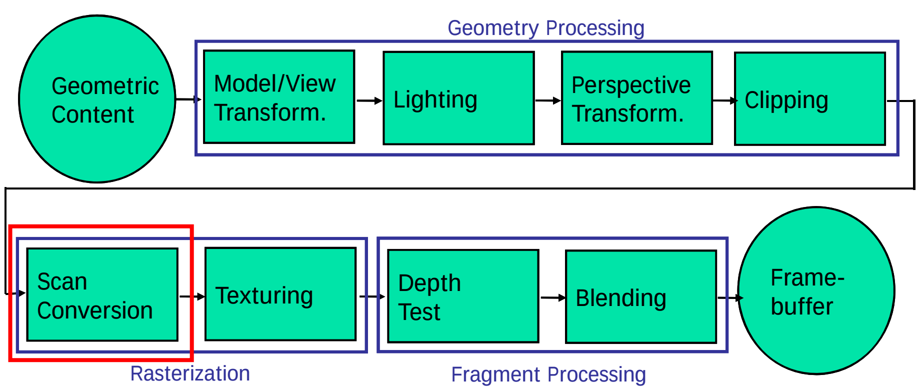
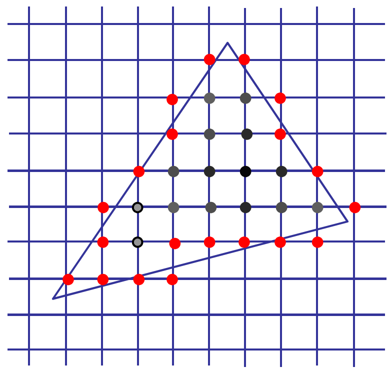
Chapter 9

**Scan Conversion (part 2)–
Drawing Polygons on Raster
Display**

Rendering Pipeline

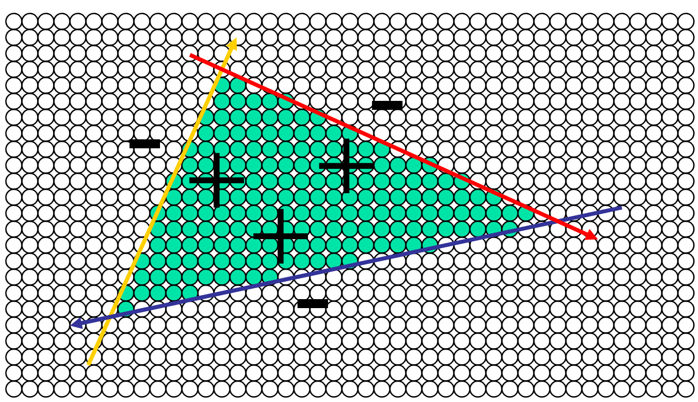


Triangle/Polygon Rasterization



Implicit Formulation

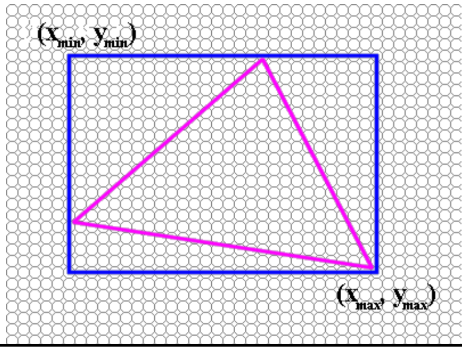
- Triangle (convex polygon) = intersection of edge half-spaces
  - Defined by set of implicit line equations



Using Implicit Edge Equations

Usage:

- Go over each pixel on screen
  - To be efficient restrict to bounding rectangle
- Check if pixel is inside/outside of triangle
  - Use sign of edge equations



Computing Edge Equations

- Implicit equation of a triangle edge:

$$L(x,y) = \frac{(y_e - y_s)}{(x_e - x_s)}(x - x_s) - (y - y_s) = 0$$

- see Bresenham algorithm
- L(x,y) positive on one side of edge, negative on the other
- Question:
  - What happens for vertical lines?

Edge Equations

- Multiply with denominator

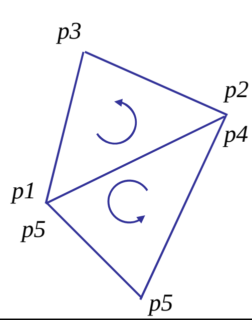
$$L(x,y) = (y_e - y_s)(x - x_s) - (y - y_s)(x_e - x_s) = 0$$

  - Avoids singularity
  - Works with vertical lines

- What about the sign?
  - Which side is in, which is out?

