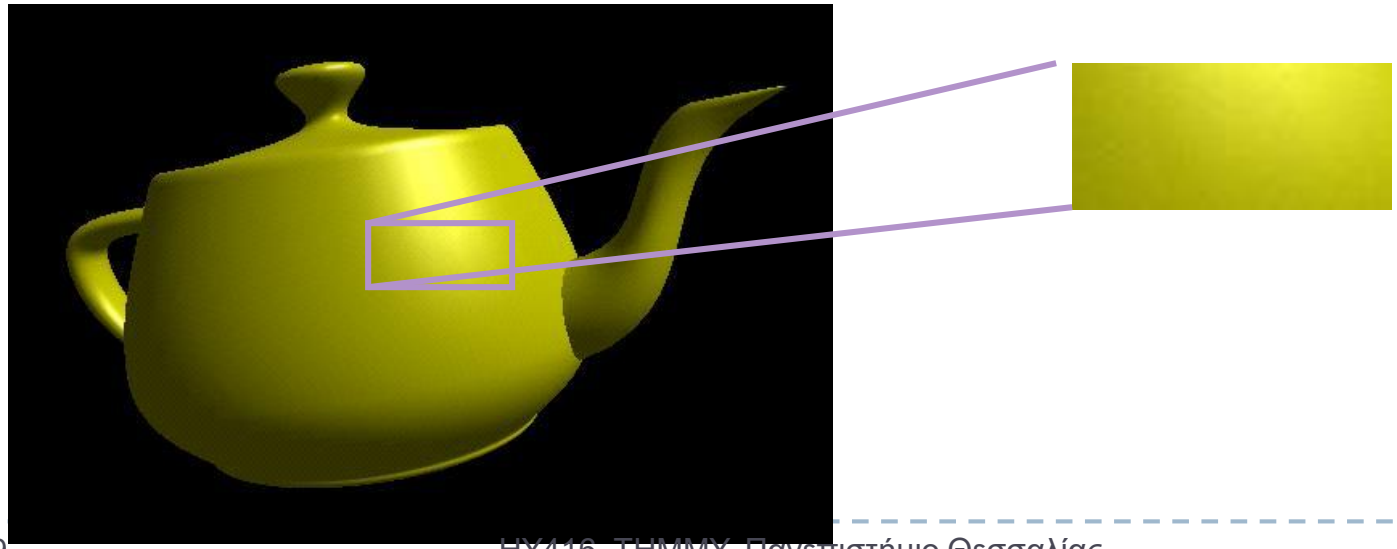


Gouraud Shading

Image taken from http://www.cs.cmu.edu/~ph/nyit/

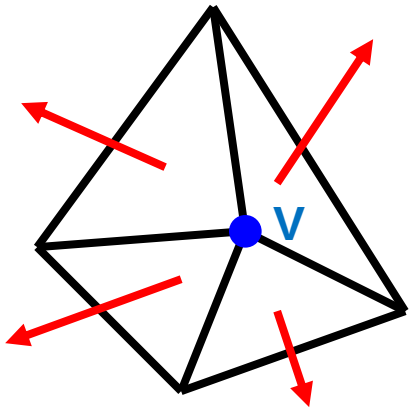
Gouraud Shading

- The smooth shading algorithm used in OpenGL
  glShadeModel(GL_SMOOTH)
- Lighting is calculated for each of the polygon vertices
- Colors are interpolated for interior pixels



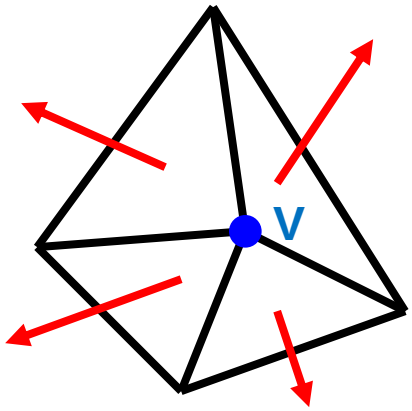
Vertex Normals

- How to compute vertex normal given the normal of each polygon?



Vertex Normals

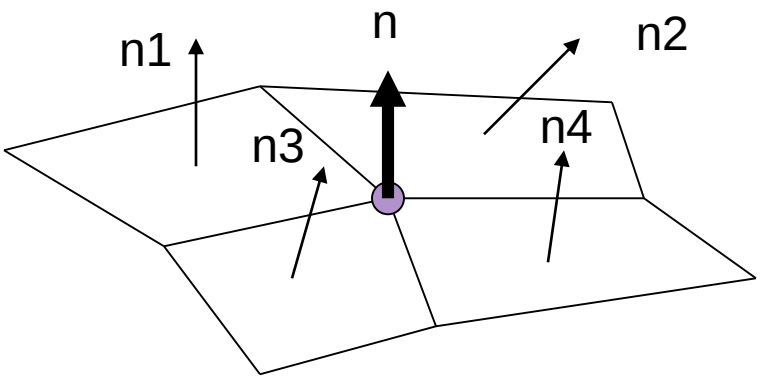
- How to compute vertex normal given the normal of each polygon?



$$N_V = \frac{\sum_{k=1}^{b} N_k}{\left|\sum_{k=1}^{b} N_k\right|}$$

Gouraud Shading

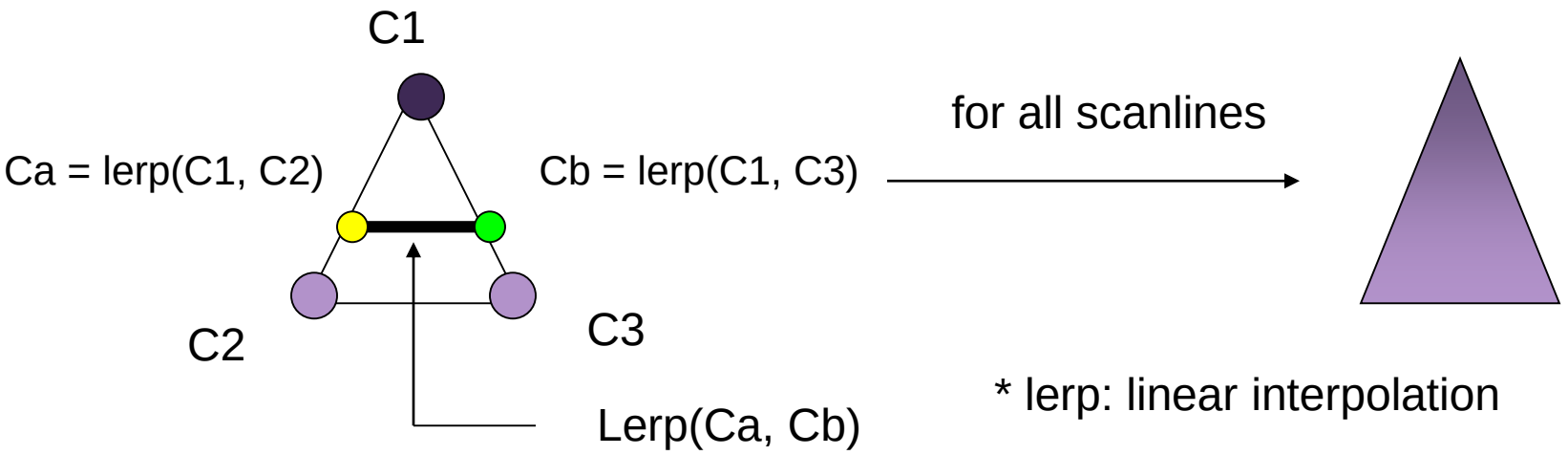
- Per-vertex lighting calculation
- Normal is needed for each vertex
- Per-vertex normal can be computed by averaging the adjust face normals



$$n = (n1 + n2 + n3 + n4) / 4.0$$

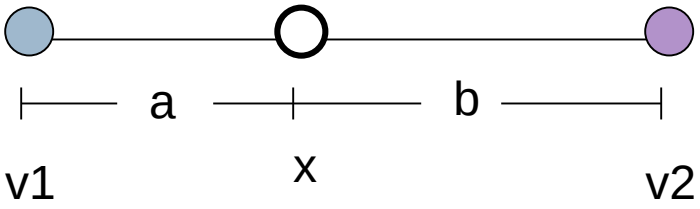
Gouraud Shading

- Compute vertex illumination (color) before the projection transformation
- Shade interior pixels: color interpolation (normals are not needed)



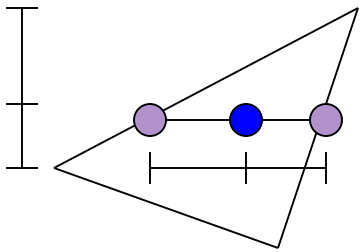
Gouraud Shading

- Linear interpolation



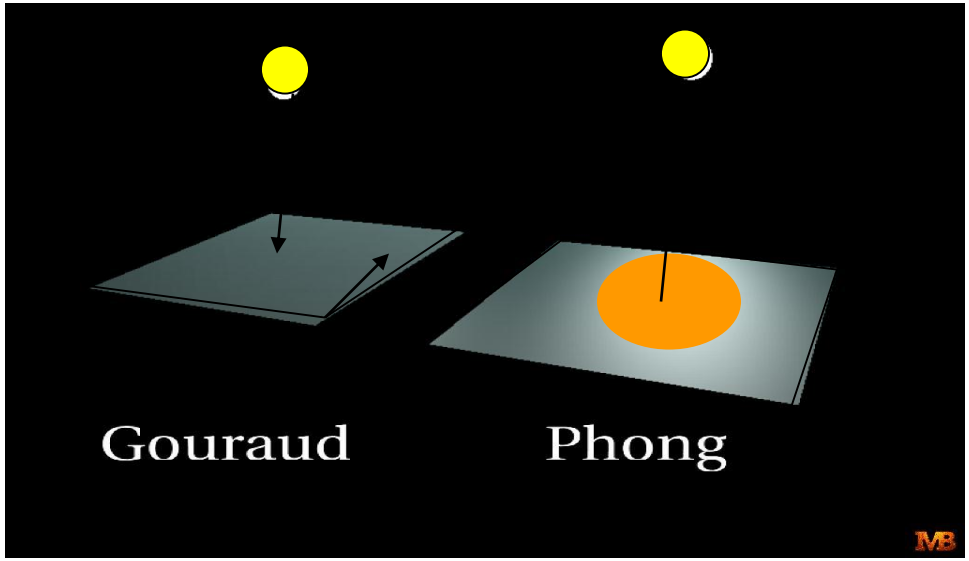
$$x = a / (a+b) * v2 + b/(a+b) * v1$$

- Interpolate triangle color: use y distance to interpolate the two end points in the scanline, and use x distance to interpolate interior pixel colors



Gouraud Shading Problem

- Lighting in the polygon interior can be inaccurate



Phong Shading

Image taken from http://www.cs.cmu.edu/~ph/nyit/

Phong (Per-Pixel) Shading

- Assume normals at vertices of polygon
- Interpolate *normals* from vertices across polygon
- Determine color at each pixel in polygon

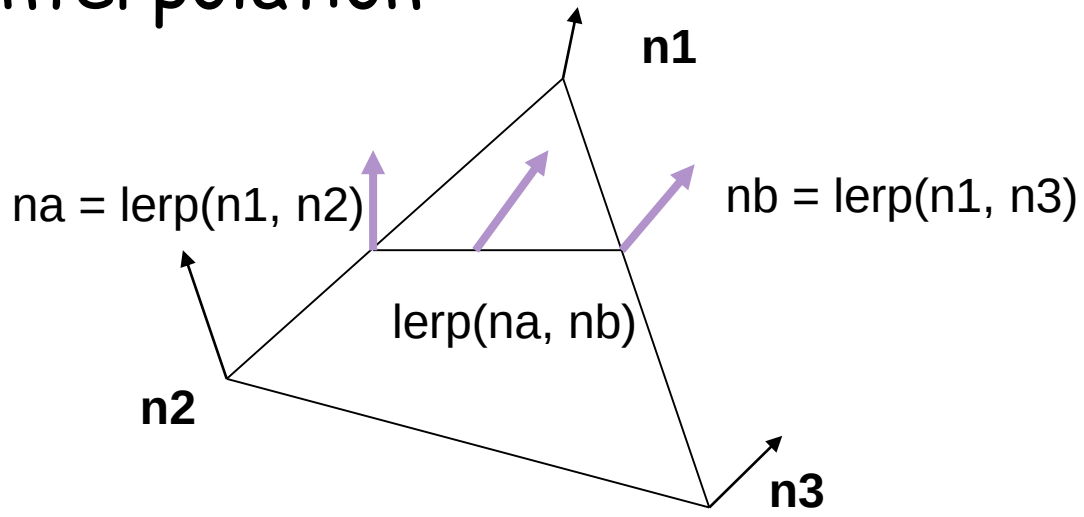
- Captures highlights better

Phong Shading

- Instead of interpolation, we calculate lighting for each pixel inside the polygon (per pixel lighting)
- We need to have normals for all the pixels – not provided by the user
- Phong shading algorithm interpolates the normals and compute lighting during rasterization (need to map the normal back to world or eye space though)

Phong Shading

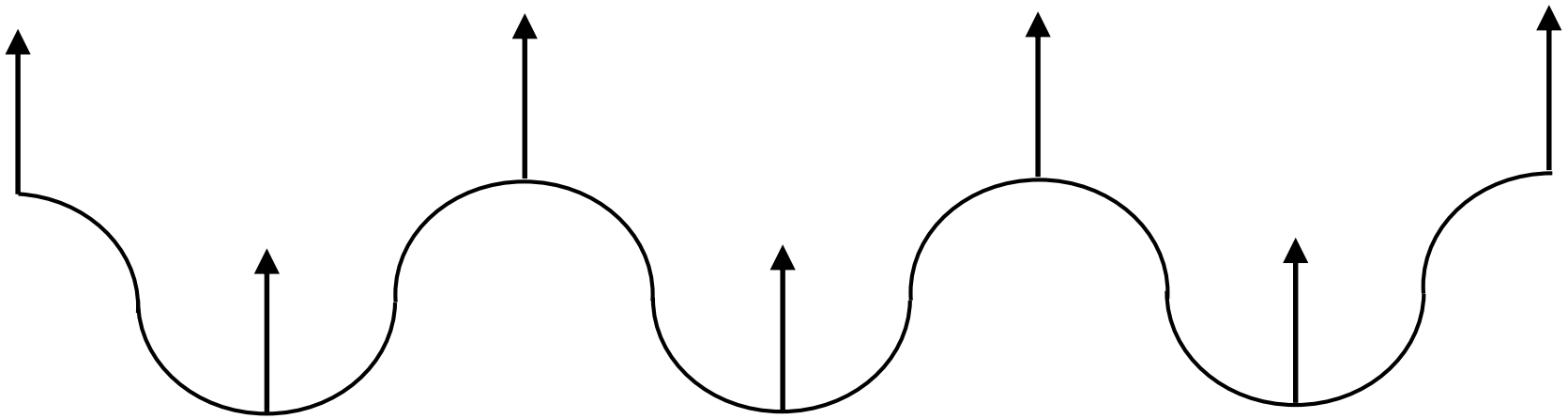
- Normal interpolation



- Slow – not supported by OpenGL and most of the graphics hardware

Phong Shading Problems

- Not perfect and highly dependent on normals

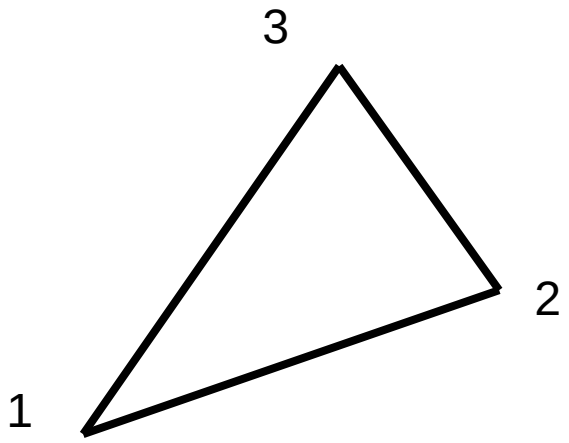


Interpolating Over Polygons

- Given values at vertices of polygon, how do we interpolate data over interior?

Interpolating Over Polygons

- Given values at vertices of polygon, how do we interpolate data over interior?
  - values could be either vertex normal or color



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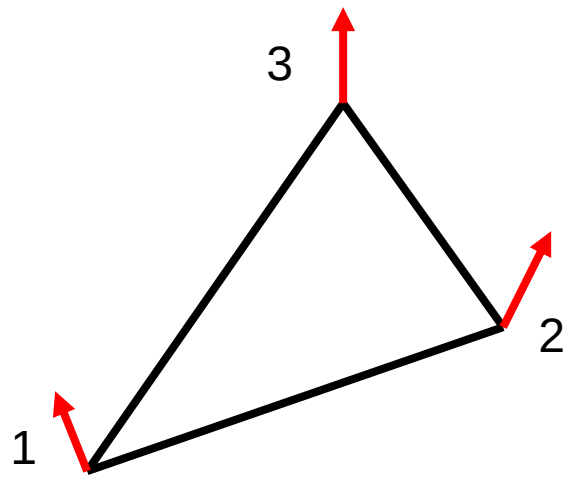

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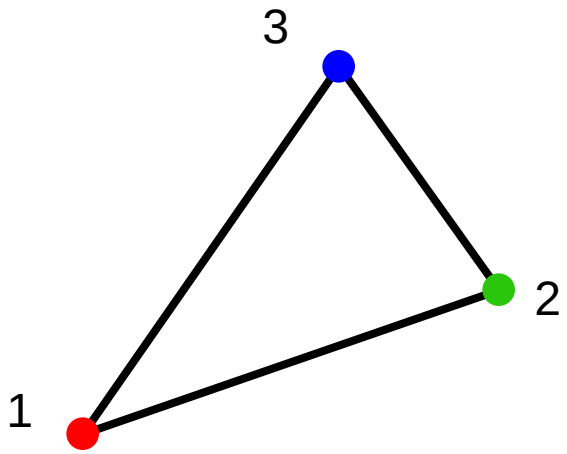

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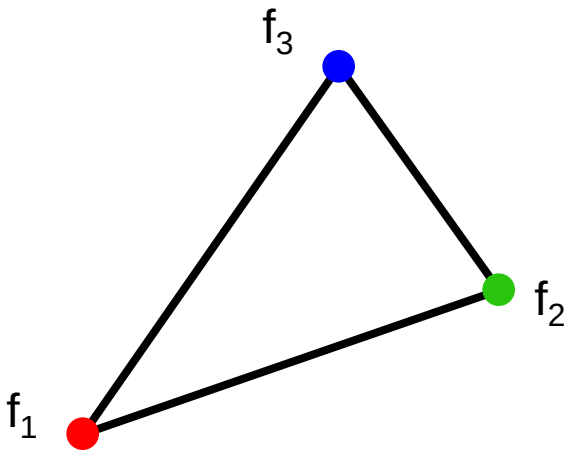

How to interpolate values for every pixel inside a polygon?

Interpolating Over Polygons

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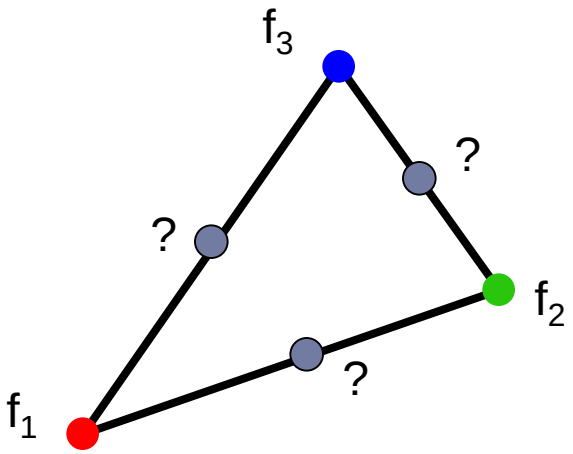

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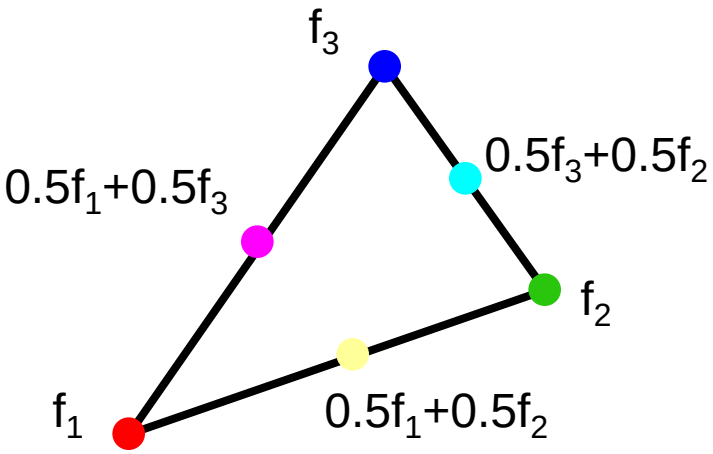

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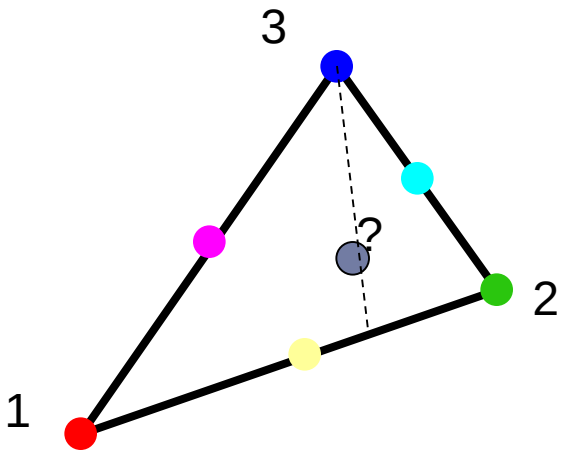

Any vertex can be represented as linear combination of polygon vertices

$V=aV_1+bV_1+cV_3$

Interpolating Over Polygons

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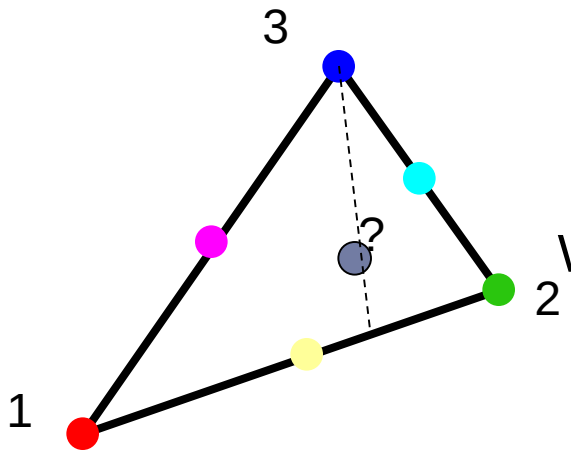

Any vertex can be represented as linear combination of polygon vertices

$V=aV_1+bV_2+cV_3$

We can interpolate values with the same weights

$f=af_1+bf_2+cf_3$

Interpolating Over Polygons

- Given values at vertices of polygon, how do we interpolate data over interior?
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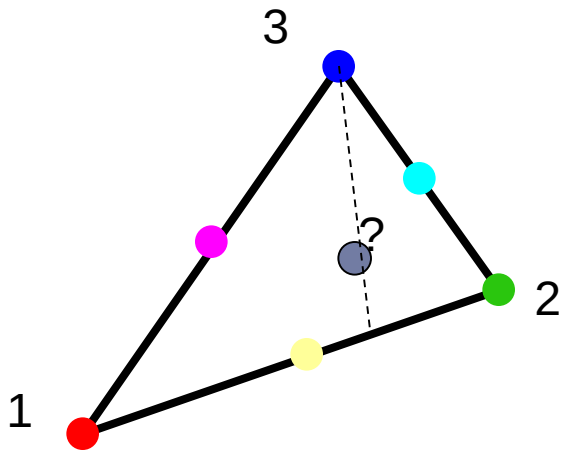

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Can we speed up this interpolation process?

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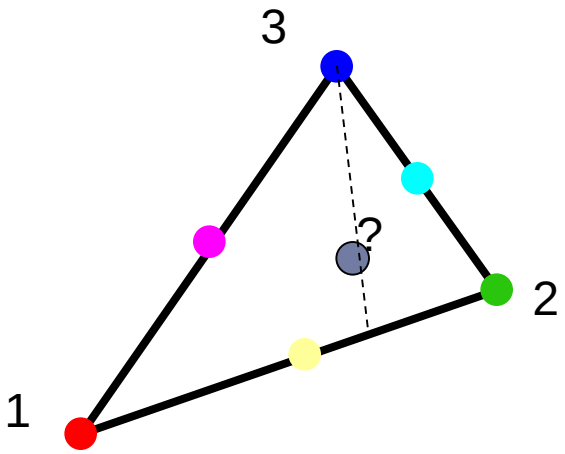

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$V=aV_1+bV_2+cV_3$

We can interpolate values with the same weights

$f=af_1+bf_2+cf_3$

Can we speed up this interpolation process?

Yes, scan line algorithm!