Edge Equations

- Determining the sign
  - Which side is "in" and which is "out" depends on order of start/end vertices…
  - Convention: specify vertices in counter-clockwise order



Edge Equations

- Counter-Clockwise Triangles
  - The equation L(x,y) as specified above is *negative inside, positive outside*
    - *Flip sign:*

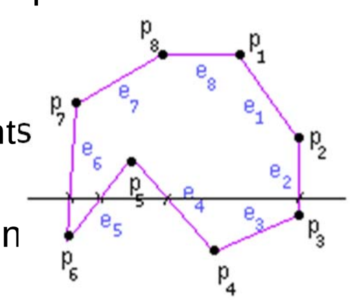
$$L(x,y) = -(y_e - y_s)(x - x_s) + (y - y_s)(x_e - x_s) = 0$$

- *Clockwise triangles*
  - *Use original formula*

$$L(x,y) = (y_e - y_s)(x - x_s) - (y - y_s)(x_e - x_s) = 0$$

Scan Conversion of Polygons

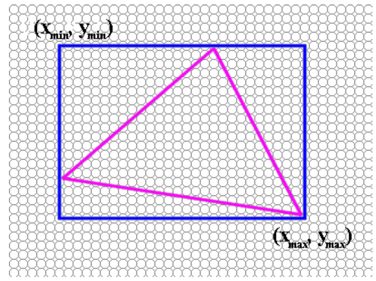
- Implicit formulation doesn't work for non-convex polygons
- Require per pixel, per edge computation
- Observation:
  - Straight line intersection with polygon = set of segments

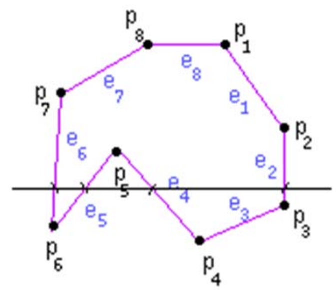


- Alternative: algorithm based on scan-line/edge intersections
  - Works for **general** polygons
  - Less per pixel computations

Scan Conversion of Polygons

- General Algorithm
  - Intersect each scanline with all edges
  - Sort intersections in x
  - Calculate parity to determine in/out
  - Fill the 'in' pixels
  - Efficiency improvement:
    - Exploit row-to-row coherence using "edge table"

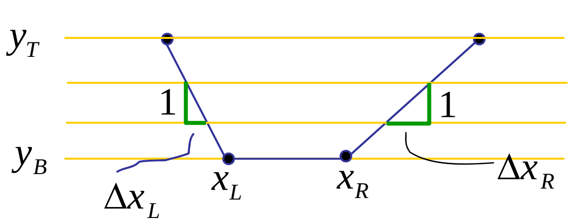




Edge Walking

- Special case: Scan-converting a trapezoid
  - Exploit continuous L and R edges
    - Predict intersections from one line to next

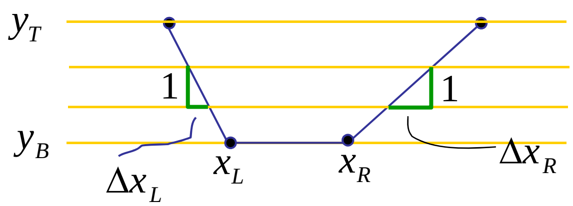
scanTrapezoid(x_L ,x_R ,y_B,y_T, Δx_L , Δx_R)



Edge Walking

scanTrapezoid($x_L, x_R, y_B, y_T, \Delta x_L, \Delta x_R$)

```
for (y=yB; y<=yT; y++) {
   for (x=xL; x<=xR; x++)
    setPixel(x,y);
   xL += DxL;
   xR += DxR;
}
```