Interpolating Over Polygons

Edge
mazY
currentX
xIncr
currentF
fIncr

maxY: highest *y*-value

currentX: *x*-value of end-point with lowest *y*-value

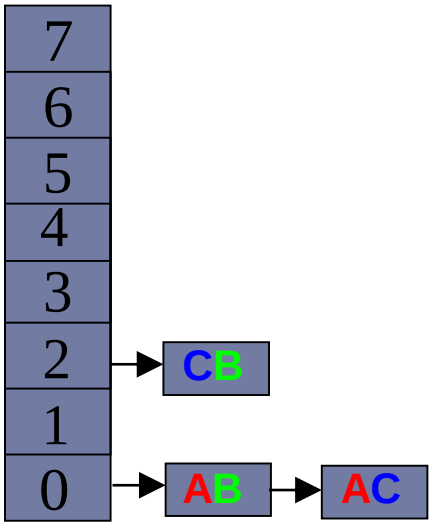
xIncr: 1 / slope

currentF: data value at end-point with lowest y-value

fIncr: $(f_0-f_1)/(y_0-y_1)$

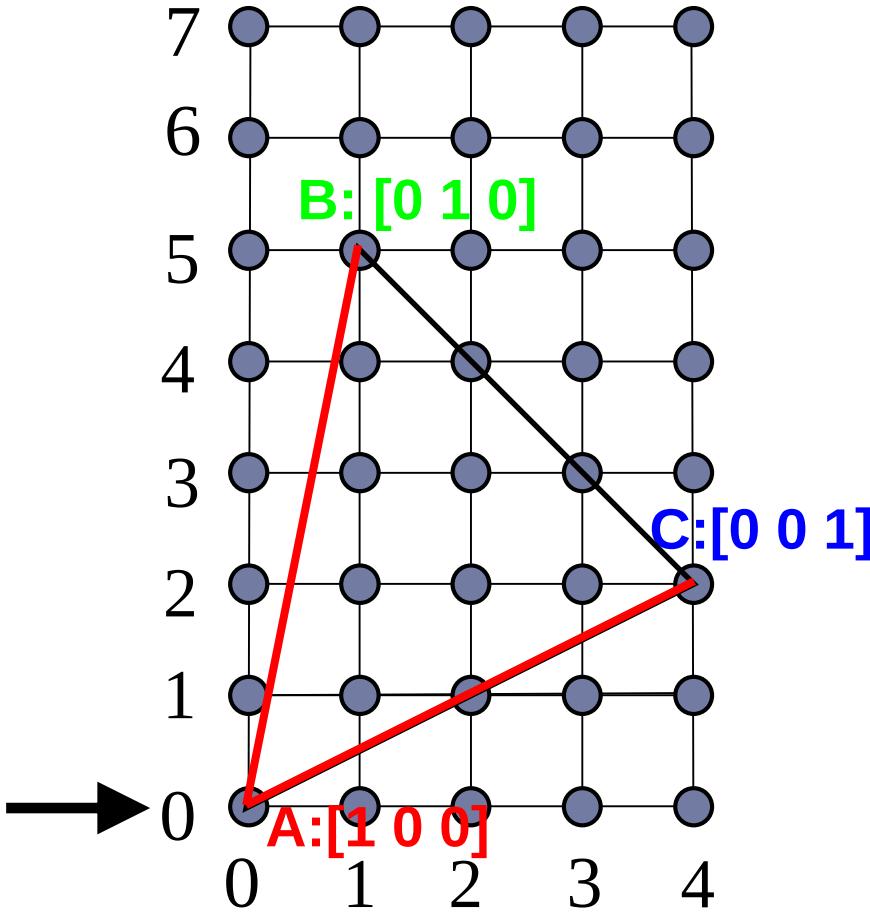
Interpolating Over Polygons

Active Edge Table



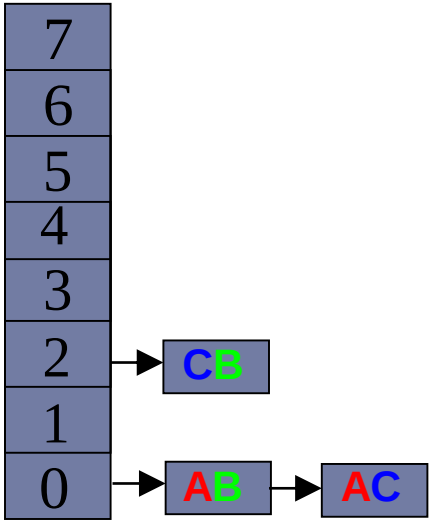
Active Edge List

	AB	AC
maxY	5	2
currentX	0	0
xIncr	$\frac{1}{5}$	2
currentF	$(1 \quad 0 \quad 0)$	$(1 \quad 0 \quad 0)$
fIncr	$(-\frac{1}{5} \quad \frac{1}{5} \quad 0)$	$(-\frac{1}{2} \quad 0 \quad \frac{1}{2})$



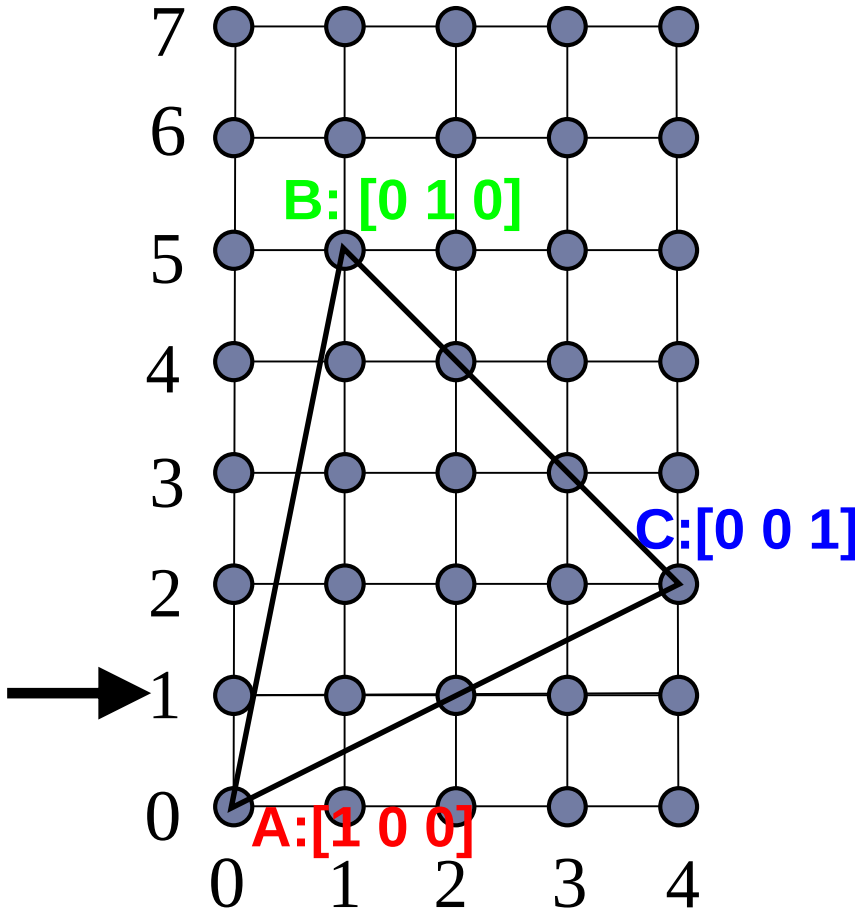
Interpolating Over Polygons

Active Edge Table



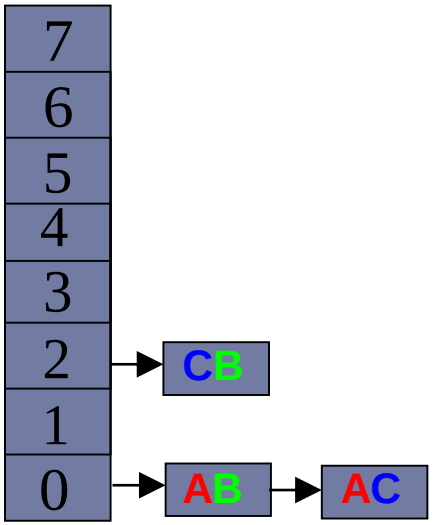
Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$



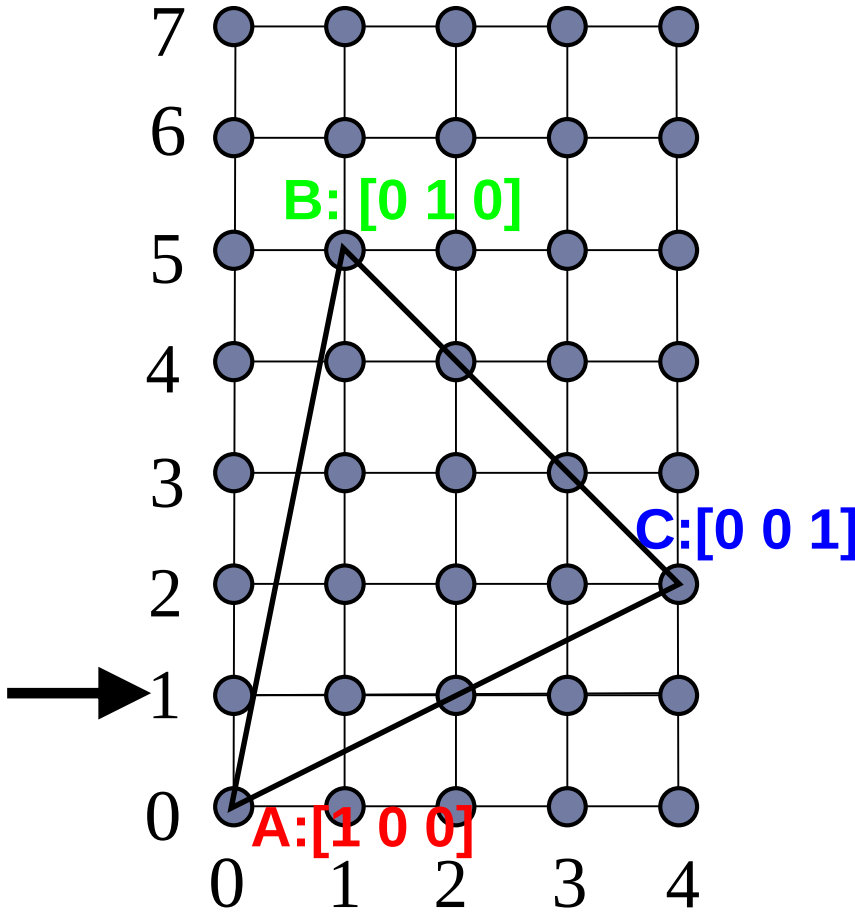
Interpolating Over Polygons

Active Edge Table



Active Edge List

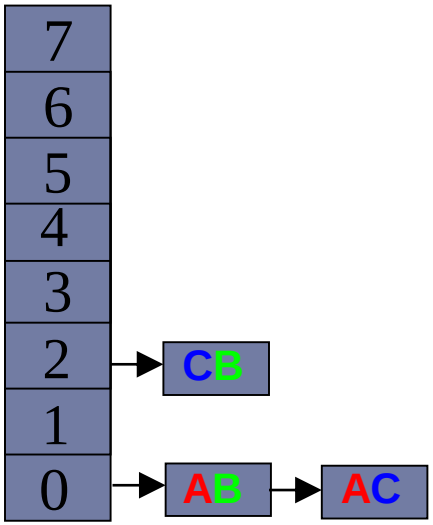
	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{-1}{2} \quad 0 \quad \frac{1}{2}\right)$



What does currentF mean?

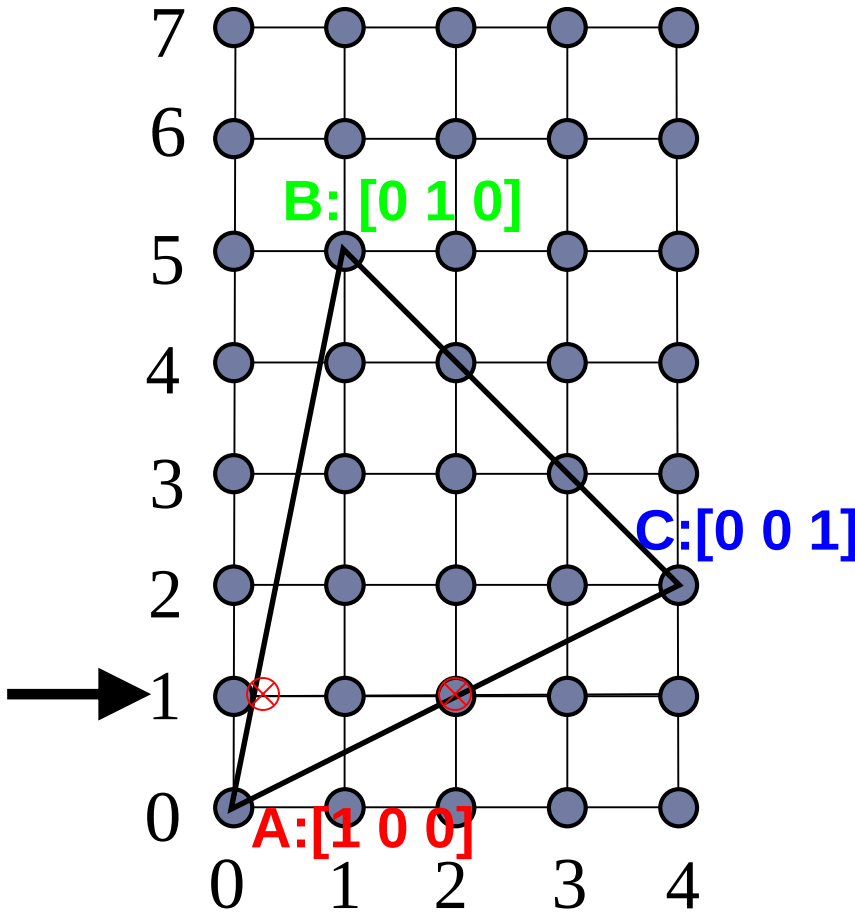
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$



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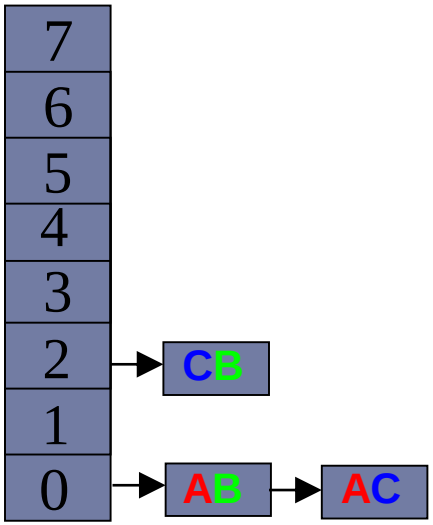
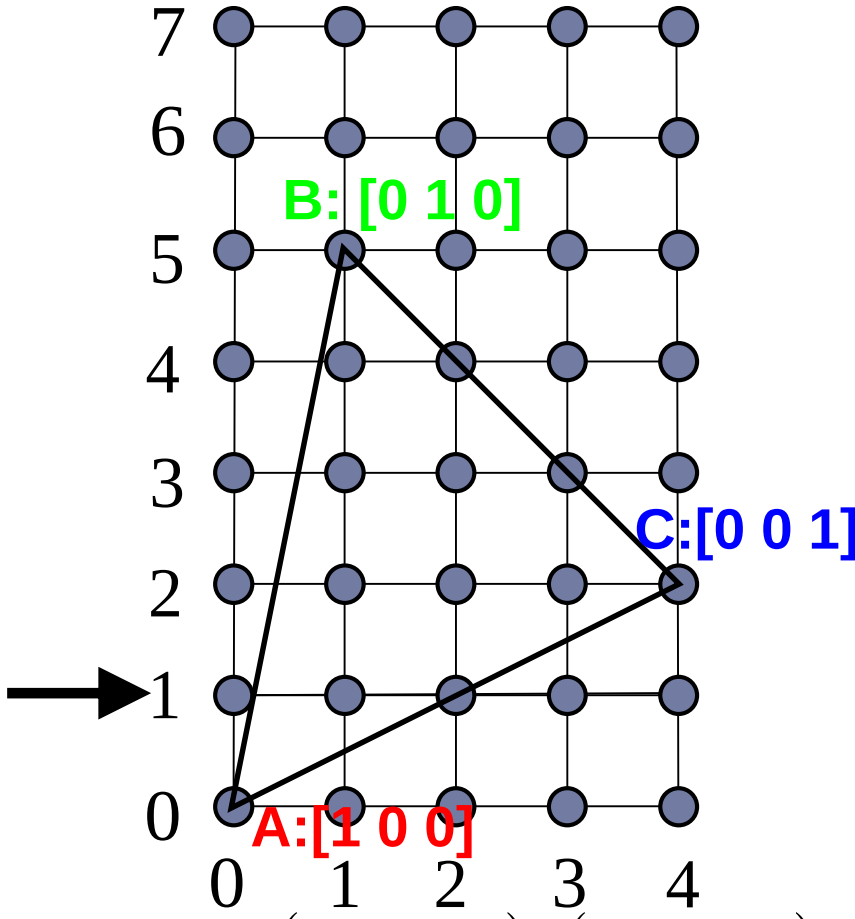


Active Edge List

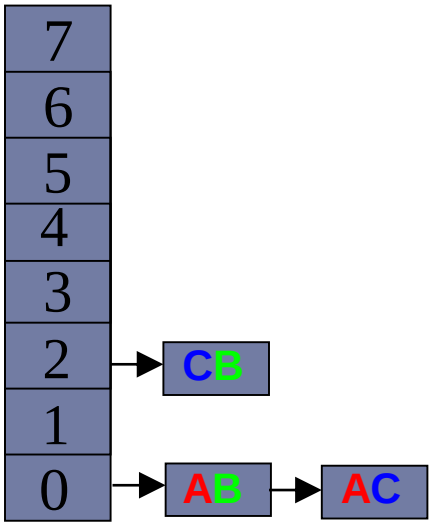
	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$



$$dF = \left(-\frac{1}{6} \quad -\frac{1}{9} \quad \frac{5}{18}\right) = \frac{\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right) - \left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)}{2 - \frac{1}{5}}$$

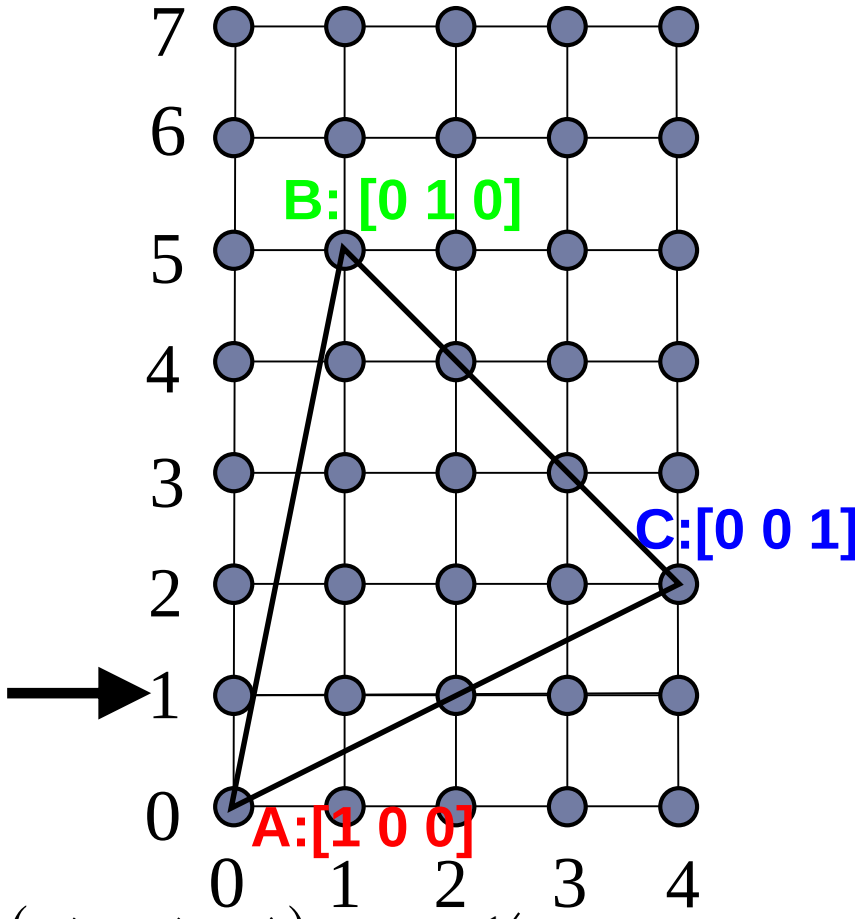
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{-1}{2} \quad 0 \quad \frac{1}{2}\right)$

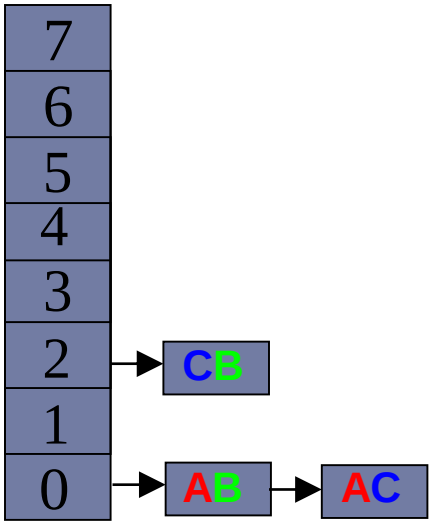


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{1}{5}$

$F = \left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$

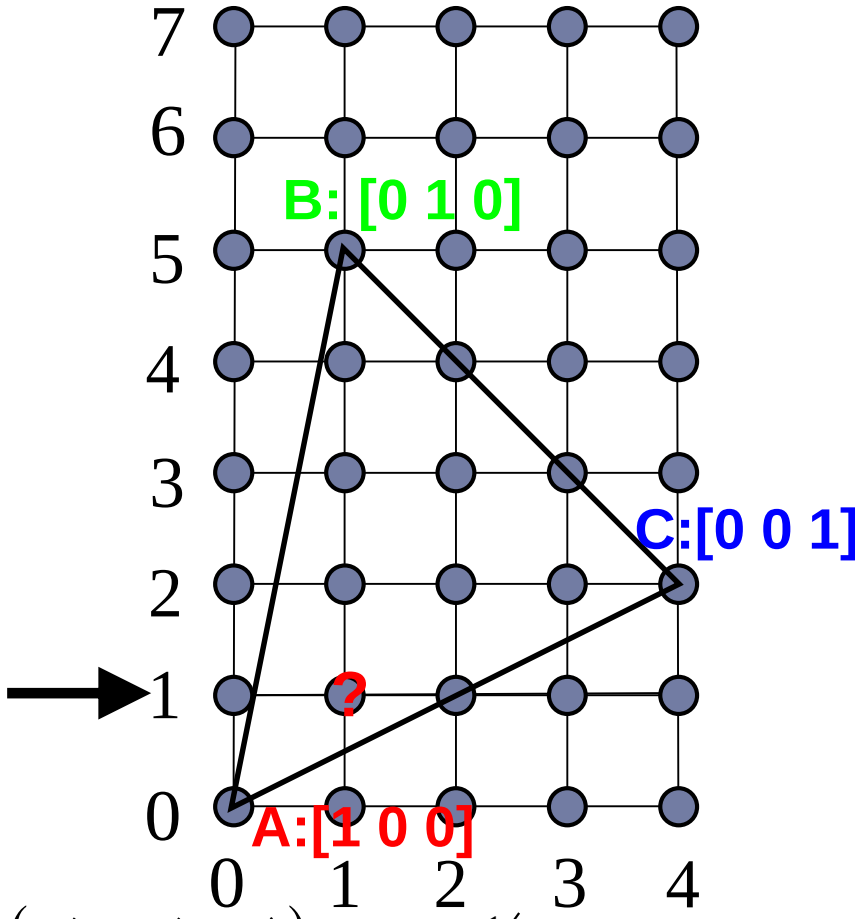
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$



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$F = \left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$

Interpolating Over Polygons

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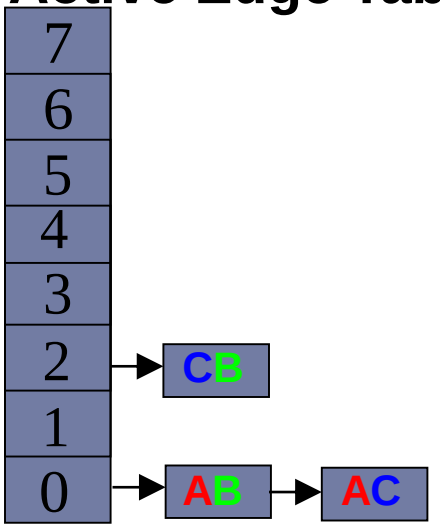
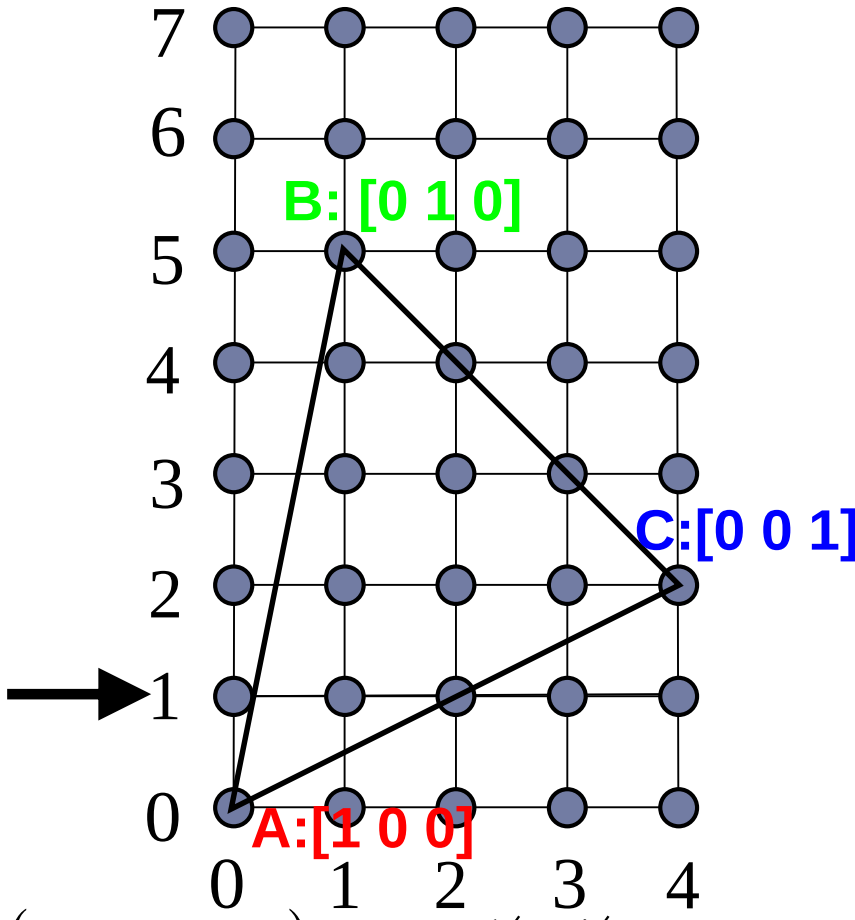


Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{-1}{2} \quad 0 \quad \frac{1}{2}\right)$

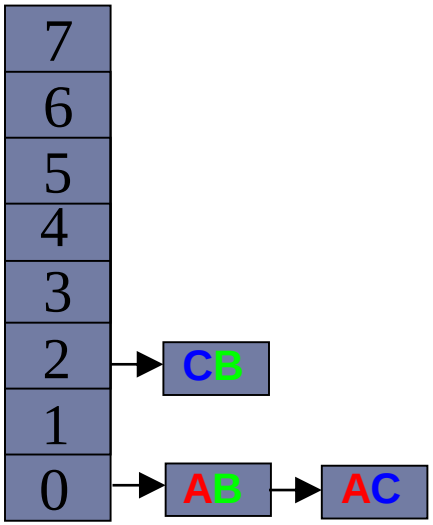


$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{1}{5} + \frac{4}{5}$$

$$F = \left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)\frac{4}{5}$$

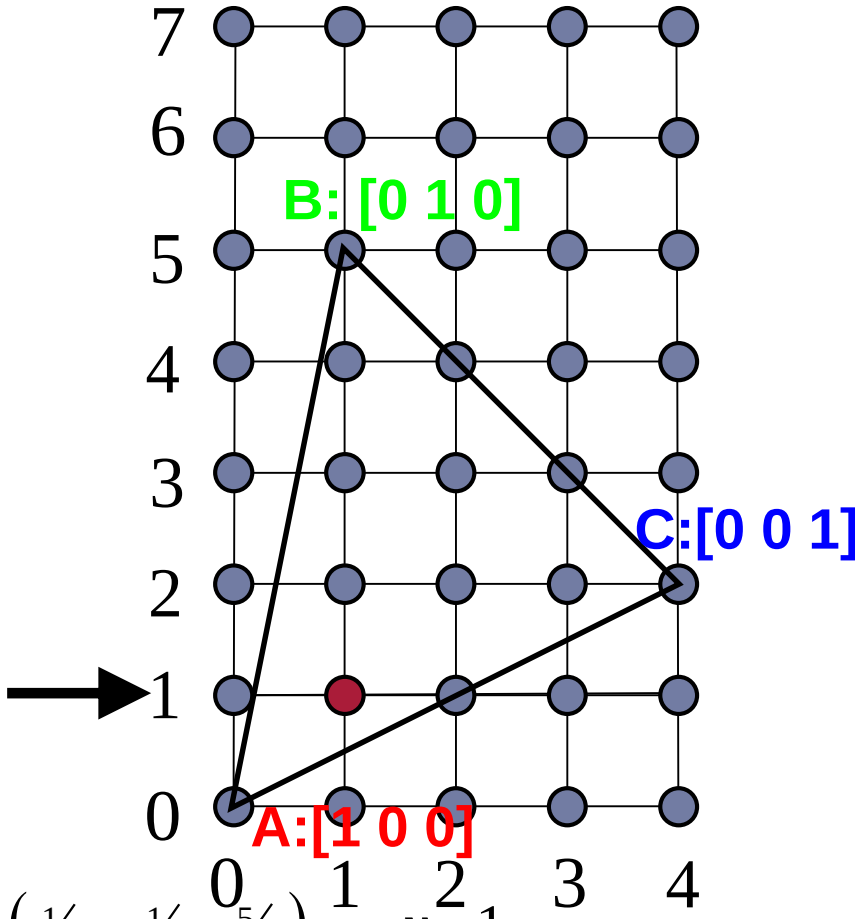
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	AC
maxY	5	2
currentX	$\frac{1}{5}$	2
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{4}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$

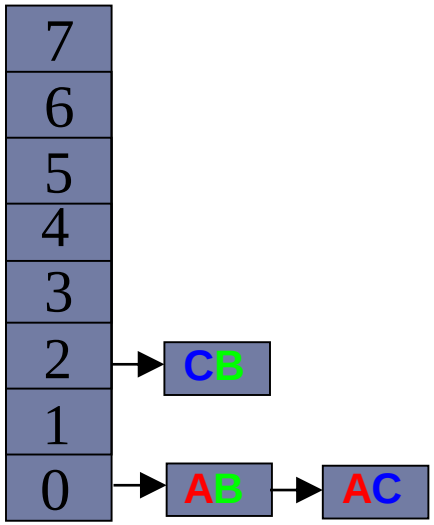


$dF = \left(-\frac{1}{6} \quad -\frac{1}{9} \quad \frac{5}{18}\right)$ $x = 1$

$F = \left(\frac{2}{3} \quad \frac{1}{9} \quad \frac{2}{9}\right)$

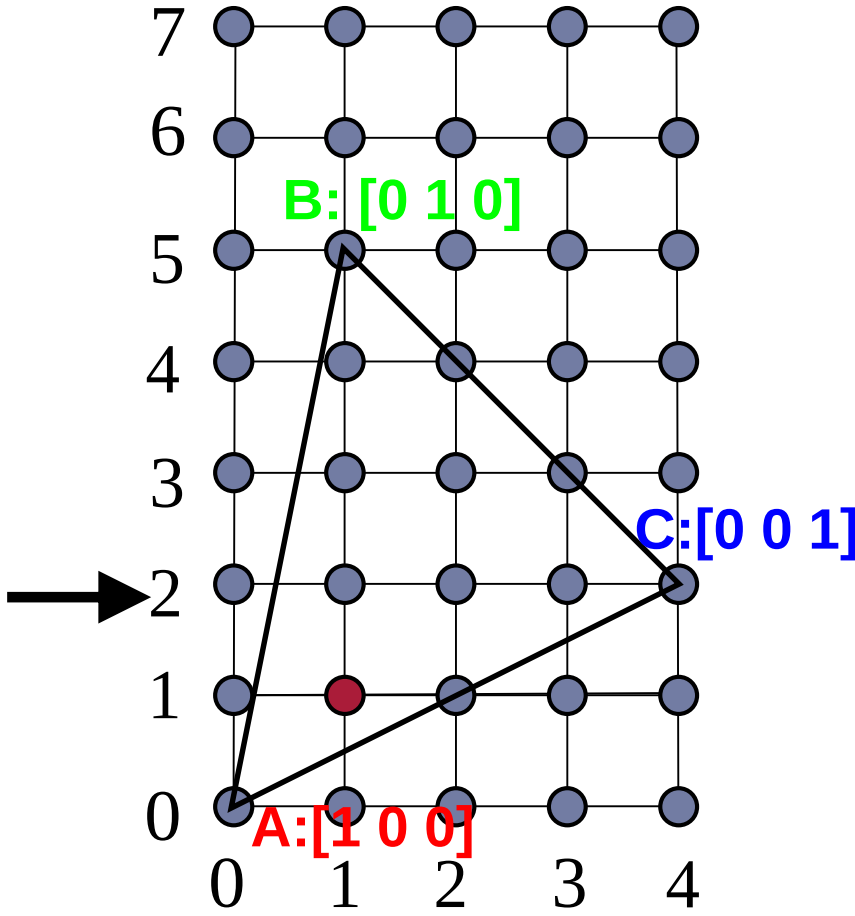
Interpolating Over Polygons

Active Edge Table



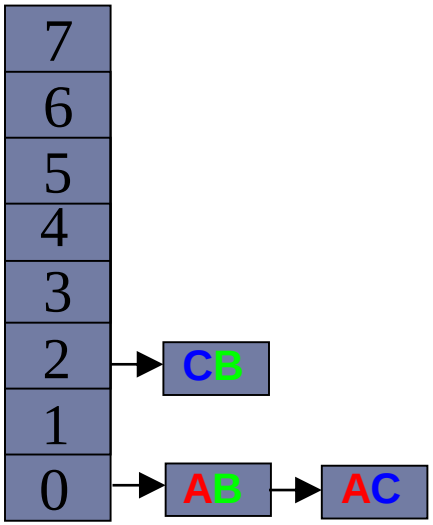
Active Edge List

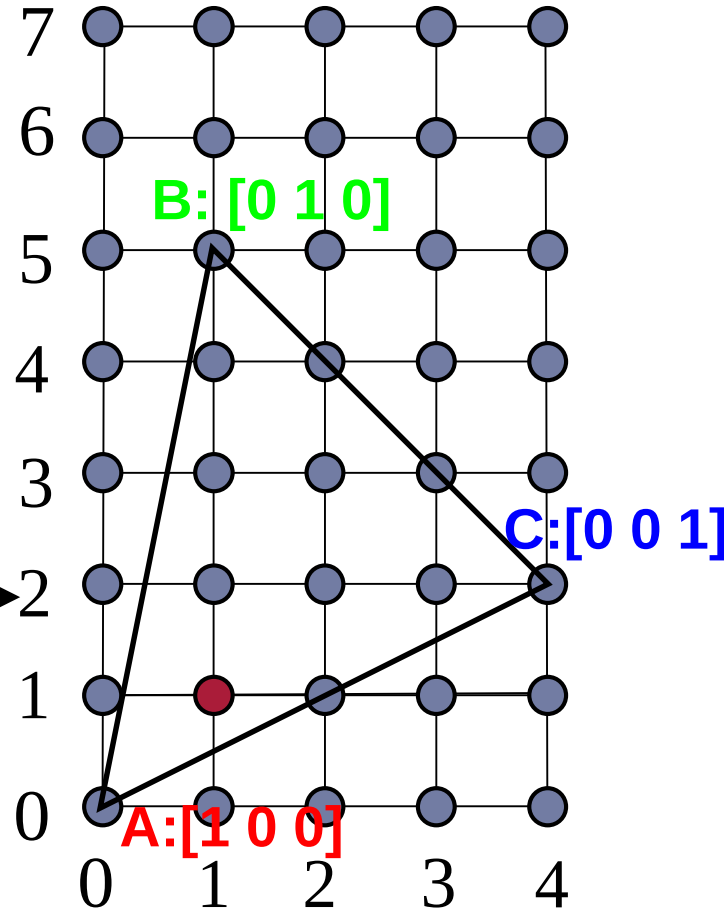
	AB	AC
maxY	5	2
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	2
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$



Interpolating Over Polygons

Active Edge Table



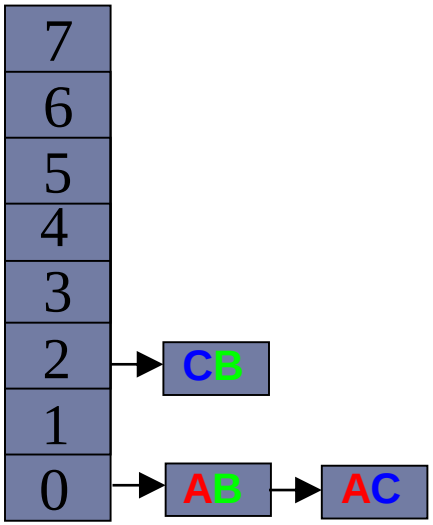


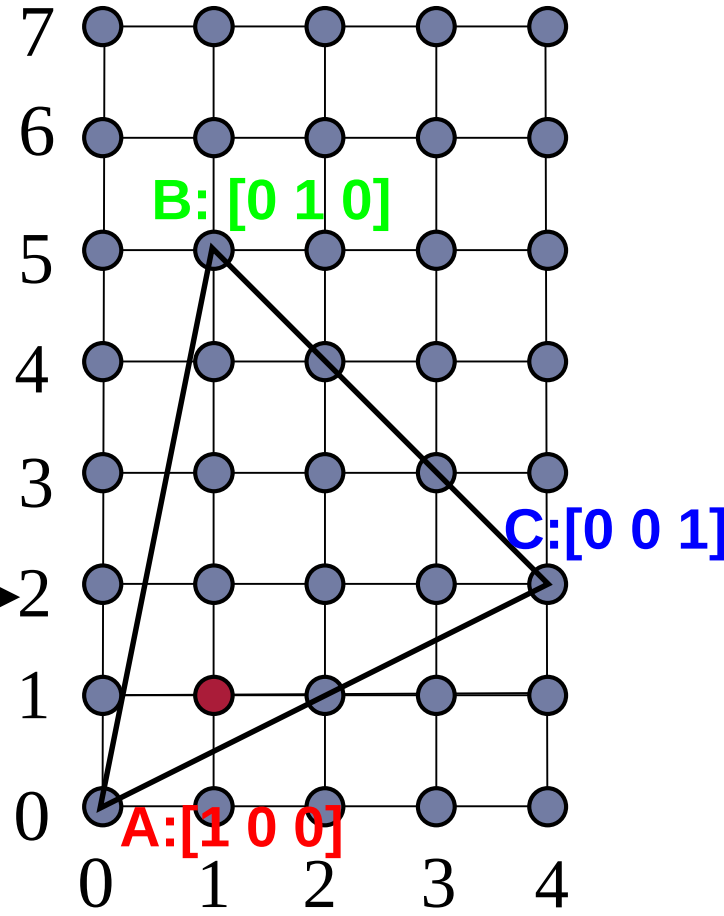
Active Edge List

	AB	AC	CB
maxY	5	2	5
currentX	$\frac{2}{5}$	4	4
xIncr	$\frac{1}{5}$	2	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

Interpolating Over Polygons

Active Edge Table



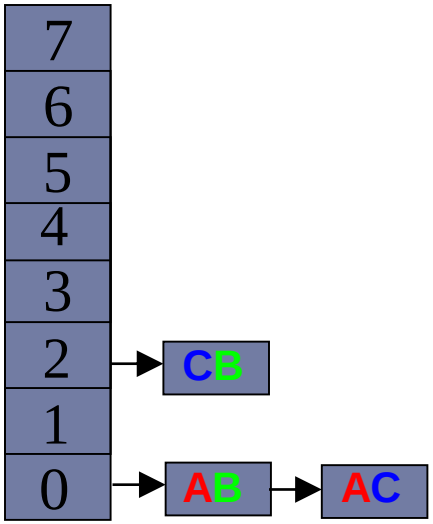


Active Edge List

	AB	AC	CB
maxY	5	2	5
currentX	$\frac{2}{5}$	4	4
xIncr	$\frac{1}{5}$	2	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$(0 \quad 0 \quad 1)$	$(0 \quad 0 \quad 1)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(-\frac{1}{2} \quad 0 \quad \frac{1}{2}\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

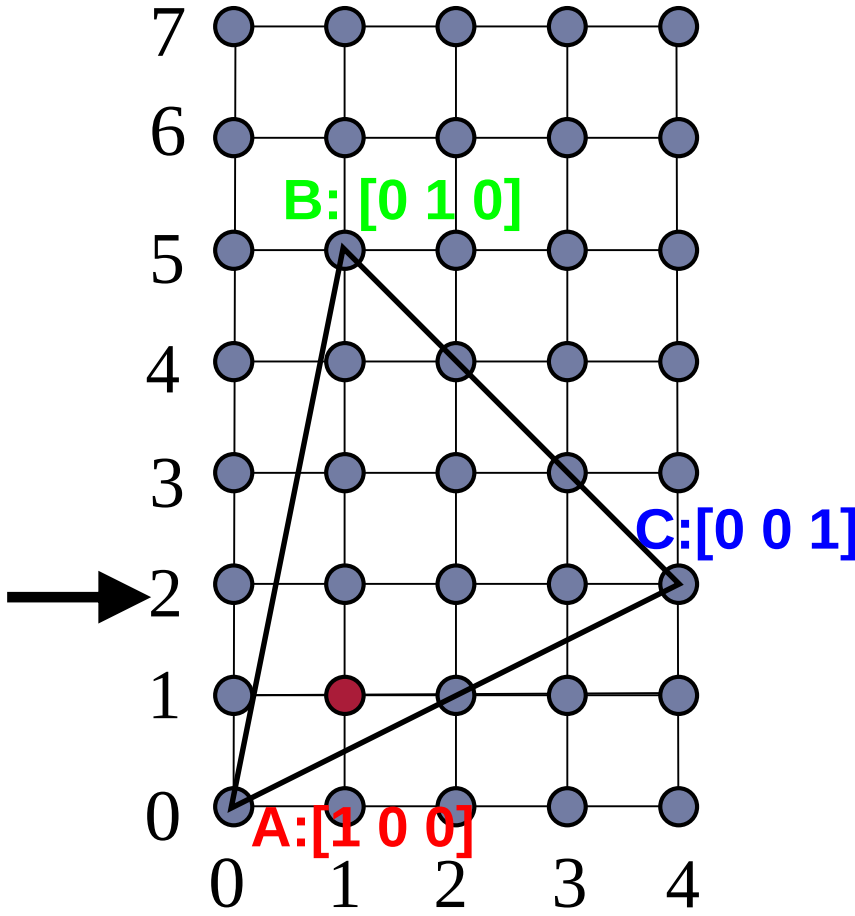
Interpolating Over Polygons

Active Edge Table



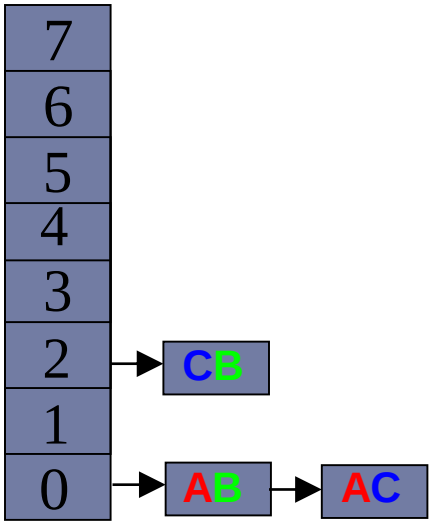
Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$



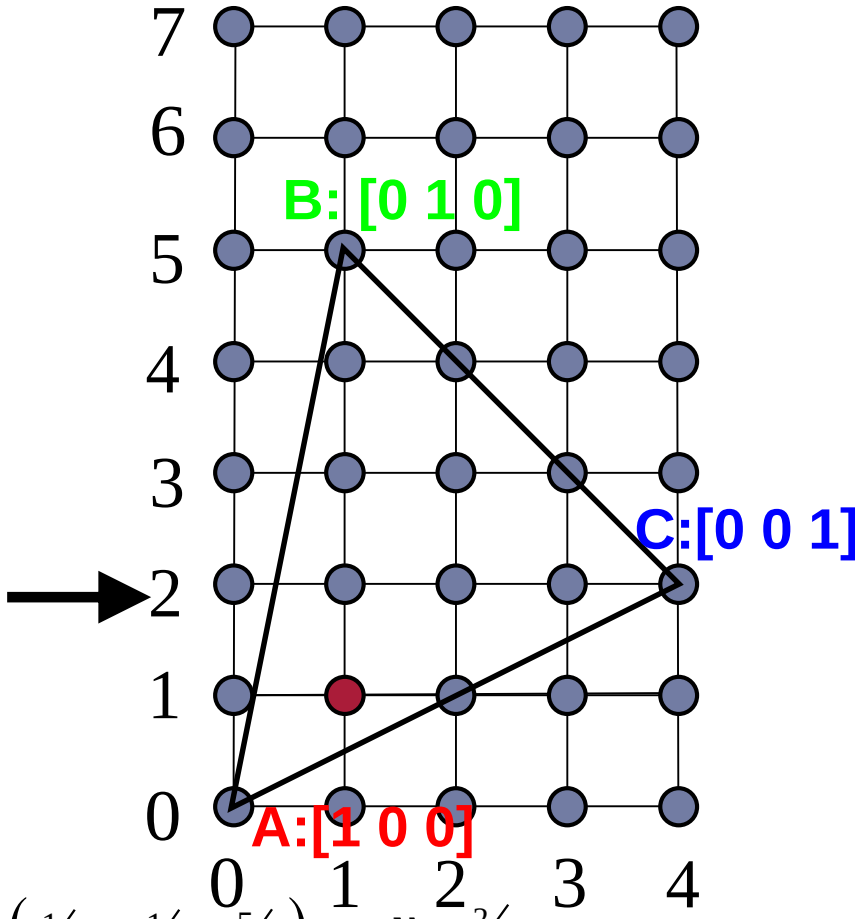
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

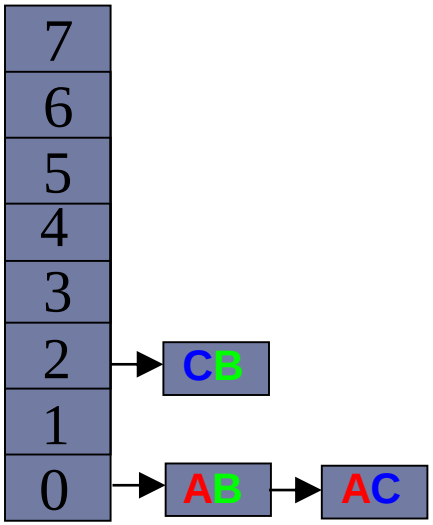


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{2}{5}$

$F = \left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$

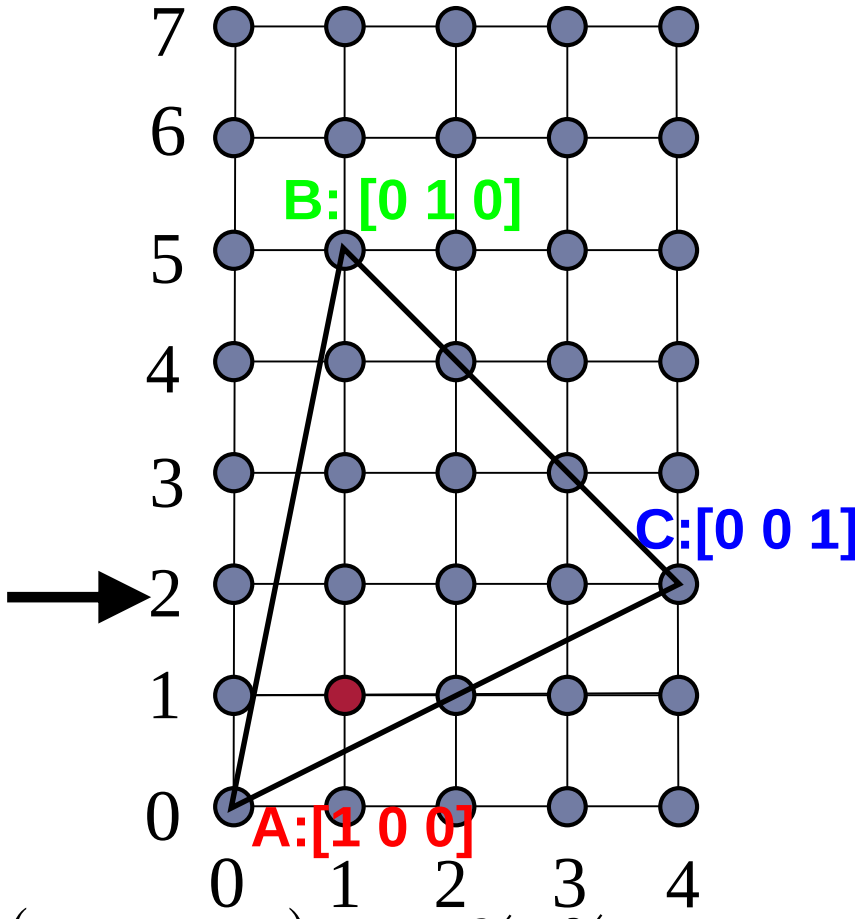
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

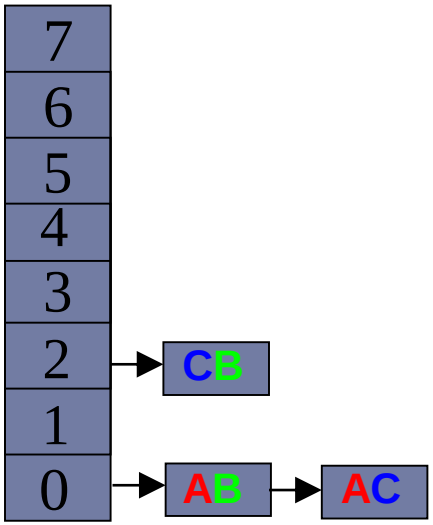


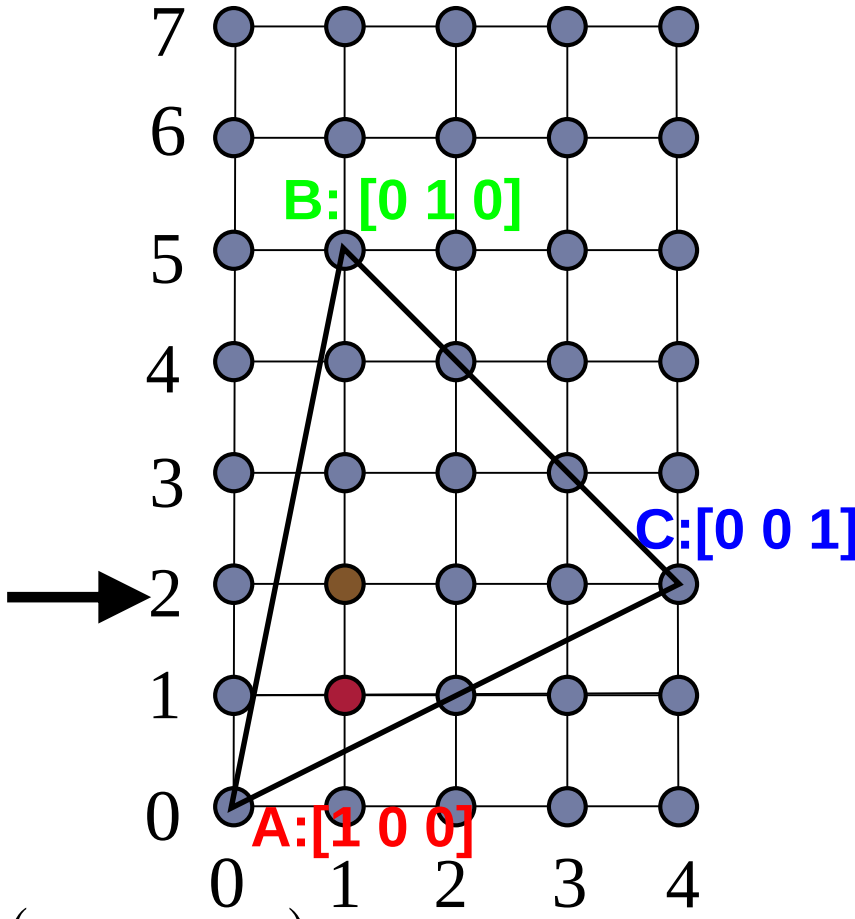
$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{2}{5} + \frac{3}{5}$$

$$F = \left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)\frac{3}{5}$$

Interpolating Over Polygons

Active Edge Table





Active Edge List

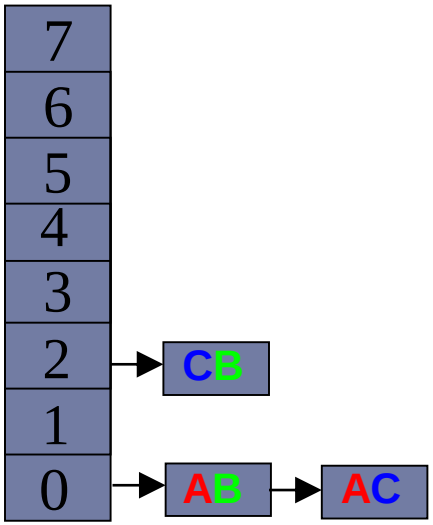
	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

$$dF = \left(-\tfrac{1}{6} \quad -\tfrac{1}{9} \quad \tfrac{5}{18}\right) \qquad x = 1$$

$$F = \left(\tfrac{1}{2} \quad \tfrac{1}{3} \quad \tfrac{1}{6}\right)$$

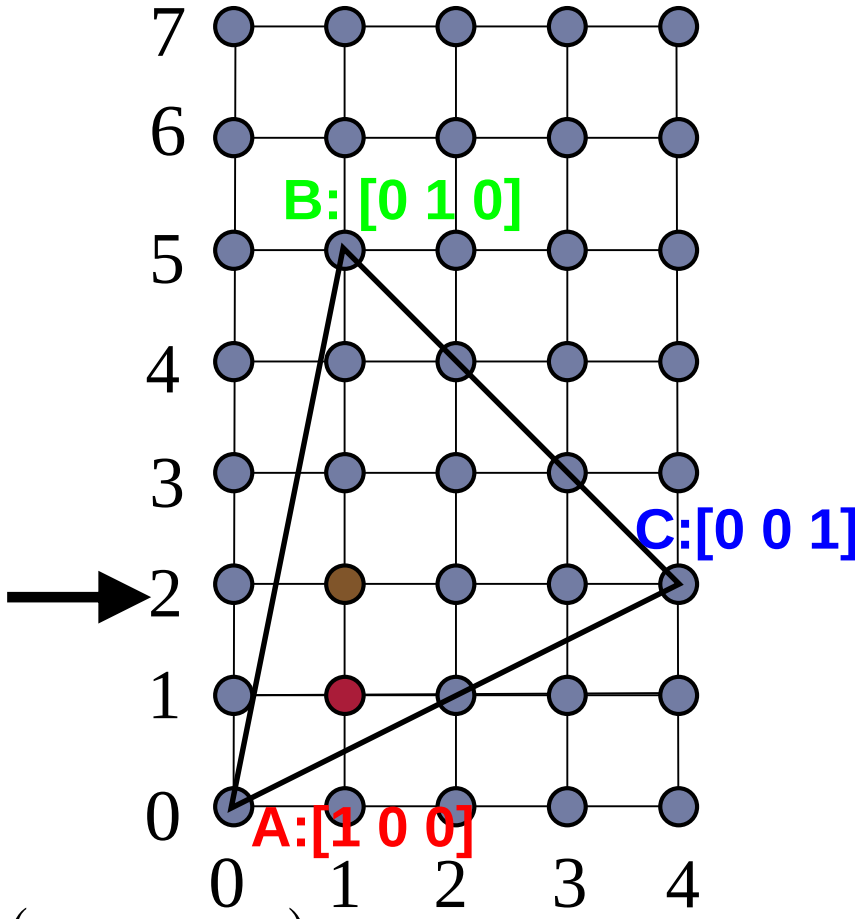
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