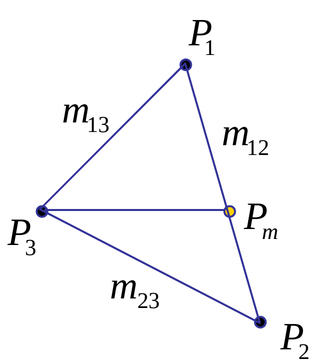


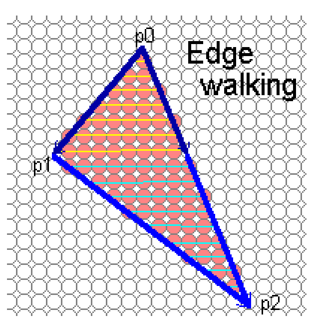
Edge Walking Triangles

- Split triangles into two “trapezoids” with continuous left and right edges

scanTrapezoid($x_3, x_m, y_3, y_1, \frac{1}{m_{13}}, \frac{1}{m_{12}}$)

scanTrapezoid($x_2, x_2, y_2, y_3, \frac{1}{m_{23}}, \frac{1}{m_{12}}$)





Edge Walking Triangles

Issues

- Many applications have small triangles
  - Setup cost is non-trivial
- Clipping triangles produces non-triangles
  - Can be avoided through re-triangulation

Discussion

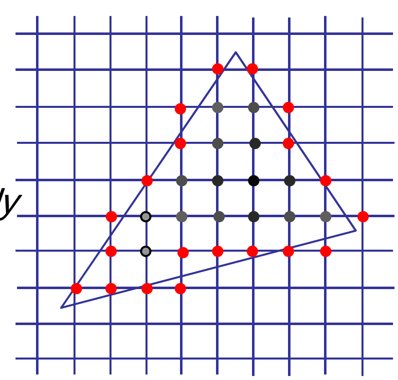
- Old hardware:
  - Use edge-walking algorithm
    - Scan-convert edges, then fill in scanlines
    - Compute interpolated values by interpolating along edges, then scanlines
  - Requires clipping of polygons against viewing volume
  - Faster if you have a few, large polygons
  - Possibly faster in software

Discussion:

- Modern GPUs:
  - Use edge equations
    - Plus plane equations for attribute interpolation
    - No clipping of primitives required
  - Faster with many small triangles
- Additional advantage:
  - Can control the order in which pixels are processed
  - Allows for more memory-coherent traversal orders
    - E.g. tiles or space-filling curve rather than scanlines

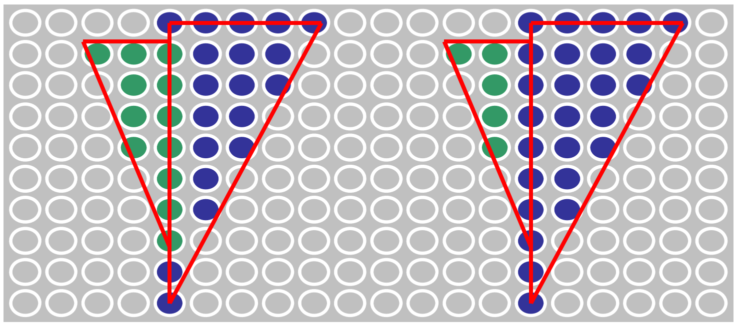
Rasterization Issues (Independent of Algorithm)

- Exactly which pixels should be lit?
  - Those pixels inside the triangle edge (of course)
  - *But what about pixels exactly on the edge?*
    - Don't draw them: gaps possible between triangles
    - Draw them: order of triangles matters



Triangle Rasterization Issues

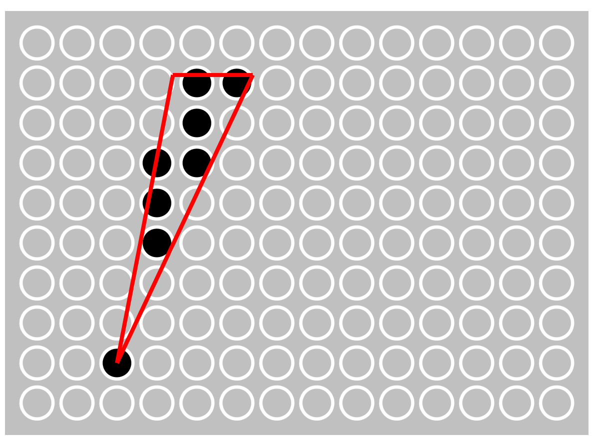
- Shared Edge Ordering



- Need a consistent (if arbitrary) rule
  - Example: draw pixels on left or top edge, but not on right or bottom edge