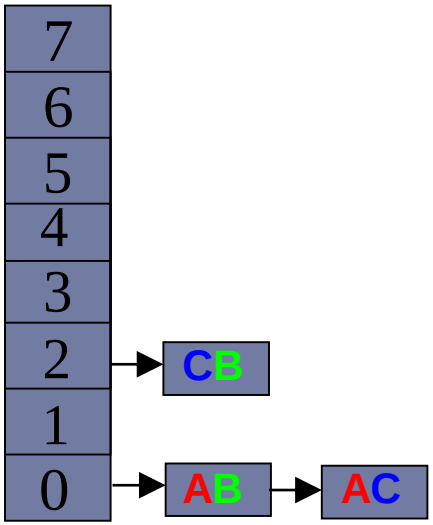


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 1+1$

$F = \left(\frac{1}{2} \quad \frac{1}{3} \quad \frac{1}{6}\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)$

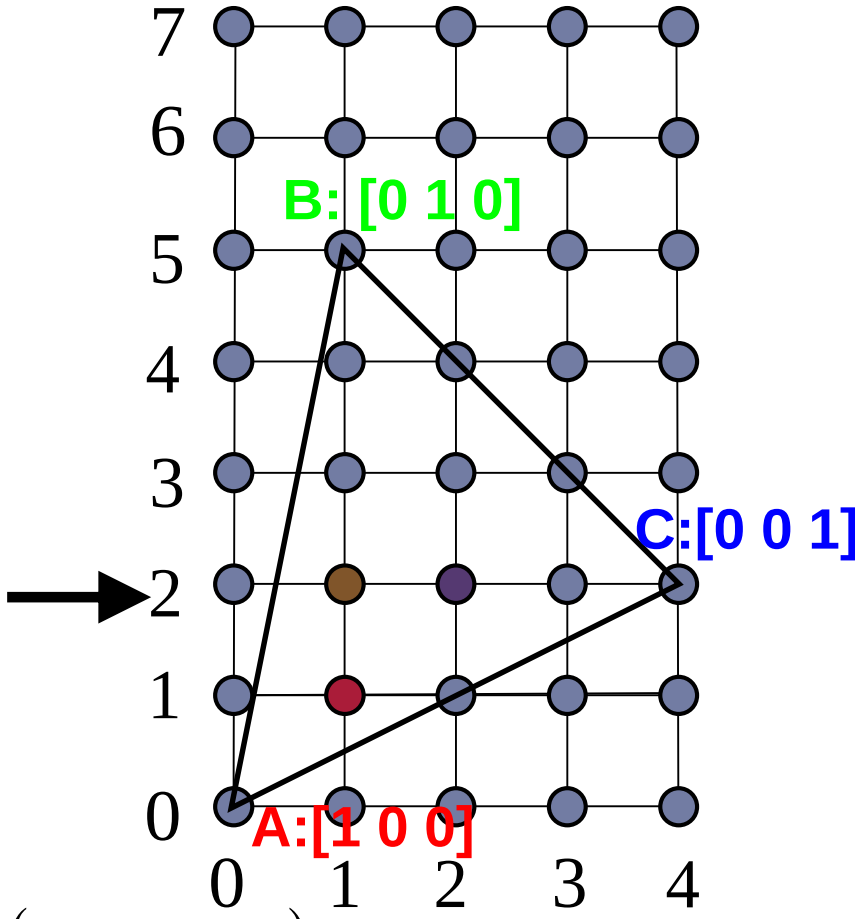
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

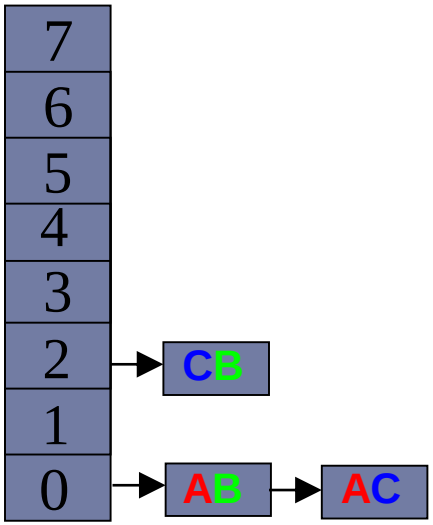


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 2$

$F = \left(\frac{1}{3} \quad \frac{2}{9} \quad \frac{4}{9}\right)$

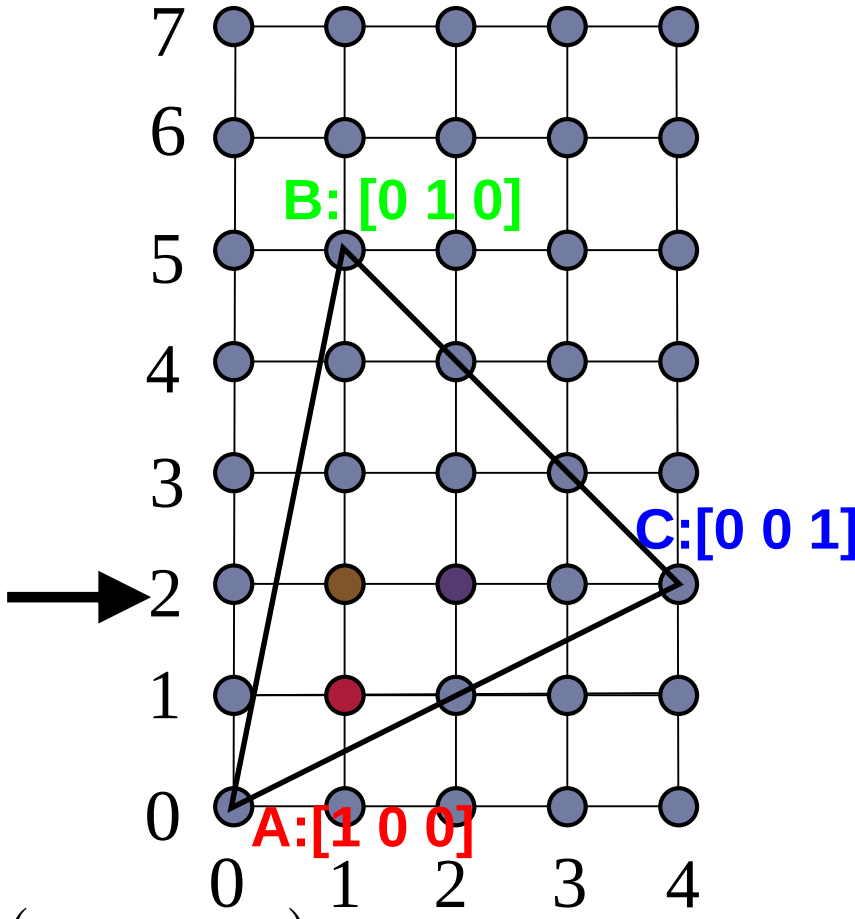
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

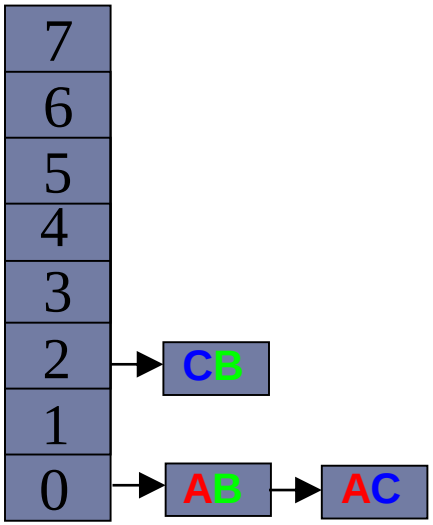


$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 2+1$$

$$F = \left(\frac{1}{3} \quad \frac{2}{9} \quad \frac{4}{9}\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)$$

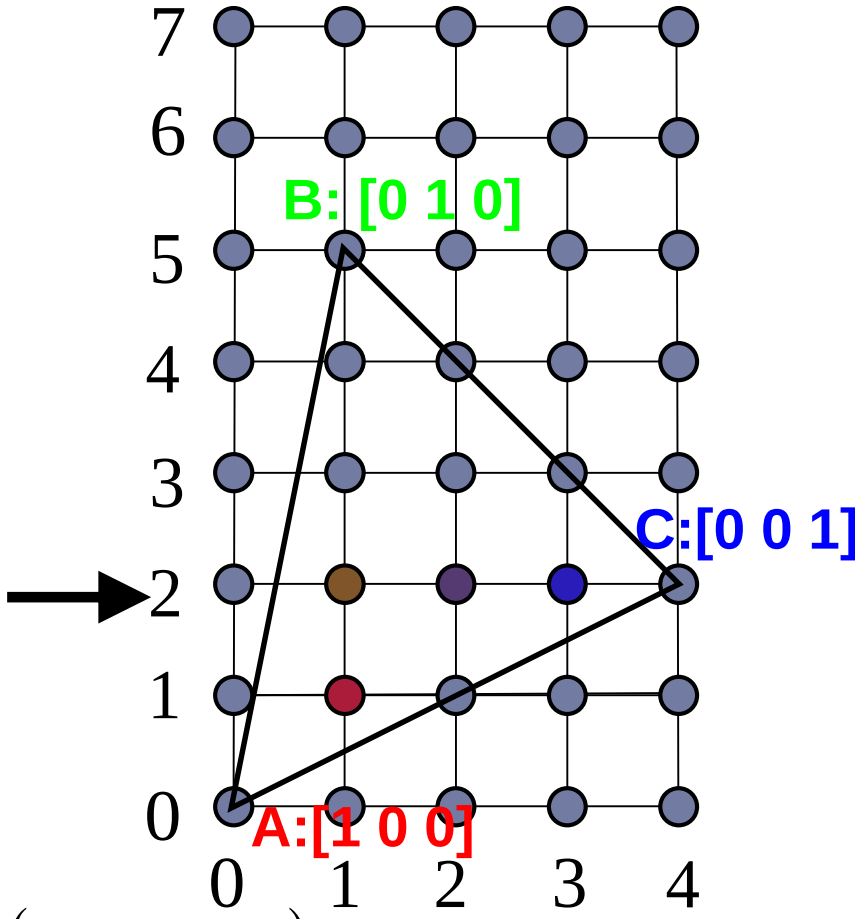
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{2}{5}$	4
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{3}{5} \quad \frac{2}{5} \quad 0\right)$	$\left(0 \quad 0 \quad 1\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

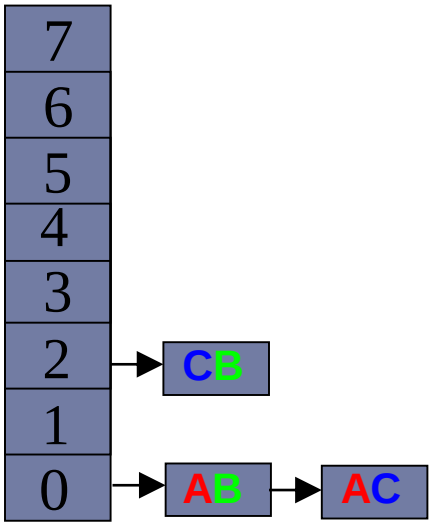


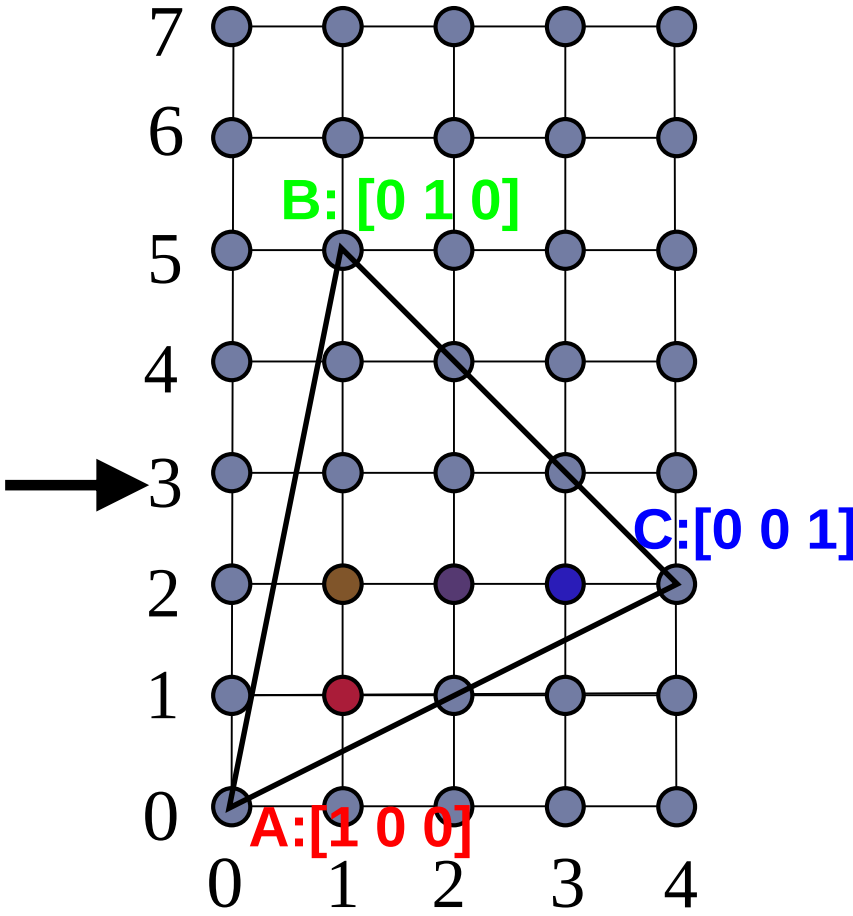
$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 3$

$F = \left(\frac{1}{6} \quad \frac{1}{9} \quad \frac{13}{18}\right)$

Interpolating Over Polygons

Active Edge Table



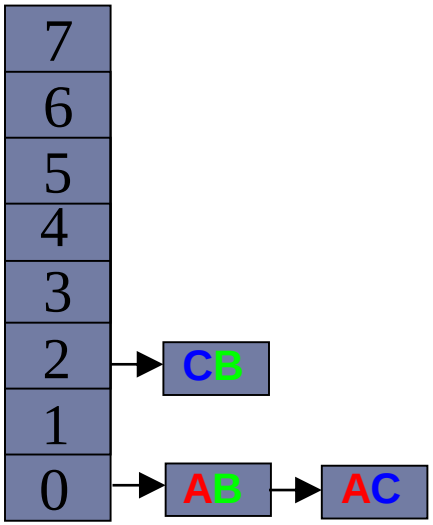


Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

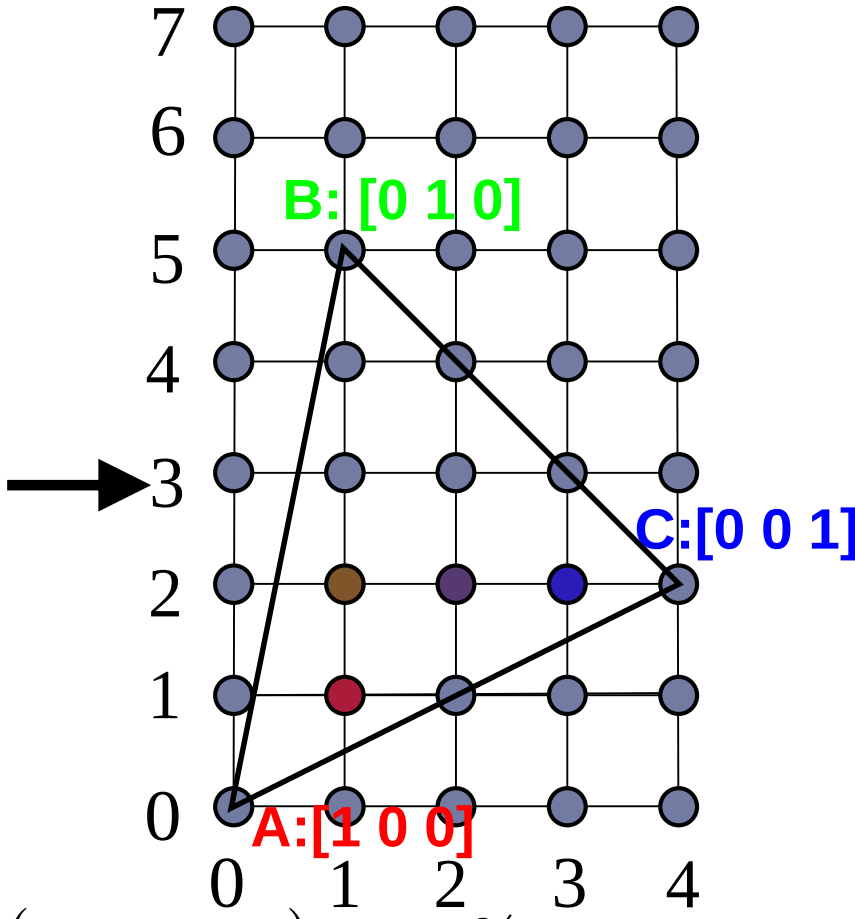
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

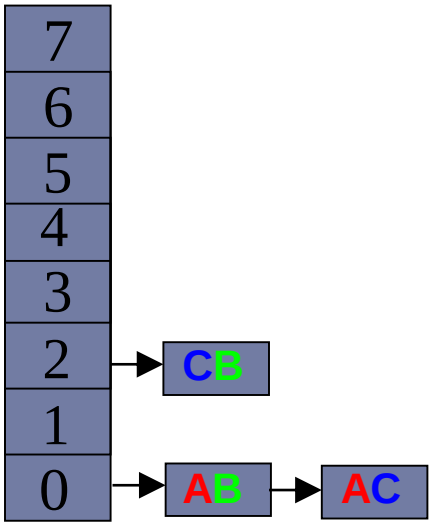


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{3}{5}$

$F = \left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$

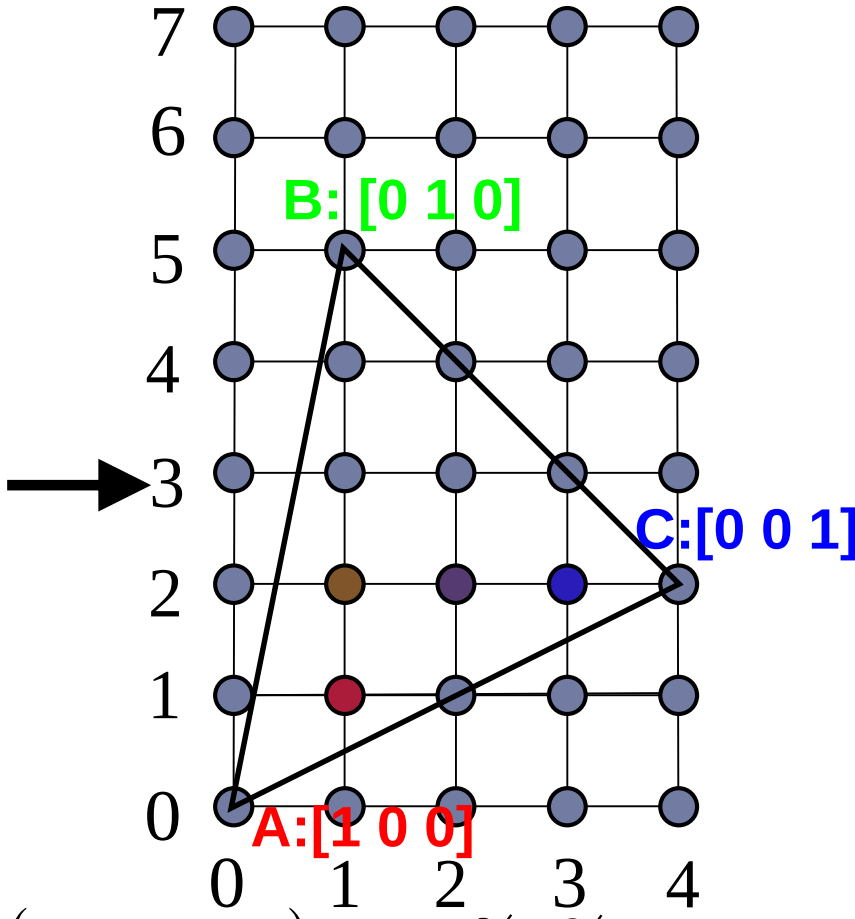
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

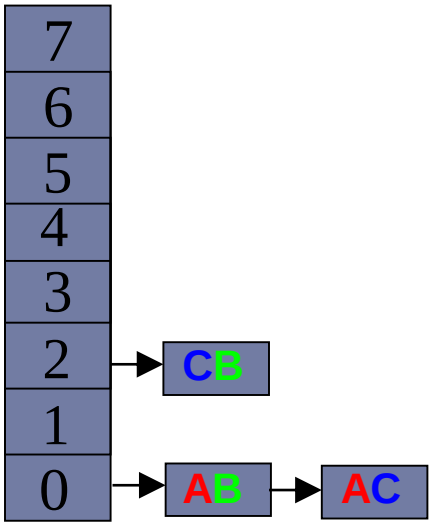


$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{3}{5} + \frac{2}{5}$$

$$F = \left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)\frac{2}{5}$$

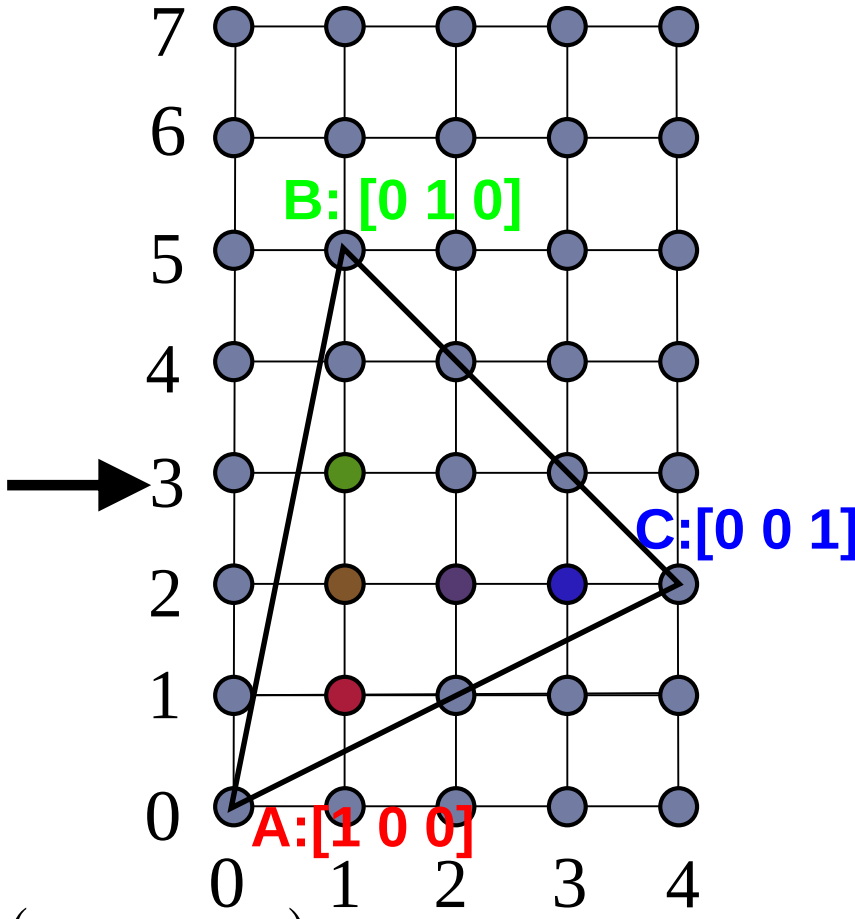
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

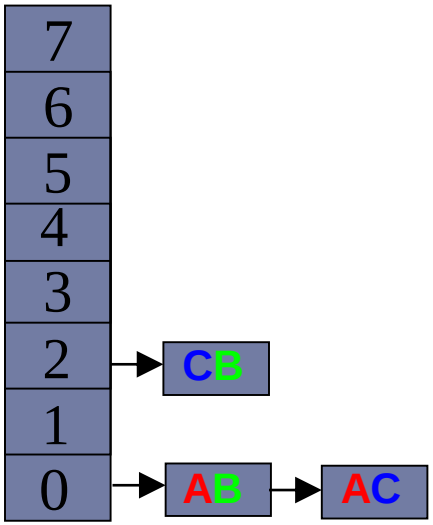


$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)$ $x = 1$

$F = \left(\frac{1}{3} \quad \frac{5}{9} \quad \frac{1}{9}\right)$

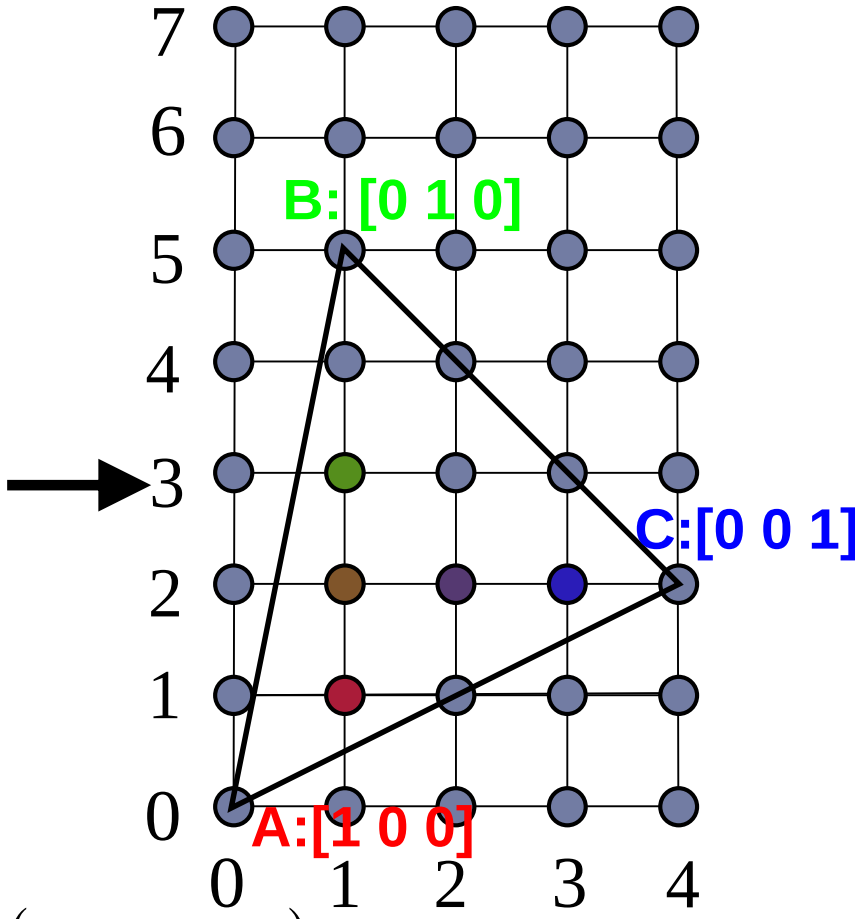
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