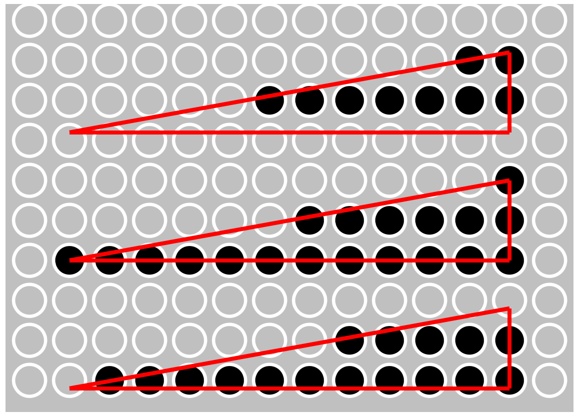
Triangle Rasterization Issues

- Sliver



Triangle Rasterization Issues

- Moving Slivers



Triangle Rasterization Issues

- These are ALIASING Problems
  - Problems associated with representing continuous functions (triangles) with finite resolution (pixels)
  - More on this problem when we talk about sampling…

Values in the interior

Barycentric coordinates

Interpolation – access triangle interior

- Interpolate between vertices:
  - z
  - r,g,b - colour components
  - u,v - texture coordinates
  - N_x, N_y, N_z - surface normals
- Equivalent
  - Barycentric coordinates
  - Bilinear interpolation
  - Plane Interpolation

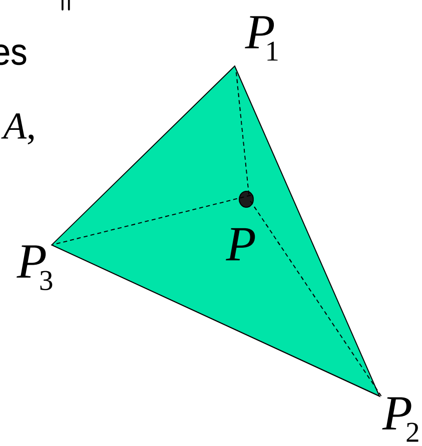
Barycentric Coordinates

- Area

$$A = \frac{1}{2}\left\| \overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} \right\|$$

- Barycentric coordinates

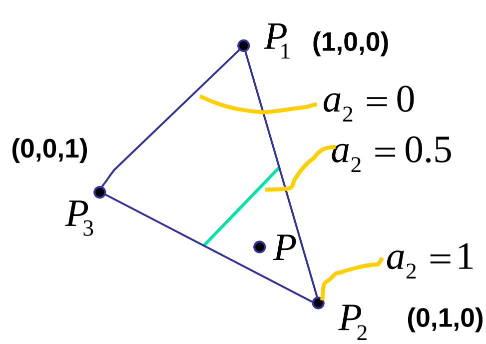
$$a_1 = A_{P_2P_3P} / A, a_2 = A_{P_3P_1P} / A,$$
$$a_3 = A_{P_1P_2P} / A,$$
$$P = a_1P_1 + a_2P_2 + a_3P_3$$



Barycentric Coordinates

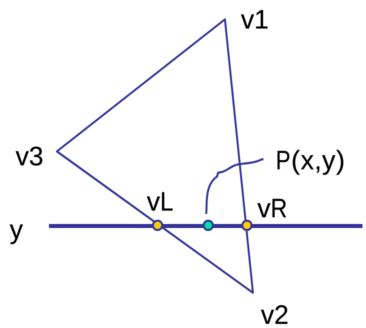
- weighted combination of vertices

$$P = a_1 \cdot P_1 + a_2 \cdot P_2 + a_3 \cdot P_3$$
$$a_1 + a_2 + a_3 = 1$$
$$0 \le a_1, a_2, a_3 \le 1$$

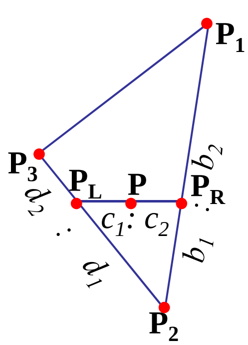


Alternative formula: Bi-Linear Interpolation

- Interpolate quantity along L and R edges
  - (as a function of y)
  - Then interpolate quantity as a function of x