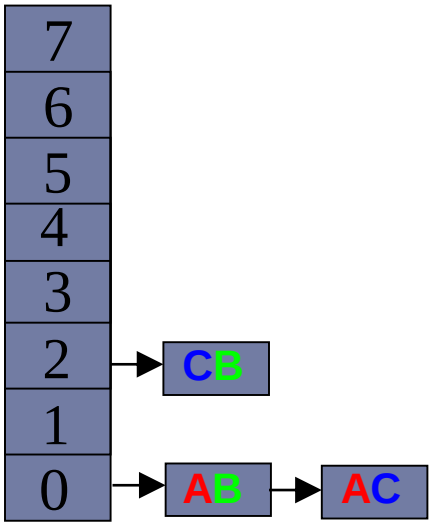


$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 1+1$$

$$F = \left(\frac{1}{3} \quad \frac{5}{9} \quad \frac{1}{9}\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)$$

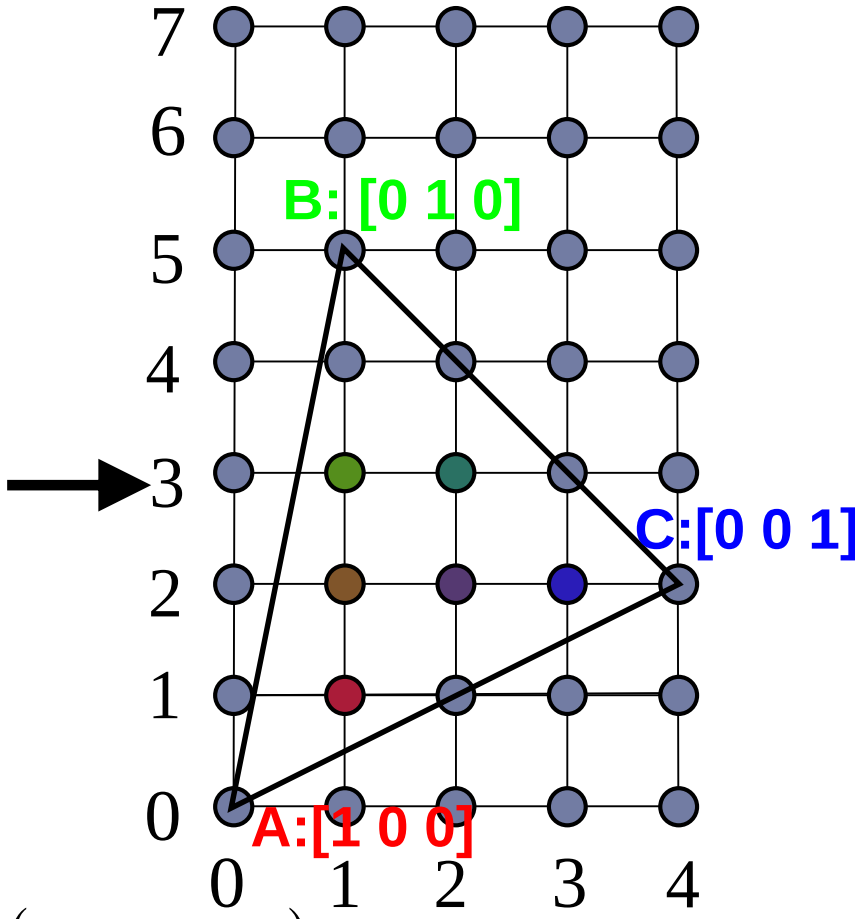
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{3}{5}$	3
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{2}{5} \quad \frac{3}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{2}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

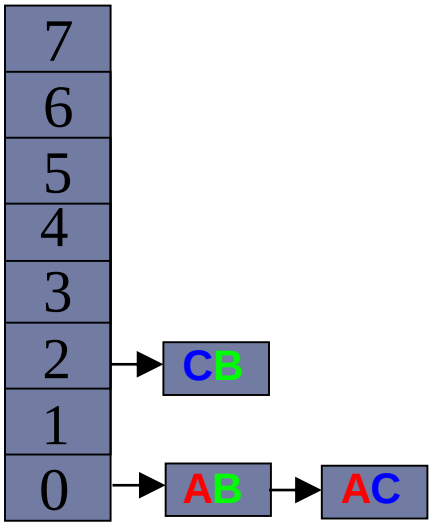


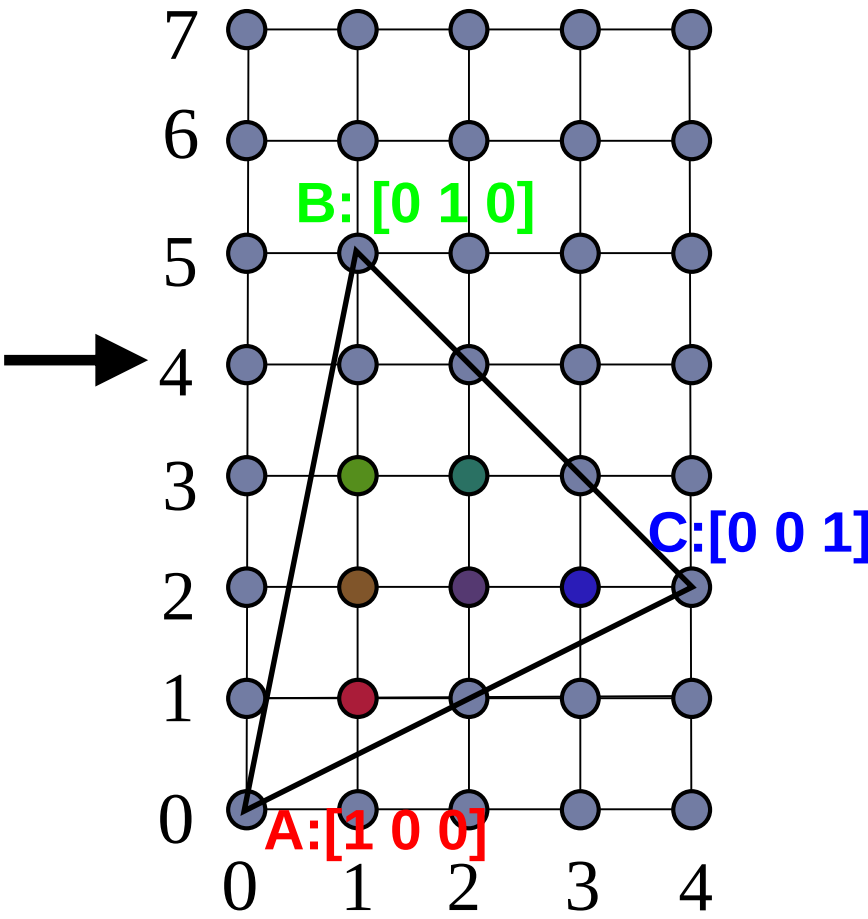
$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = 2$

$F = \left(\frac{1}{6} \quad \frac{4}{9} \quad \frac{7}{18}\right)$

Interpolating Over Polygons

Active Edge Table



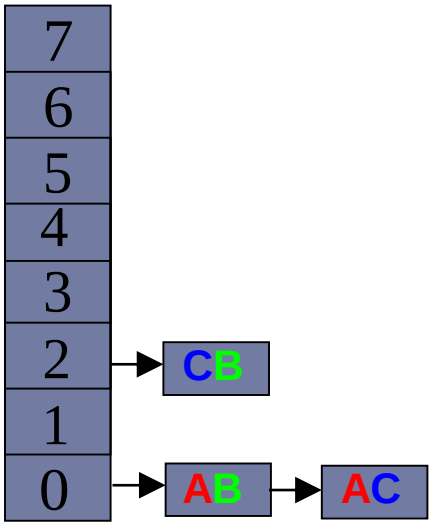


Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{4}{5}$	2
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{1}{5} \quad \frac{4}{5} \quad 0\right)$	$\left(0 \quad \frac{2}{3} \quad \frac{1}{3}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

Interpolating Over Polygons

Active Edge Table



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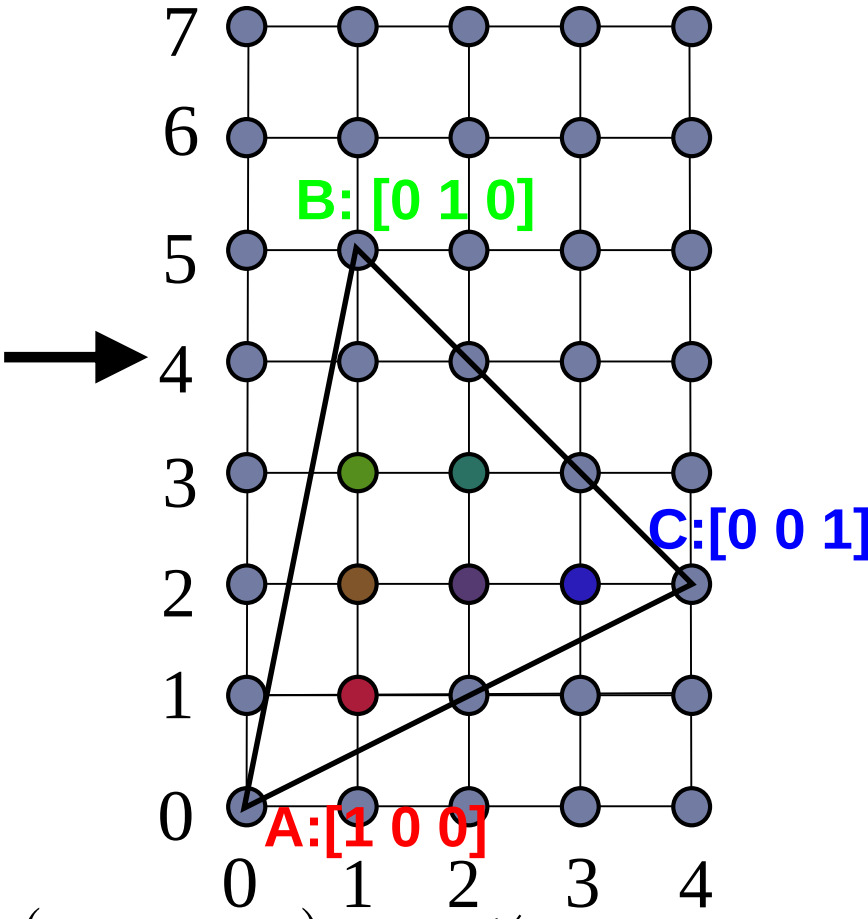
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

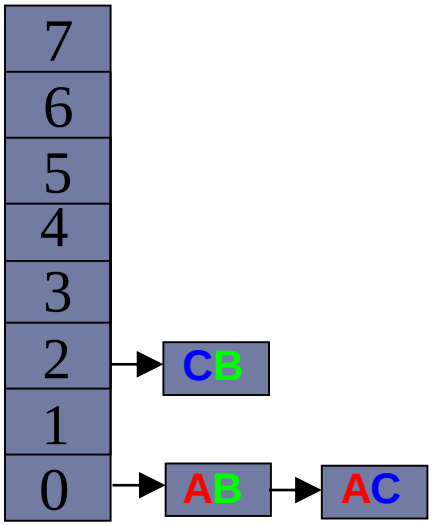


$dF = \left(-\frac{1}{6} \quad -\frac{1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{4}{5}$

$F = \left(\frac{1}{5} \quad \frac{4}{5} \quad 0\right)$

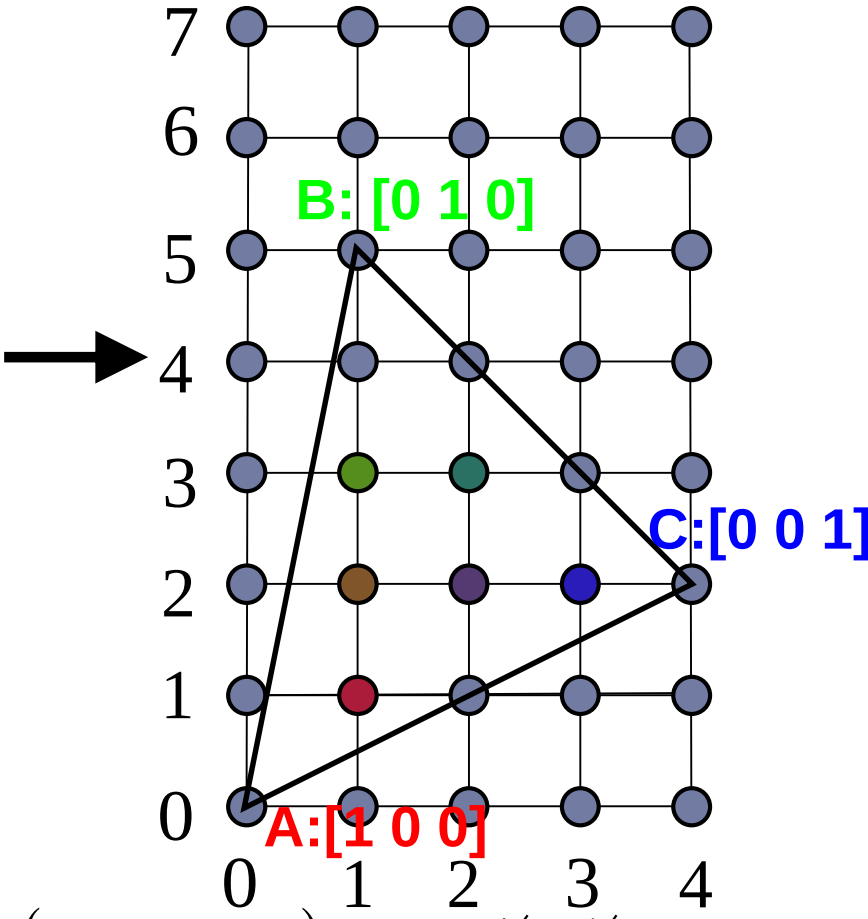
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{4}{5}$	2
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{1}{5} \quad \frac{4}{5} \quad 0\right)$	$\left(0 \quad \frac{2}{3} \quad \frac{1}{3}\right)$
fIncr	$\left(\frac{-1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad \frac{-1}{3}\right)$

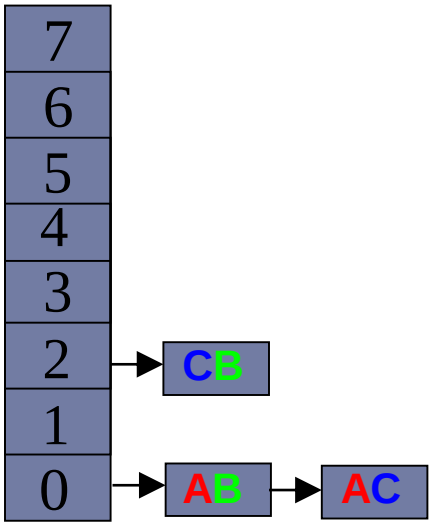


$$dF = \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right) \qquad x = \frac{4}{5} + \frac{1}{5}$$

$$F = \left(\frac{1}{5} \quad \frac{4}{5} \quad 0\right) + \left(\frac{-1}{6} \quad \frac{-1}{9} \quad \frac{5}{18}\right)\frac{1}{5}$$

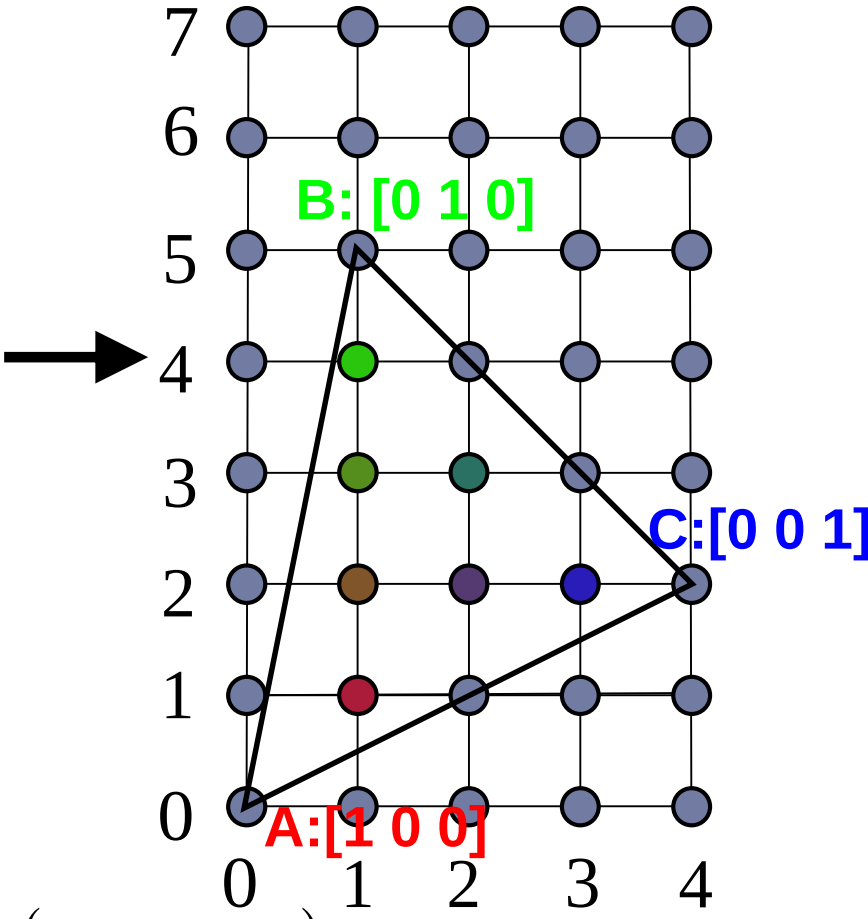
Interpolating Over Polygons

Active Edge Table



Active Edge List

	AB	CB
maxY	5	5
currentX	$\frac{4}{5}$	2
xIncr	$\frac{1}{5}$	-1
currentF	$\left(\frac{1}{5} \quad \frac{4}{5} \quad 0\right)$	$\left(0 \quad \frac{2}{3} \quad \frac{1}{3}\right)$
fIncr	$\left(-\frac{1}{5} \quad \frac{1}{5} \quad 0\right)$	$\left(0 \quad \frac{1}{3} \quad -\frac{1}{3}\right)$

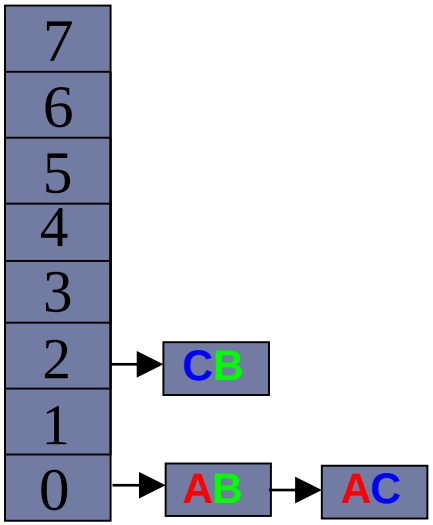


$dF = \left(-\frac{1}{6} \quad -\frac{1}{9} \quad \frac{5}{18}\right)$ $x = 1$

$F = \left(\frac{1}{6} \quad \frac{7}{9} \quad \frac{1}{18}\right)$

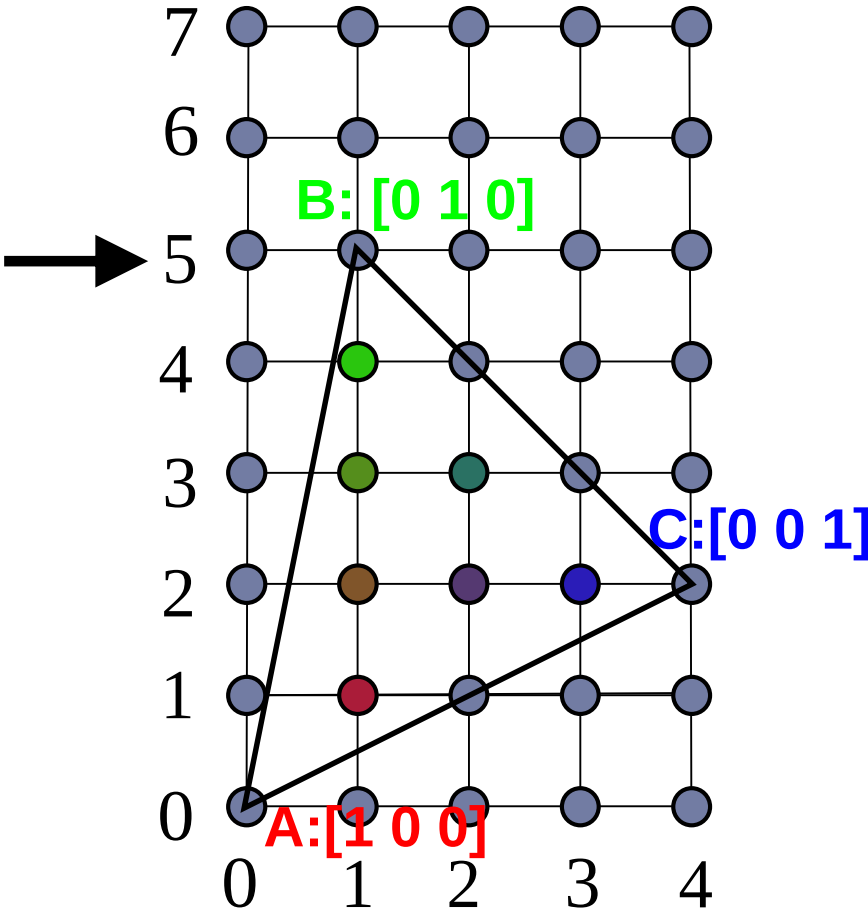
Interpolating Over Polygons

Active Edge Table



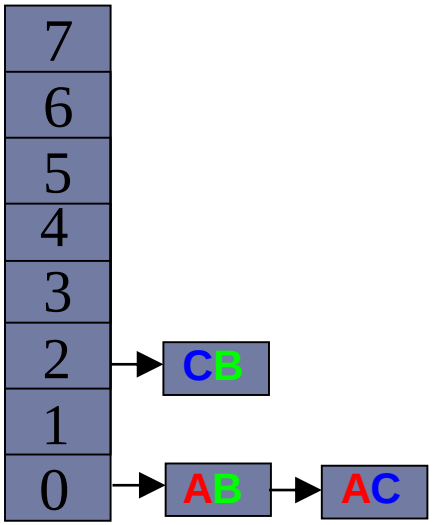
Active Edge List

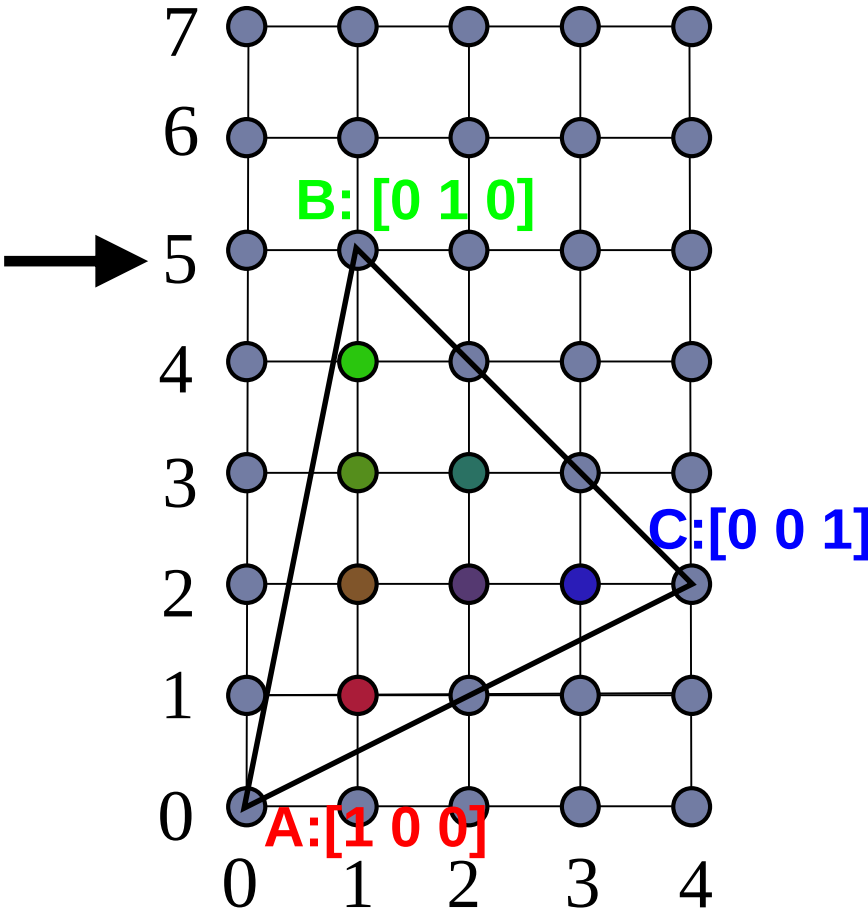
	AB	CB
maxY	5	5
currentX	1	1
xIncr	$\frac{1}{5}$	-1
currentF	$(0 \quad 1 \quad 0)$	$(0 \quad 1 \quad 0)$
fIncr	$(-\frac{1}{5} \quad \frac{1}{5} \quad 0)$	$(0 \quad \frac{1}{3} \quad -\frac{1}{3})$



Interpolating Over Polygons

Active Edge Table



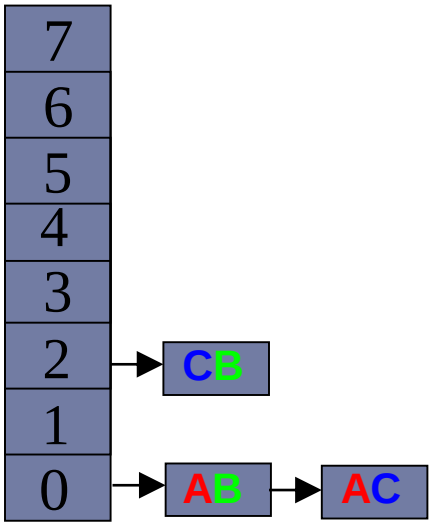


Active Edge List

	AB	CB
maxY	5	5
currentX	1	1
xIncr	$\frac{1}{5}$	-1
currentF	$(0 \quad 1 \quad 0)$	$(0 \quad 1 \quad 0)$
fIncr	$(-\frac{1}{5} \quad \frac{1}{5} \quad 0)$	$(0 \quad \frac{1}{3} \quad -\frac{1}{3})$

Interpolating Over Polygons

Active Edge Table



Active Edge List

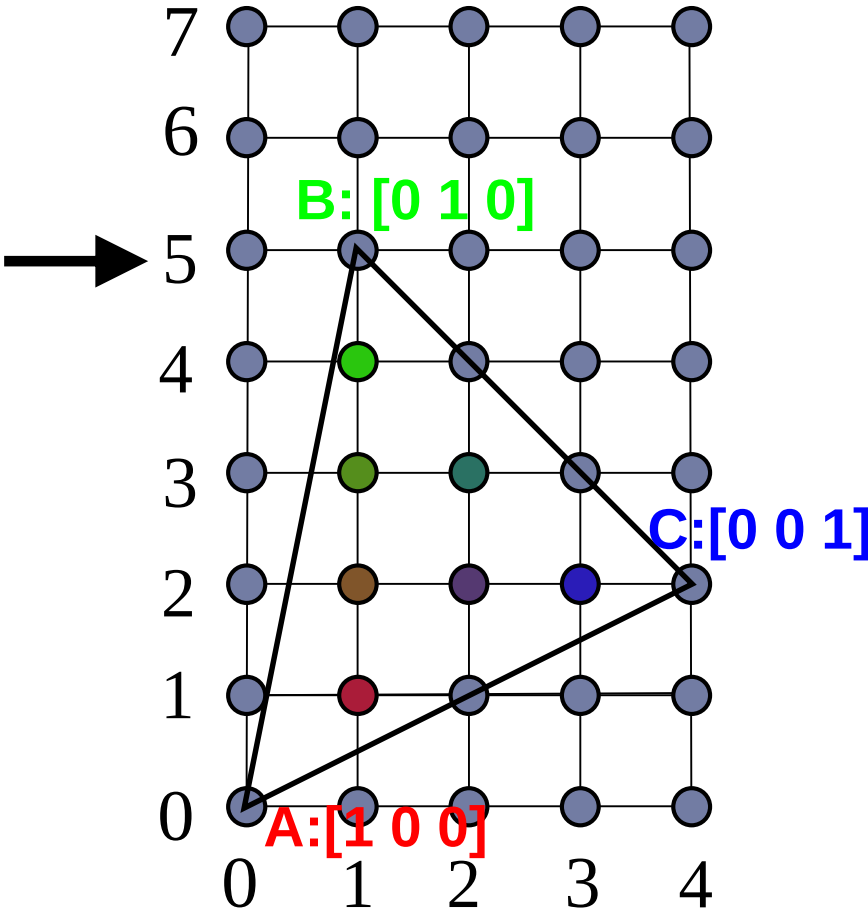
maxY

currentX

xIncr

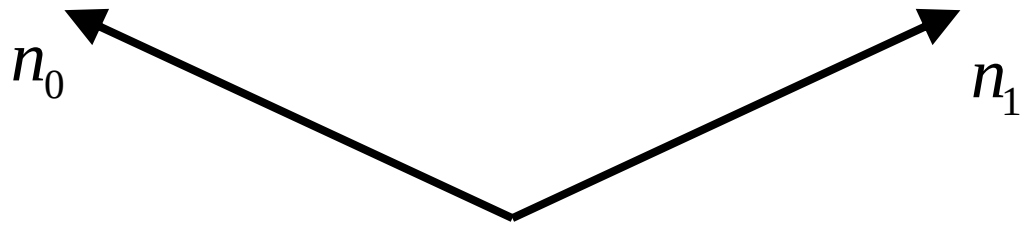
currentF

fIncr



Interpolating Normals

- Exactly the same as colors
- Must renormalize
- Does not produce even spacing



Interpolating Normals

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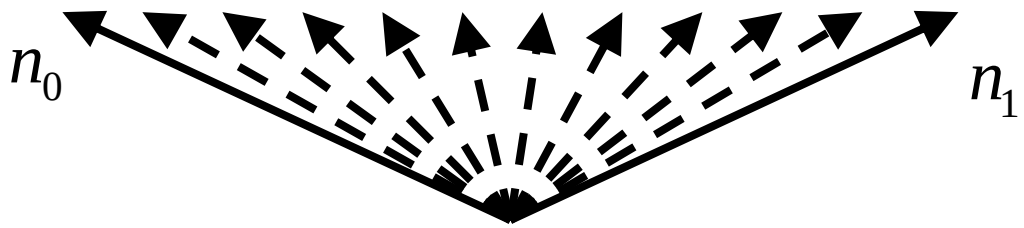

Interpolating Normals

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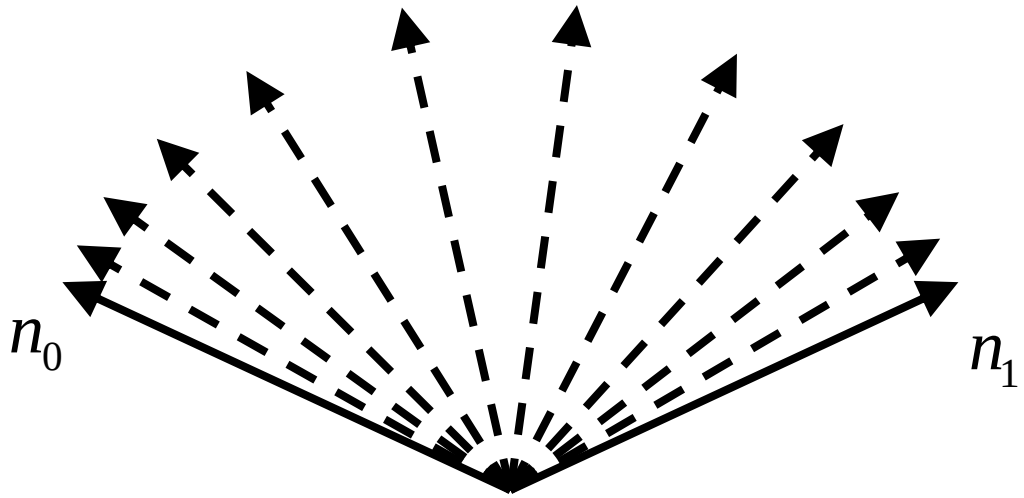


Texture Mapping

- Geometry and lighting alone do not provide sufficient visible detail
- "Paste" 2D image onto 3D surface

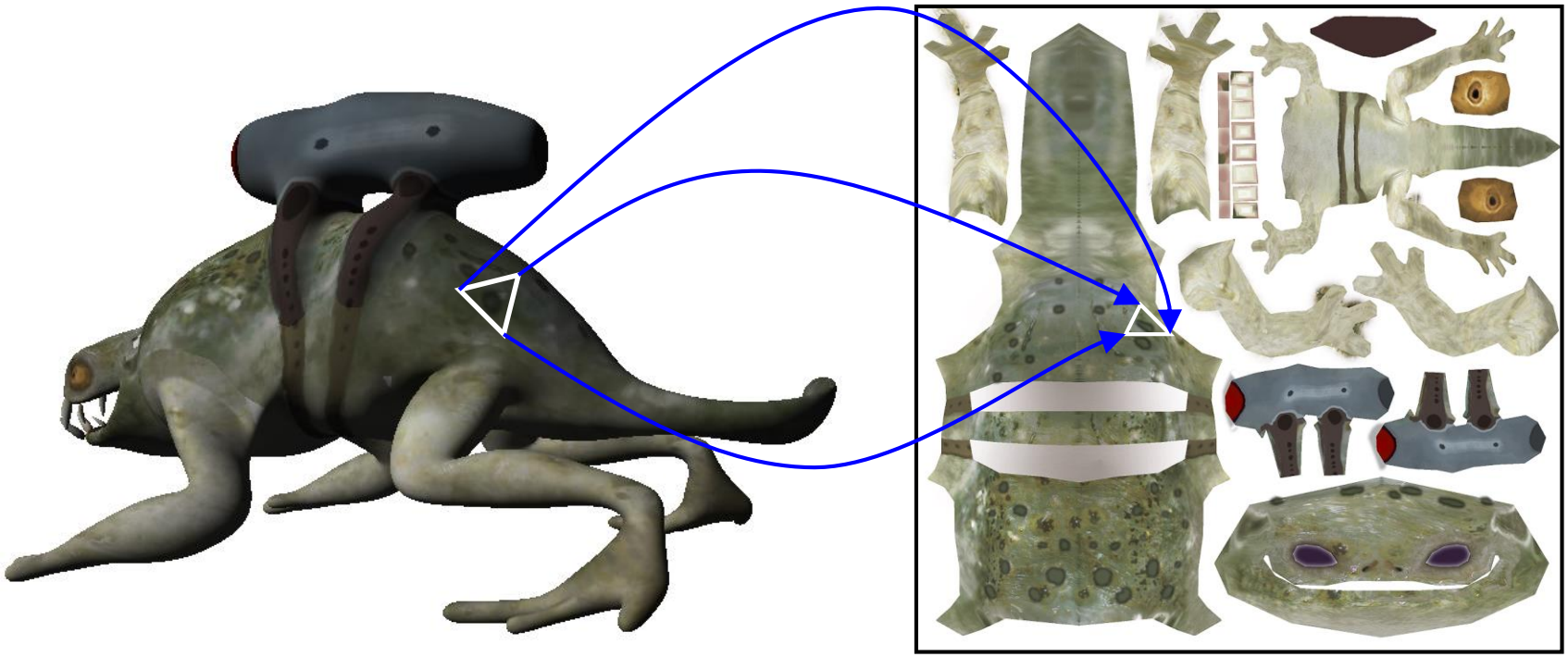
- Surface appears much more complex than reality

Texture Mapping

Texture Mapping

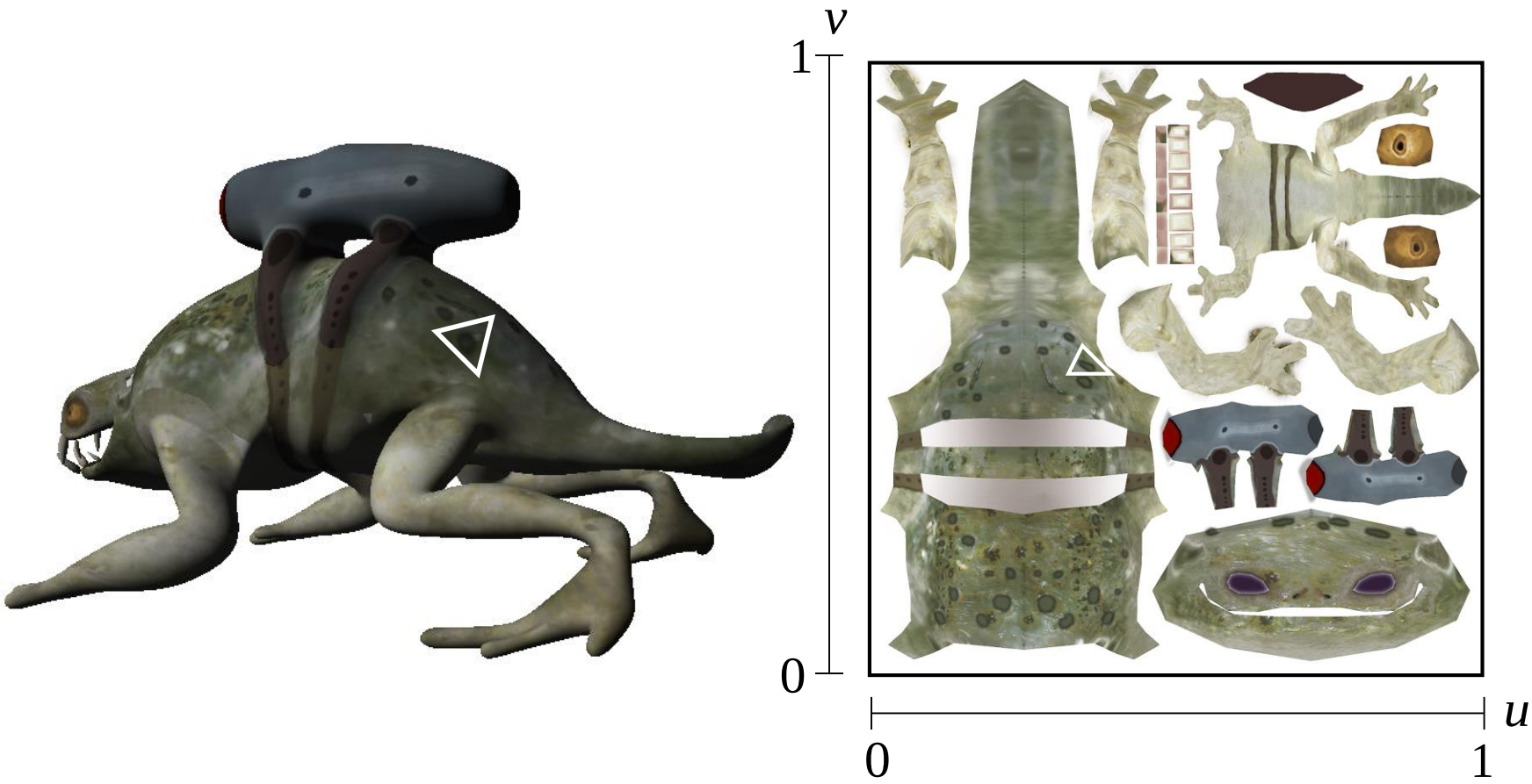
Texture Mapping

Texture Mapping



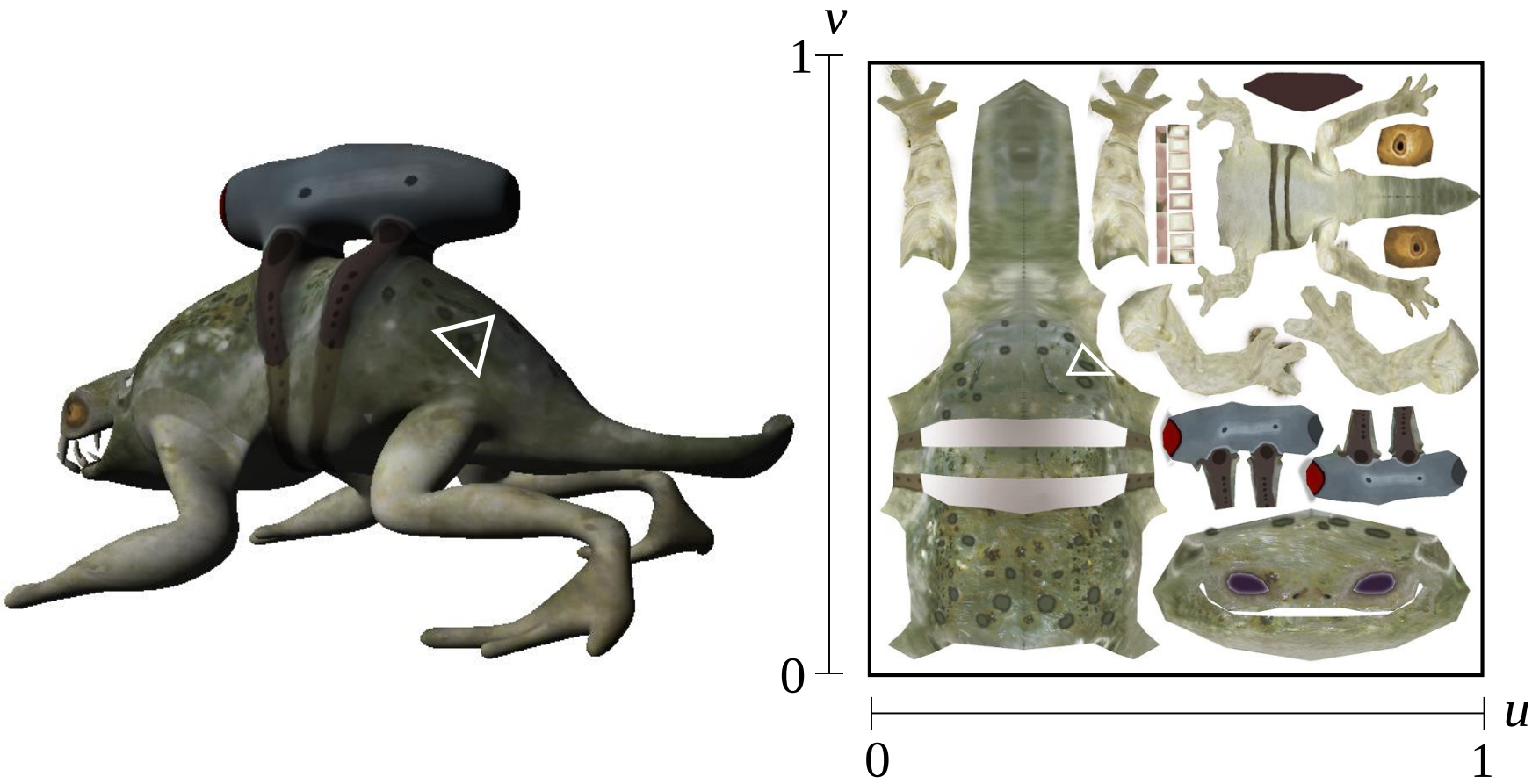
Texture Mapping

- Assume texture parameterized by *u*, *v*



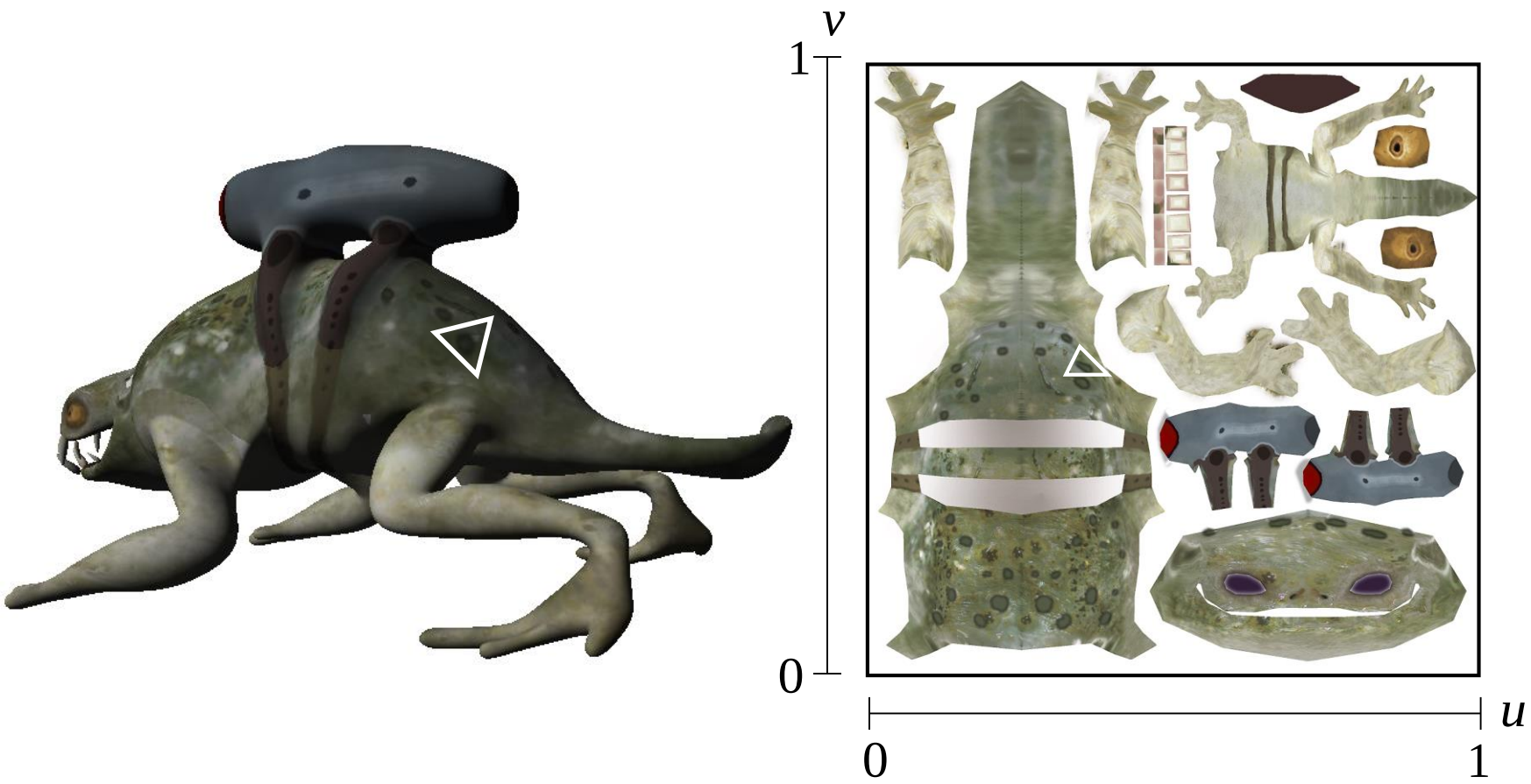
Texture Mapping

- Any *u*, *v* coordinate maps to a point on the image



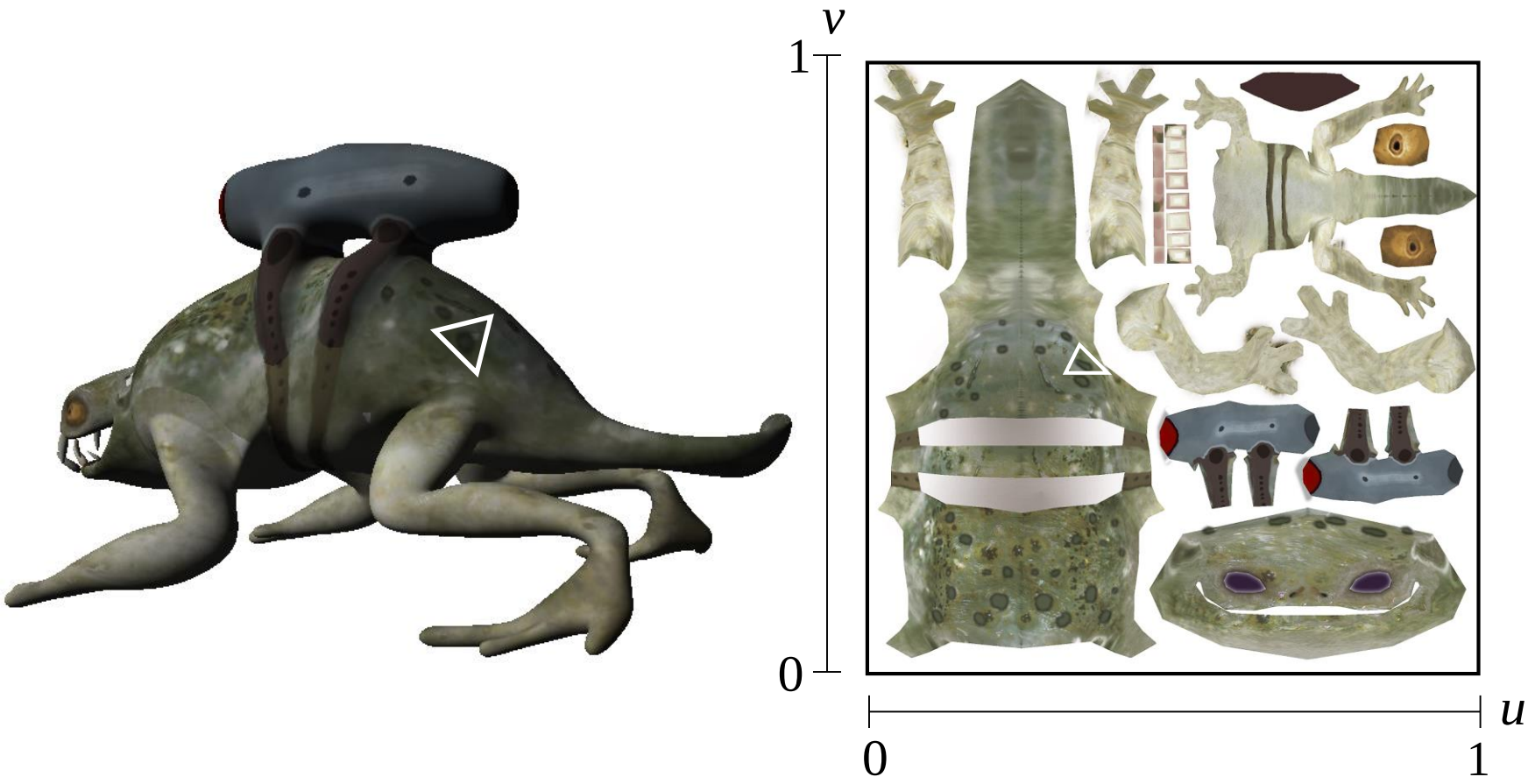
Texture Mapping

- Associate *texture coordinates* with each vertex on the surface

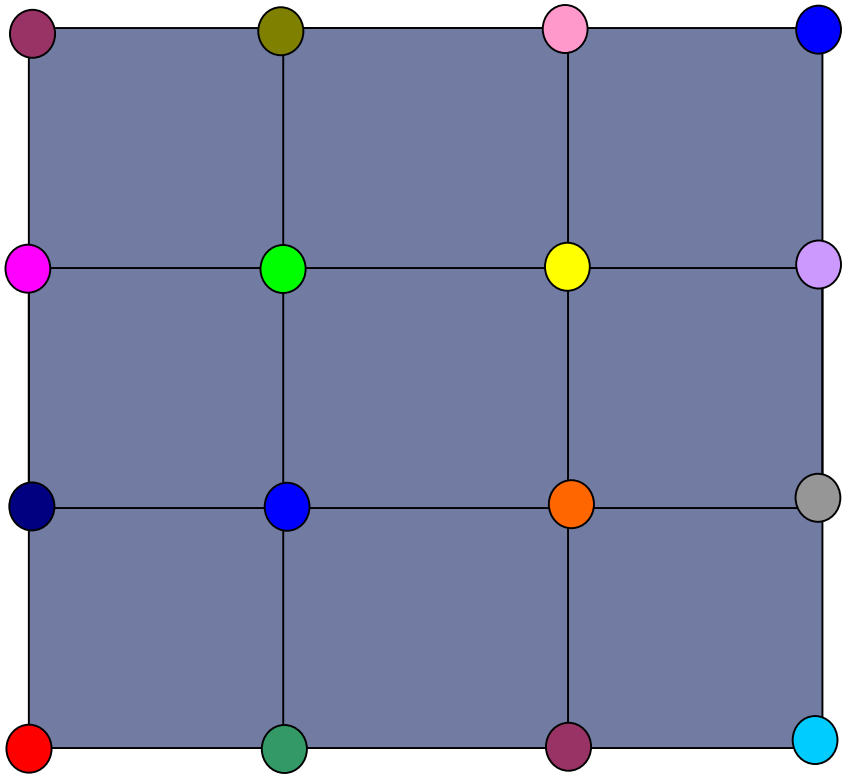


Texture Mapping

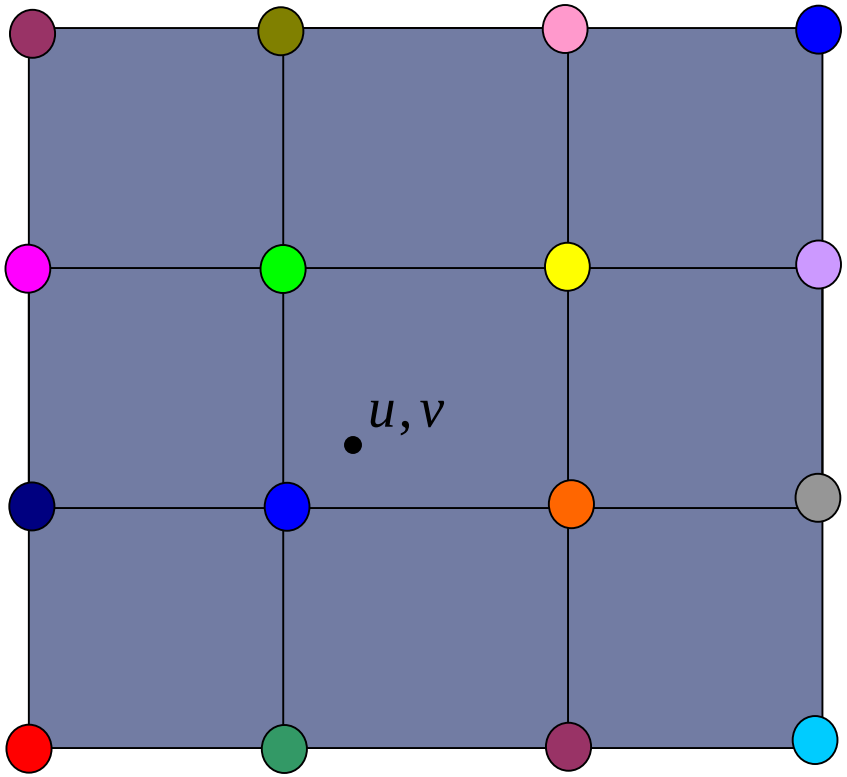
- During polygon drawing, lookup color from texture using interpolated texture coordinates