Bi-Linear interpolation



- Formulation

$$P = \frac{c_2}{c_1+c_2}\cdot P_L + \frac{c_1}{c_1+c_2}\cdot P_R$$

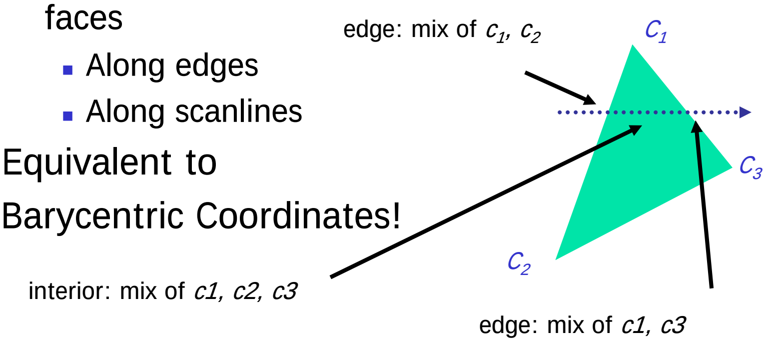
$$P_L = \frac{d_2}{d_1+d_2}P_2 + \frac{d_1}{d_1+d_2}P_3$$

$$P_R = \frac{b_2}{b_1+b_2}P_2 + \frac{b_1}{b_1+b_2}P_1$$

$$P = \frac{c_2}{c_1+c_2}\left(\frac{d_2}{d_1+d_2}P_2 + \frac{d_1}{d_1+d_2}P_3\right) + \frac{c_1}{c_1+c_2}\left(\frac{b_2}{b_1+b_2}P_2 + \frac{b_1}{b_1+b_2}P_1\right)$$

Bi-Linear Interpolation

- Most common approach, and what OpenGL does
  - Perform Phong lighting at the vertices
  - Linearly interpolate the resulting colors over faces
    - Along edges
    - Along scanlines
- Equivalent to Barycentric Coordinates!

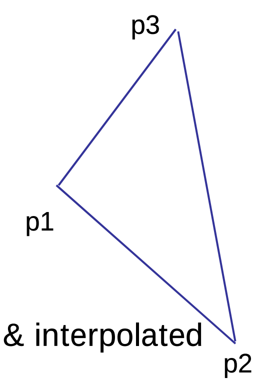


Another Alternative: Plane Equation

- Observation: Values vary linearly in image plane
  - E.g.: r = Ax + By + C
    - r= red channel of the color
    - Same for g, b, Nx, Ny, Nz, z...
  - From info at vertices we know:

$$r_1 = Ax_1 + By_1 + C$$
$$r_2 = Ax_2 + By_2 + C$$
$$r_3 = Ax_3 + By_3 + C$$

    - Solve for A, B, C
    - One-time set-up cost per triangle & interpolated value



Discussion

- Which algorithm (formula) to use when?
  - Bi-linear interpolation
    - Together with trapezoid scan conversion
  - Plane equations
    - Together with implicit (edge equation) scan conversion
  - Barycentric coordinates
    - Too expensive in current context
    - But: method of choice for ray-tracing
      - Whenever you only need to compute the value for a single pixel

Validation

- All formulations should provide same value
- Can verify barycentric properties

$$a_1 + a_2 + a_3 = 1$$
$$0 \le a_1, a_2, a_3 \le 1$$

Shading

Computing lighting impact inside triangle interior

Shading

- Input to Scan Conversion:
  - Vertices of triangles (lines, quadrilaterals…)
  - Color (per vertex)
    - Specified with glColor
    - Or: computed with lighting
  - World-space normal (per vertex)
    - Left over from lighting stage
- Shading Task:
  - Determine color of every pixel in the triangle

Shading

- How can we assign pixel colors using this information?
  - Easiest: flat shading
    - Whole triangle gets one color (color of 1st vertex)
  - Better: Gouraud shading
    - Linearly interpolate color across triangle
  - Even better: Phong shading
    - Linearly interpolate the normal vector
    - Compute lighting for every pixel
    - Note: not supported by rendering pipeline as discussed so far

Flat Shading

- Simplest approach: calculate illumination at one point per polygon (e.g. center)