Sampling Textures

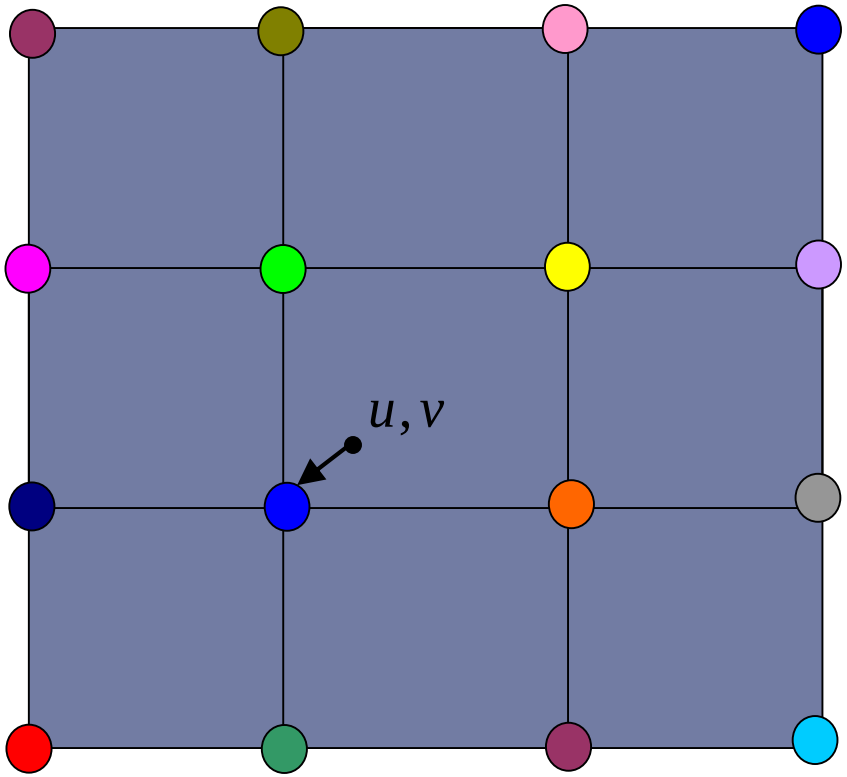


Sampling Textures



Sampling Textures

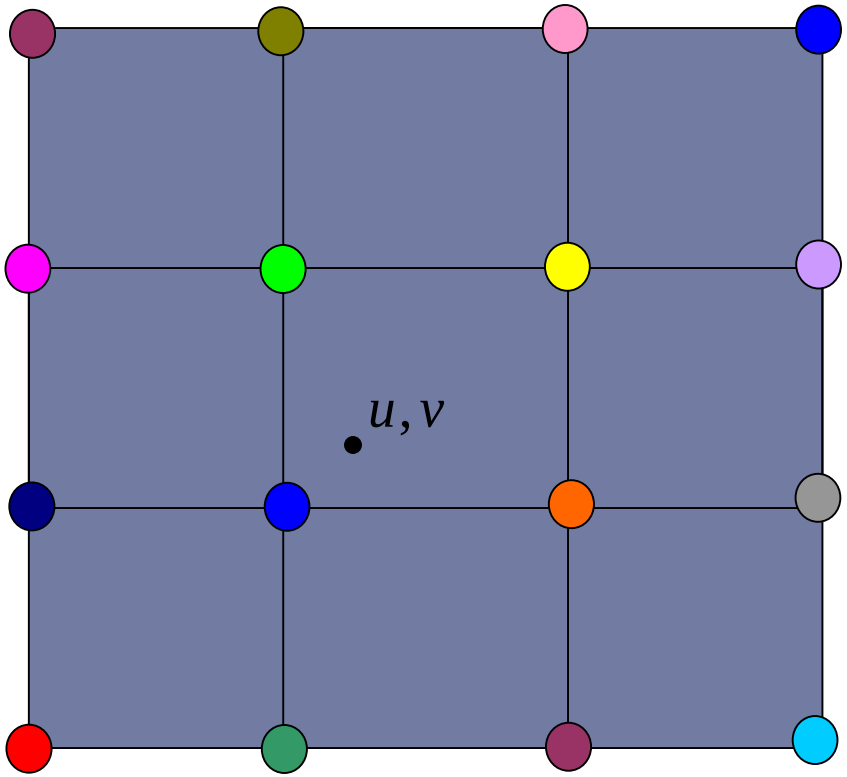
- Nearest neighbor
  - Blocky results



Nearest Sampling Example

Sampling Textures

- Nearest neighbor
  - Blocky results
- Linear blending
  - Smooth appearance



Sampling Textures

- Nearest neighbor
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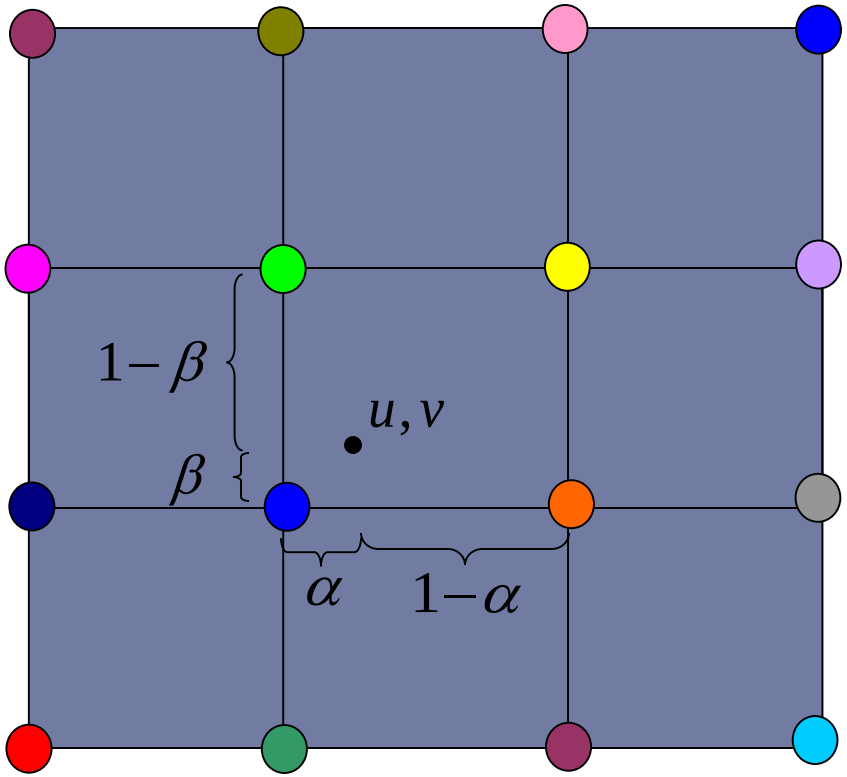
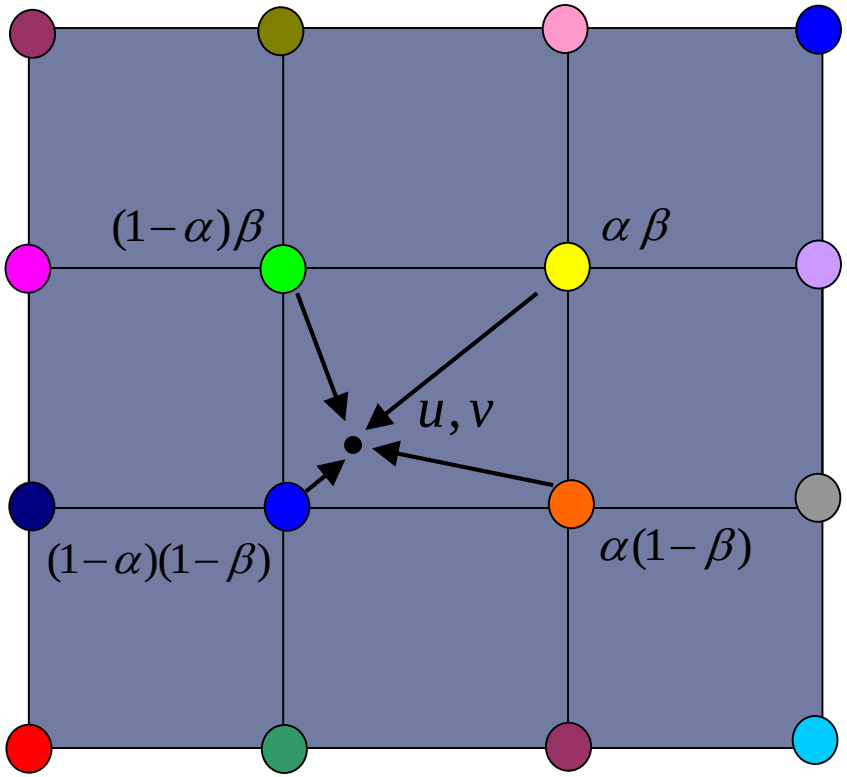


Sampling Textures

- Nearest neighbor
  - Blocky results
- Linear blending
  - Smooth appearance

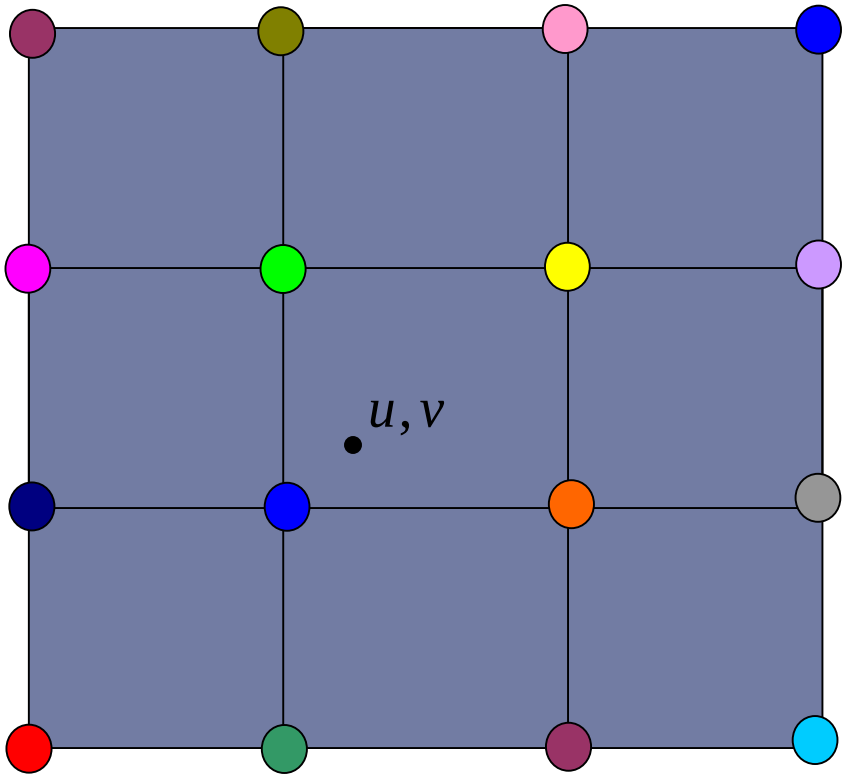


Nearest Sampling Example

Linear Sampling Example

Sampling Textures

- Nearest neighbor
  - Blocky results
- Linear blending
  - Smooth appearance
- Can be much more complicated



Other Uses of Texture Mapping

- Environment Mapping
- Bump/Normal Mapping
- Displacement Mapping
- ….

- Any attribute of the surface position, normal, color, etc… can be placed in a texture

Environment Mapping

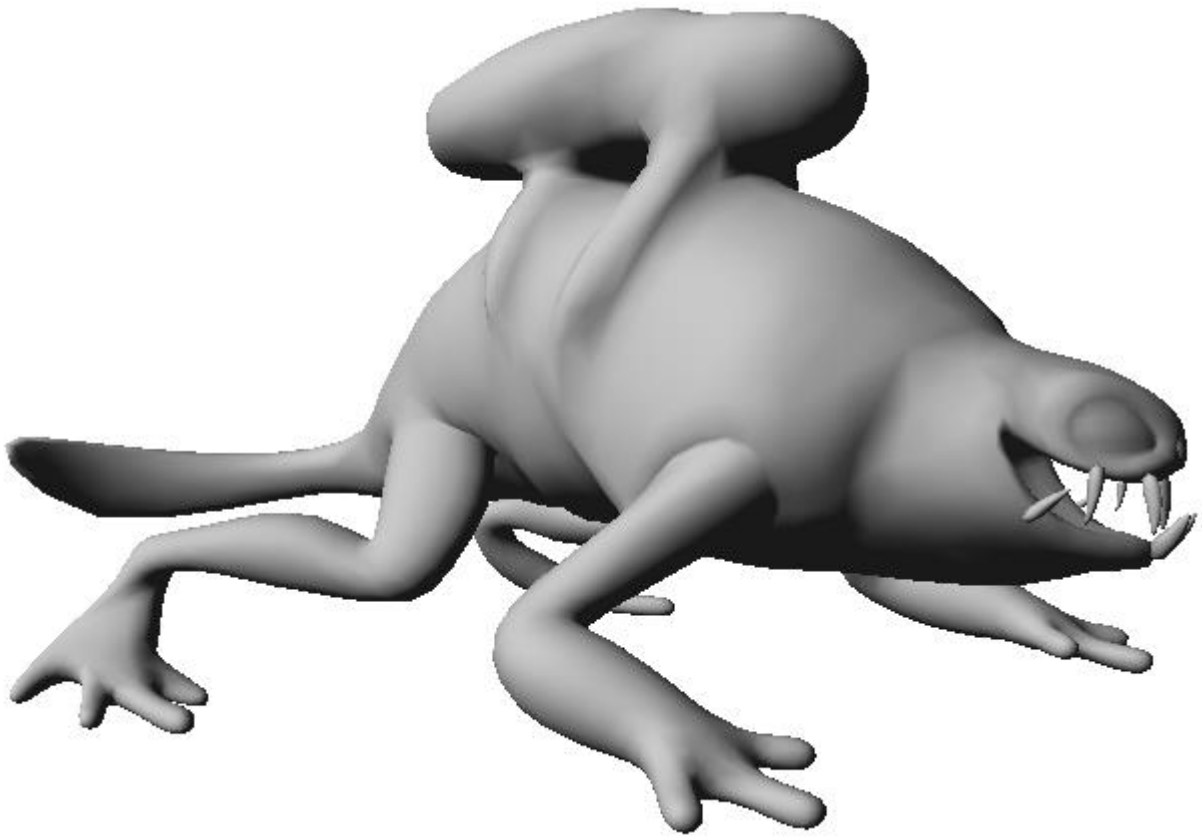
- How to create this effect?

Environment Mapping

- Cheap attempt at modeling reflections
- Makes surfaces look metallic

- Use six textures to model faces of a cube
- Assume cube faces infinitely far away
- The normal (or reflected eye vector) is used to find which of the textures to use and what texture coordinate

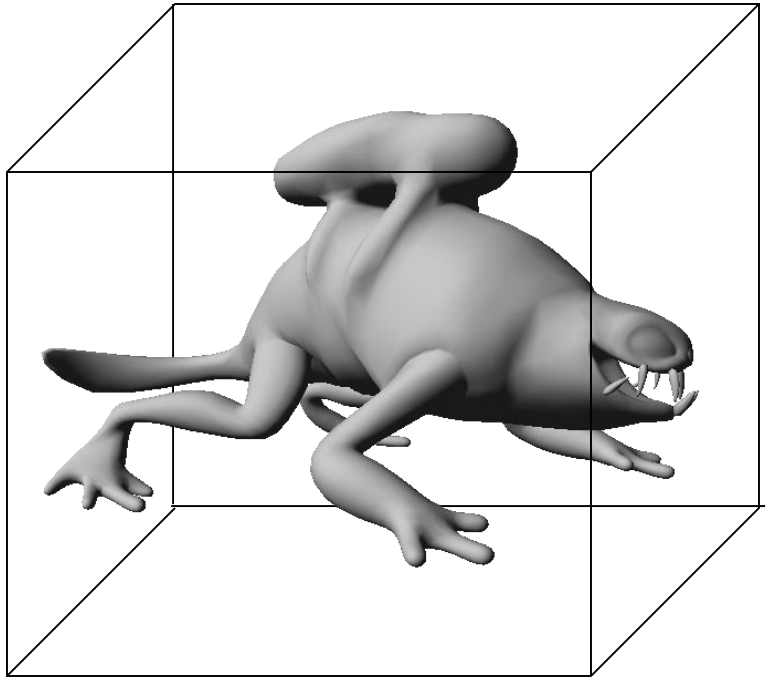
Environment Mapping



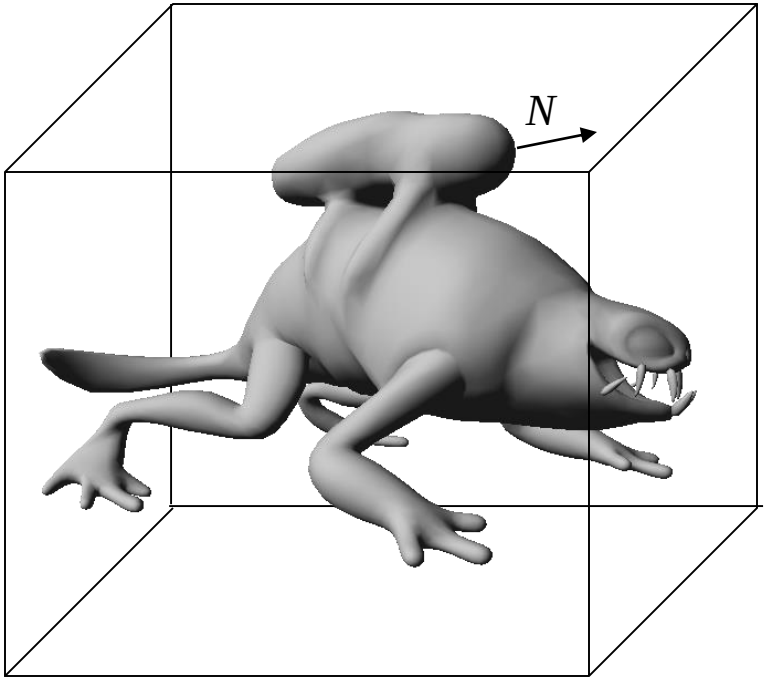
Environment Mapping

Environment Mapping

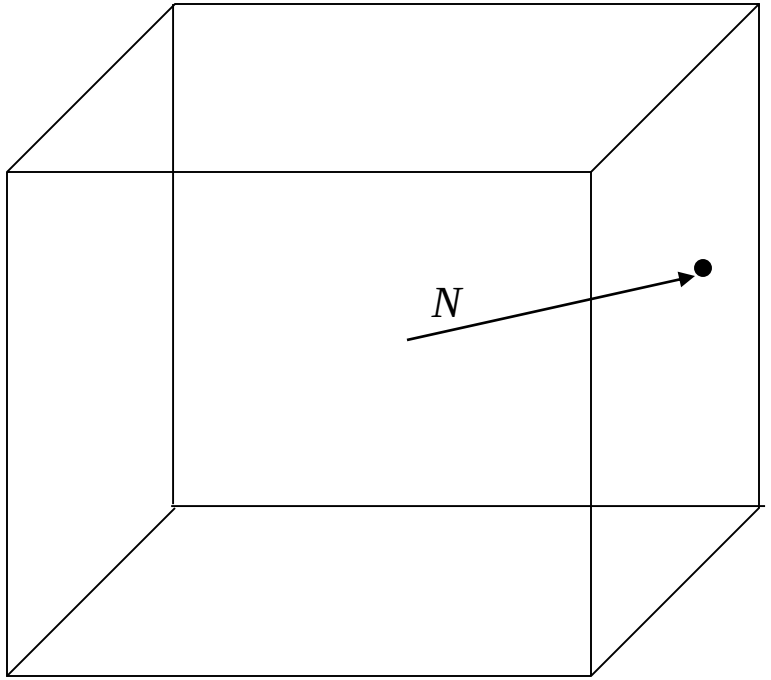
Environment Mapping



Environment Mapping

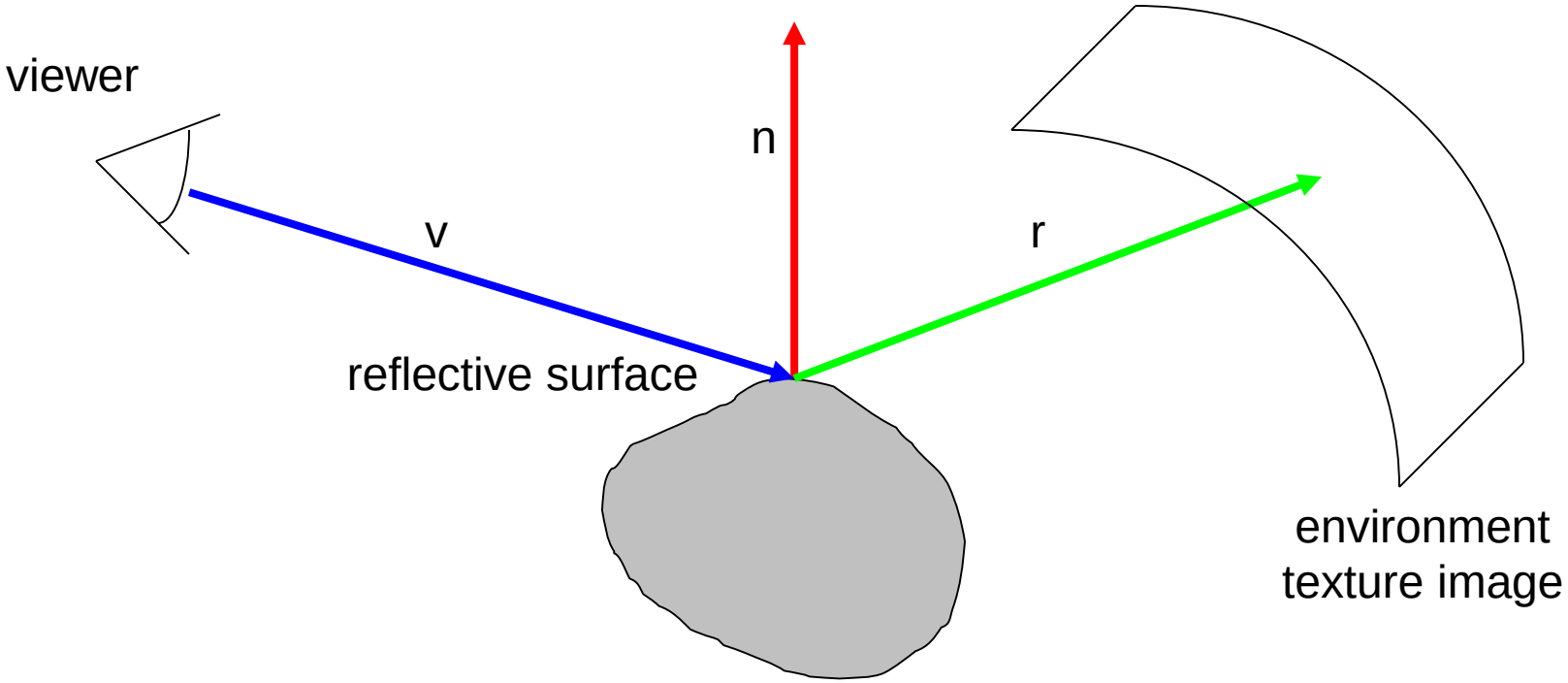


Environment Mapping



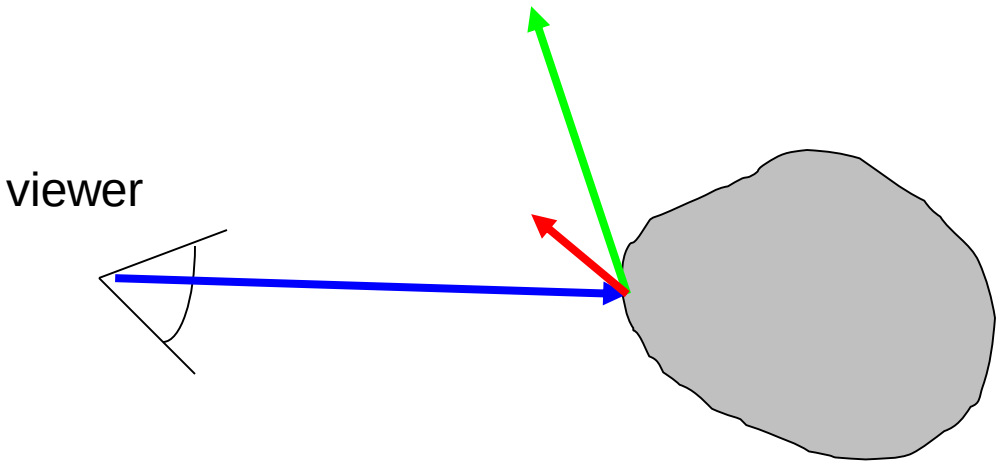
Environment Mapping

Reflected ray: $\boldsymbol{r}=2(\boldsymbol{n}\cdot\boldsymbol{v})\boldsymbol{n}-\boldsymbol{v}$

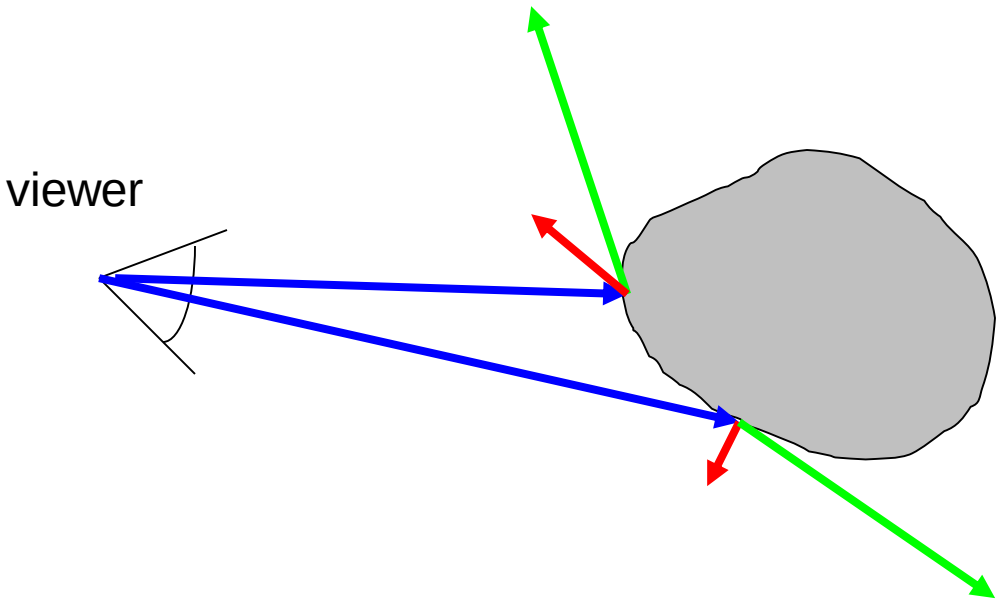


Texture is transferred in the direction of the reflected ray r from the environment map onto the object
What is in the map?

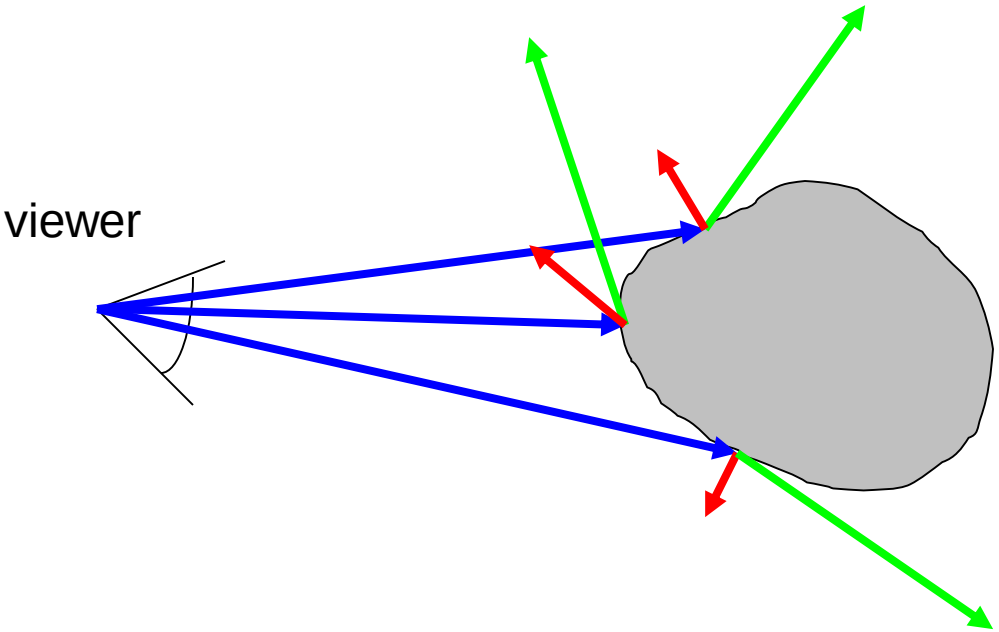
How to represent the map



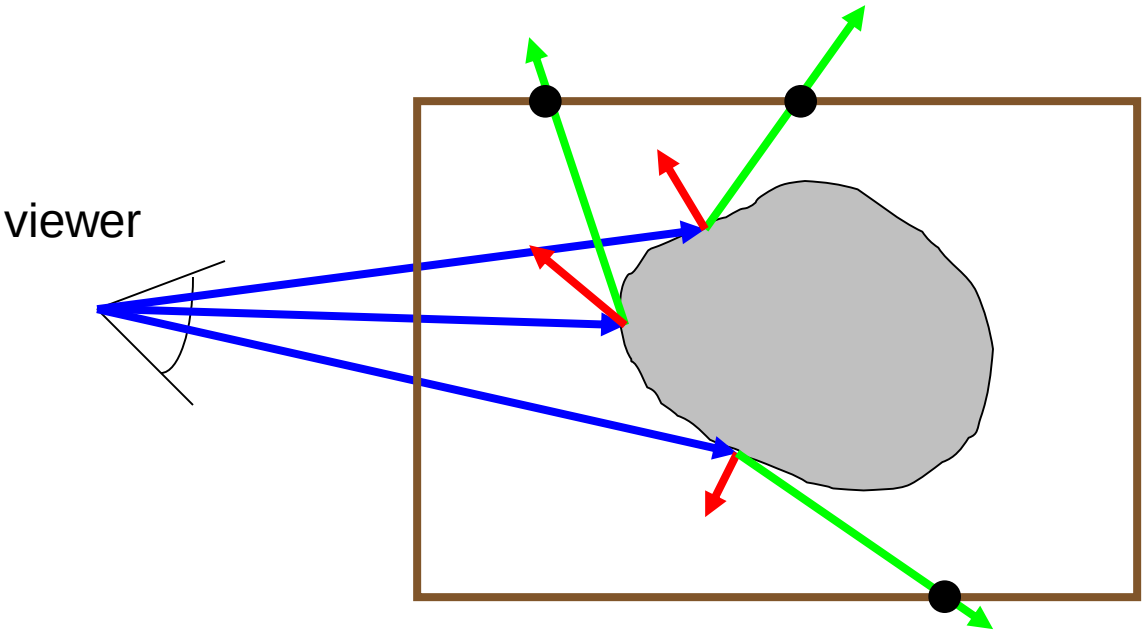
How to represent the map



How to represent the map

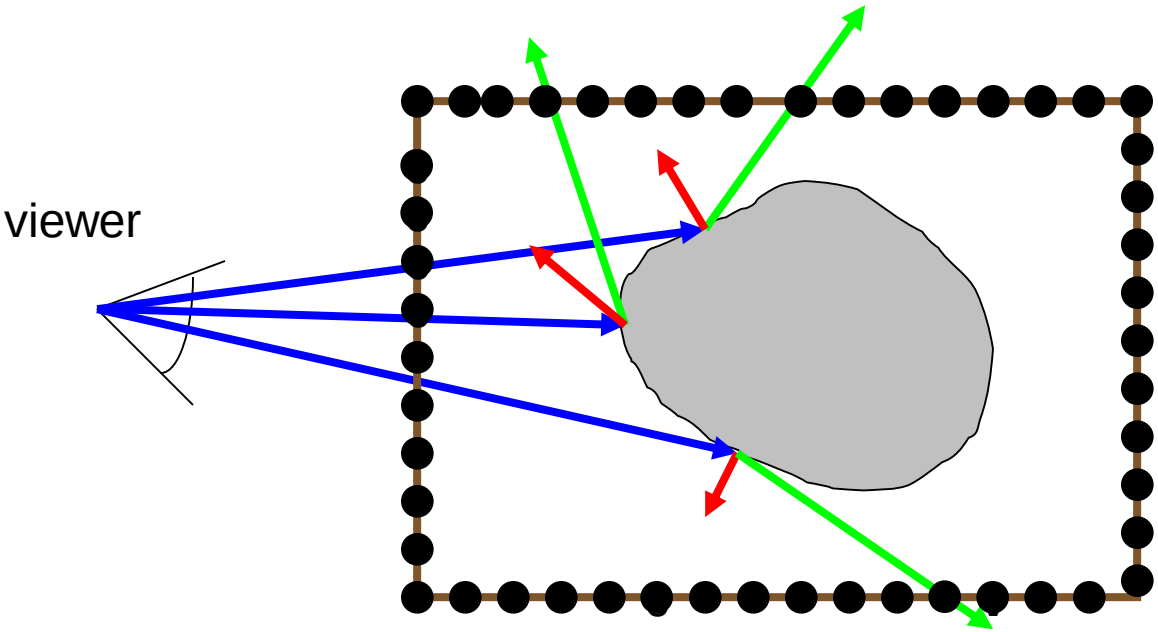


How to represent the map



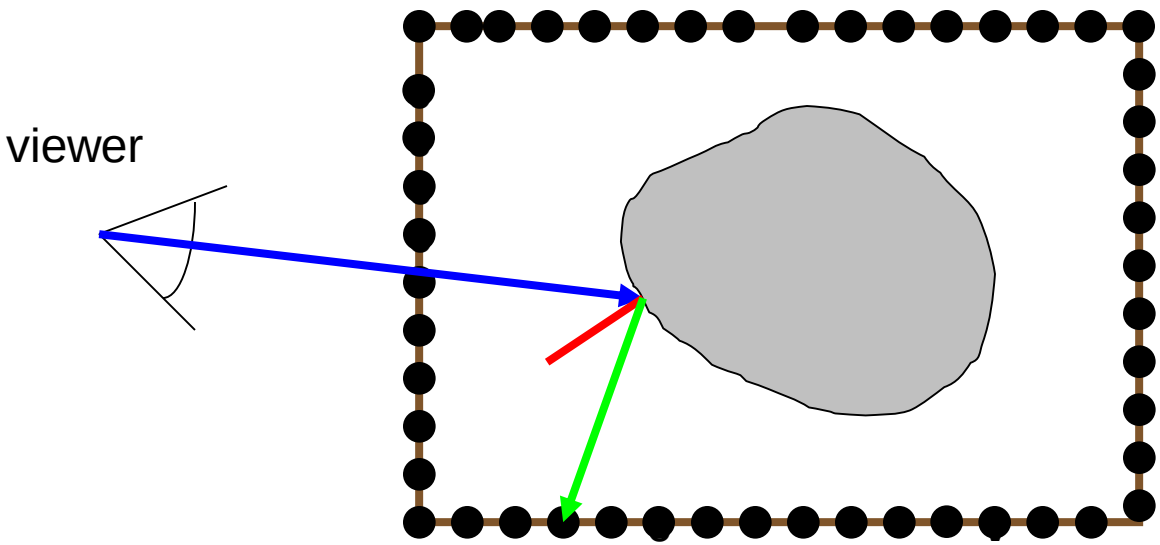
- Store colors of every possible direction in texture maps

How to represent the map



- Store colors of every possible direction in texture maps

How to represent the map

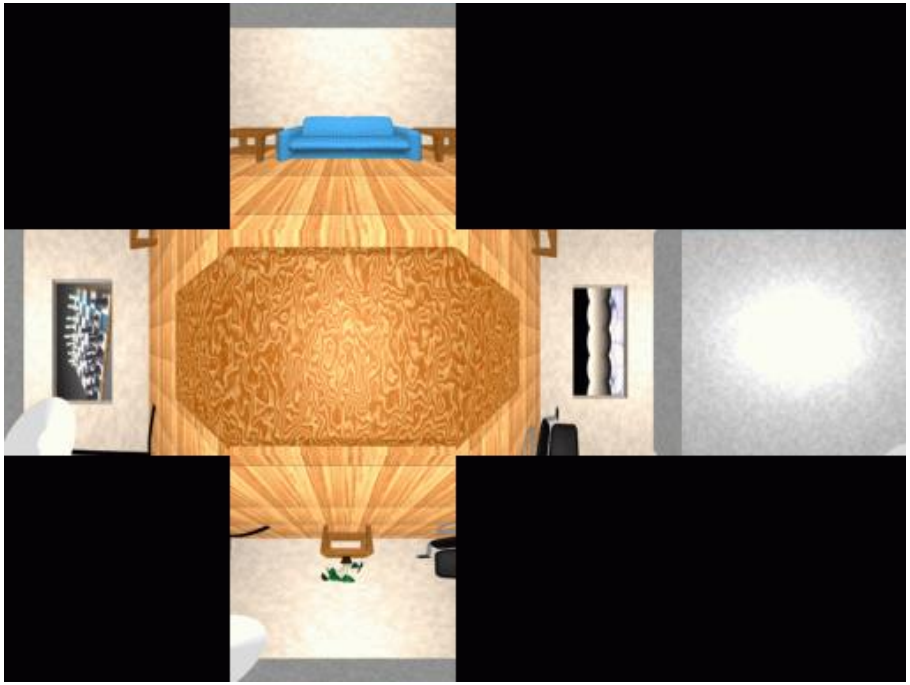


- Store colors of every possible direction in texture maps
- Look up texture maps based on reflected vector

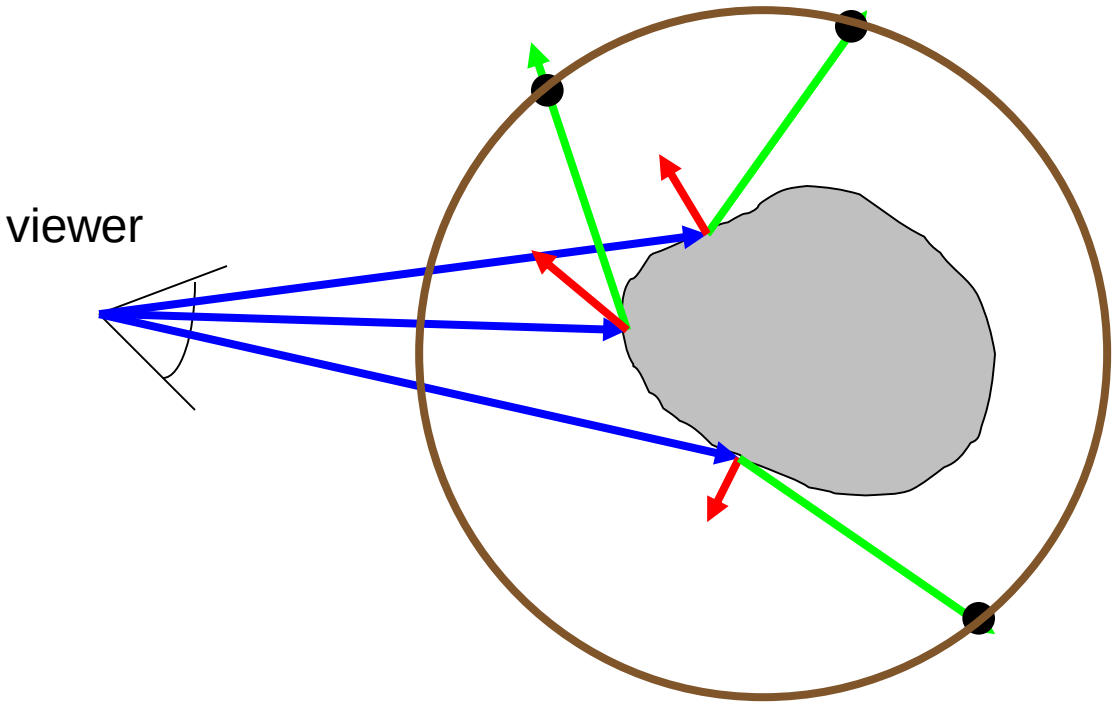
Cubic Mapping

- The map resides on the surfaces of a cube around the object
  - Typically, align the faces of the cube with the coordinate axes
- To generate the map:
  - For each face of the cube, render the world from the center of the object with the cube face as the image plane
    - Rendering can be arbitrarily complex (it's off-line)
- To use the map:
  - Index the R ray into the correct cube face
  - Compute texture coordinates

Cubic Map Example



How to represent the map



- Store colors of every possible direction in texture maps

Sphere Mapping

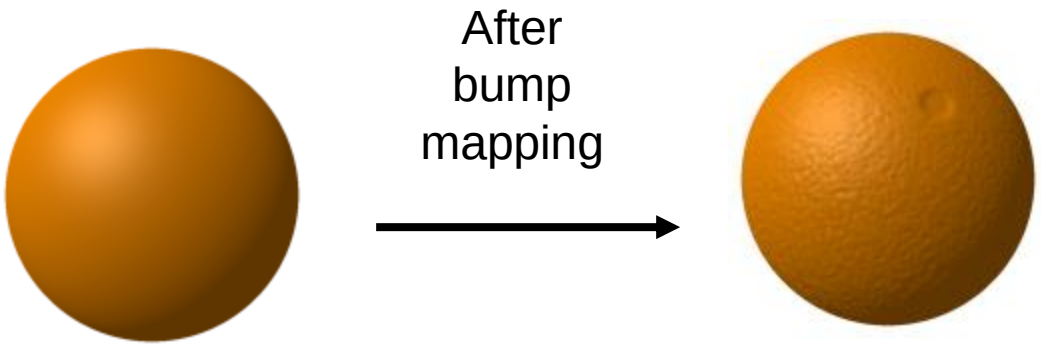
- Map lives on a sphere
- To generate the map:
  - Render a spherical panorama from the designed center point
- To use the map:
  - Use the orientation of the R ray to index directly into the sphere

Example

Bump/Normal Mapping

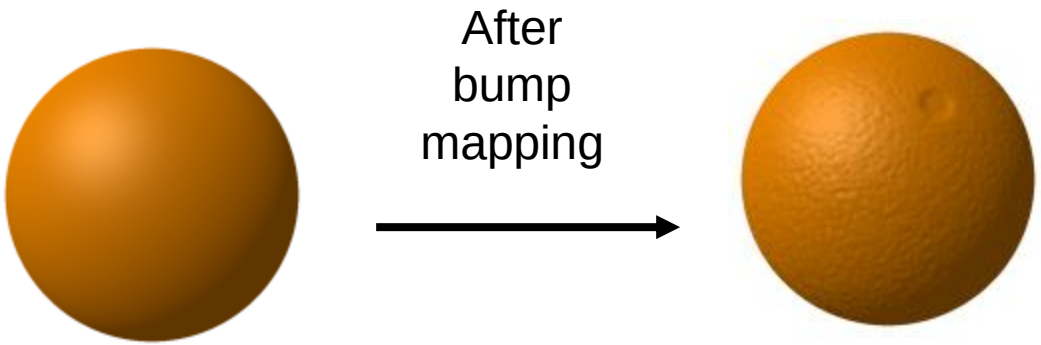
Bump/Normal Mapping

- Idea: perturb surface normal



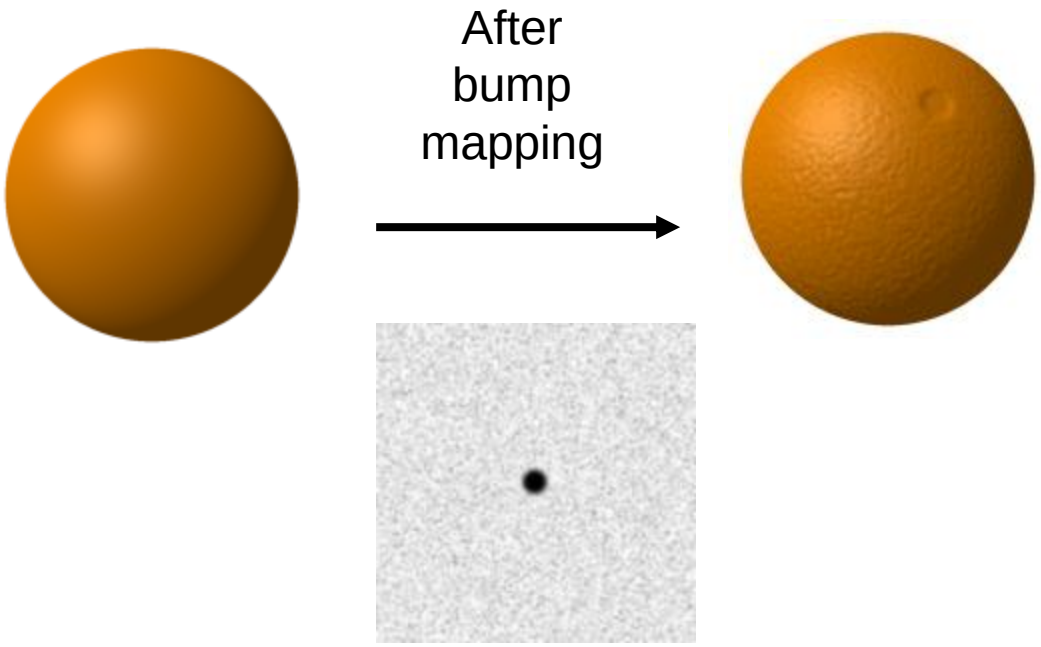
Bump/Normal Mapping

- Replace colors R,G,B with coordinates X,Y,Z
- Interpret pixels as normal vectors
- Makes the shading look more complicated than geometry really is



Bump/Normal Mapping

- Idea: perturb surface normal



Bump/Normal Mapping Example

Bump/Normal Mapping Example

Bump/Normal Mapping Example

Displacement Mapping

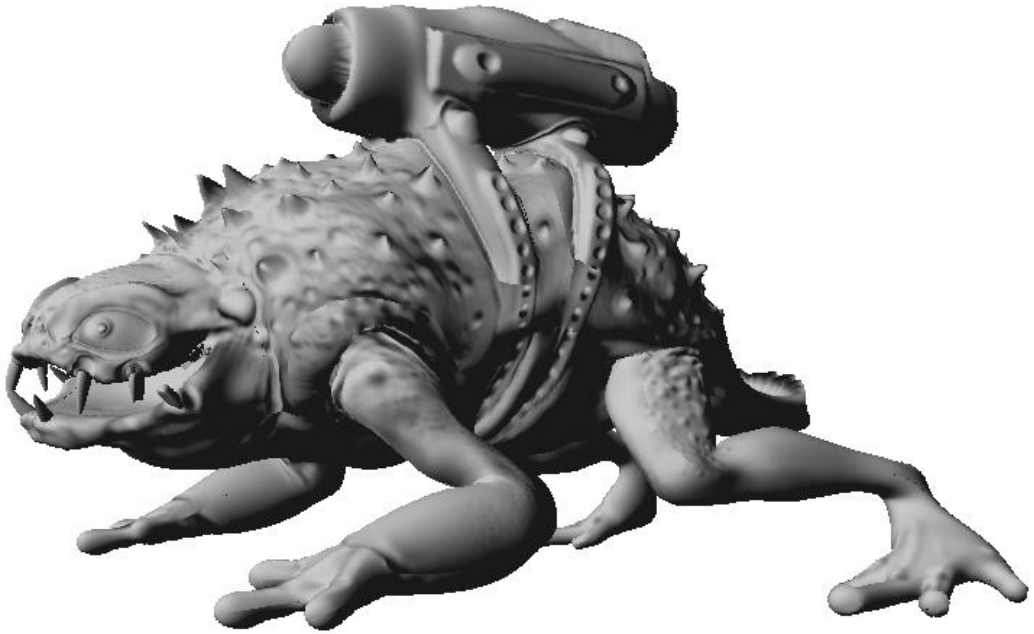
- Offset geometry in direction of normal
- Encode offset inside texture
- Used to actually change the geometry and provide more detail (especially silhouette)

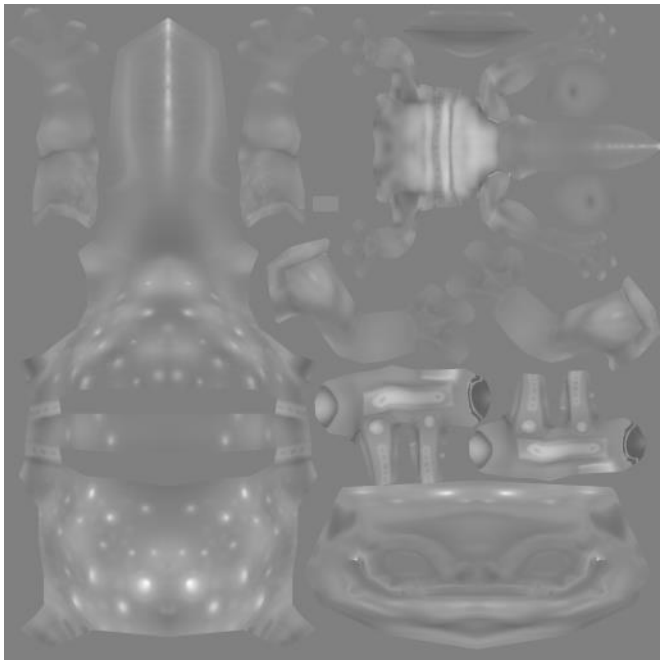
- Difficult/expensive to perform with current hardware

Bump/Normal Mapping Example

Displacement Mapping Example

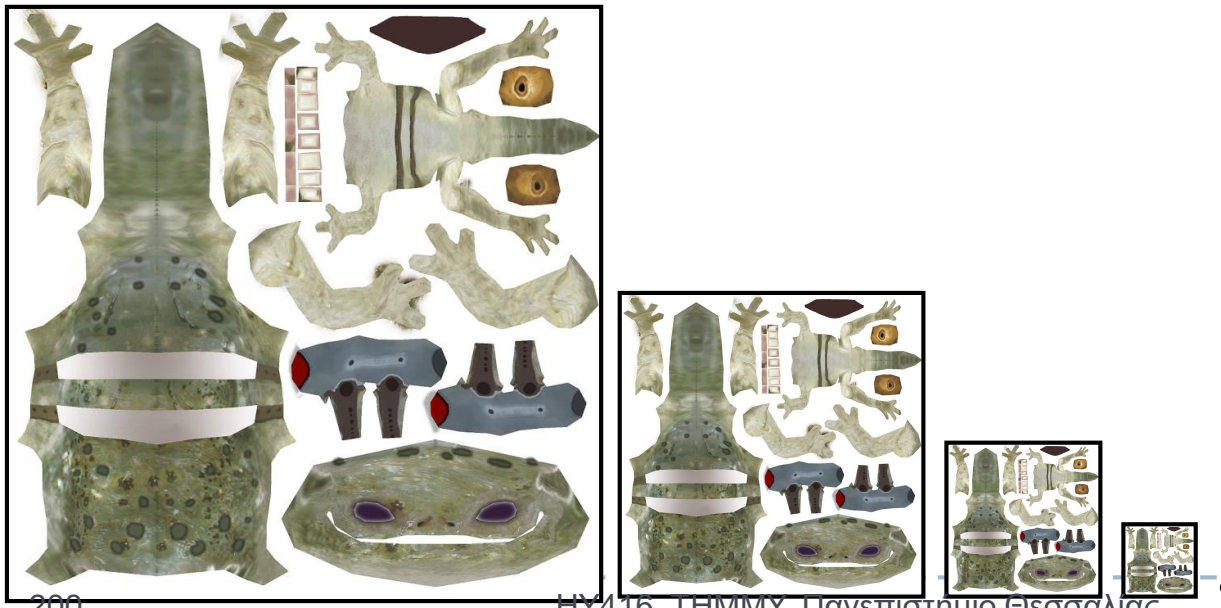
Displacement Mapping Example





Mipmapping

- Set of down-sampled textures
- Pick one based on size of sampling region
- Speed up rendering processing



Αναφορές

- CSCE 441: Computer Graphics, TAMU, Jinxiang Chai.
- Computer Graphics, Brown Univ.

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