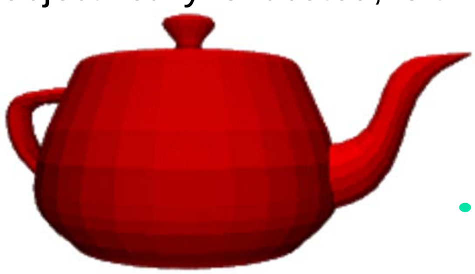
- Obviously inaccurate for smooth surfaces

Flat Shading Approximations

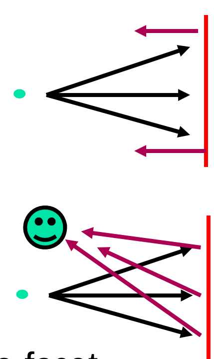
- If an object really is faceted, is this accurate?

Flat Shading Approximations

- If an object really is faceted, is this accurate?



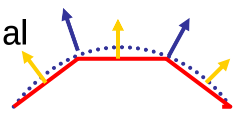
- no!
  - For point sources, direction to light varies across the facet
  - For specular reflectance, direction to eye varies across the facet



Improving Flat Shading

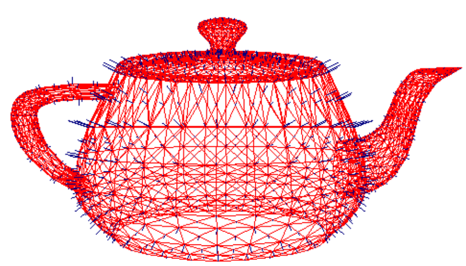
- What if we evaluate Phong lighting model at each pixel of the polygon?
  - Better, but result still clearly faceted

- Gouraud Shading: For smoother-looking surfaces introduce vertex normals at each vertex
  - Usually different from facet normal
  - Used only for shading
  - Think of as a better approximation of the real surface that the polygons approximate



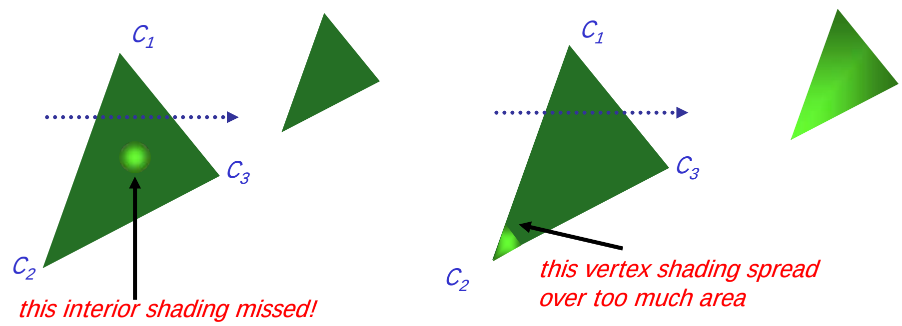
Vertex Normals

- Vertex normals may be
  - Provided with the model
  - Computed from first principles
  - Approximated by averaging the normals of the facets that share the vertex



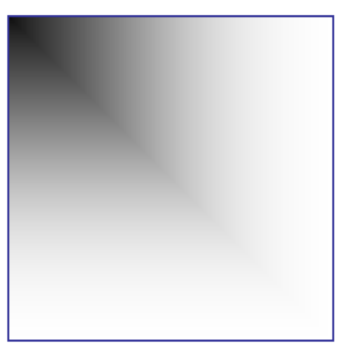
Gouraud Shading Artifacts

- Often appears dull, chalky
- Lacks accurate specular component
  - if included, will be averaged over entire polygon



Gouraud Shading Artifacts

- Mach bands
  - Eye enhances discontinuity in first derivative
  - Very disturbing, especially for highlights



Phong Shading

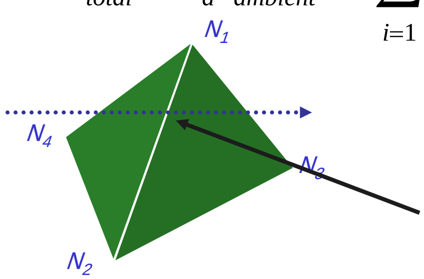
- linearly interpolating surface normal across the facet, applying Phong lighting model at every pixel
  - Same input as Gouraud shading
  - Pro: much smoother results
  - Con: considerably more expensive

- Not the same as Phong lighting
  - Common confusion
  - Phong lighting: empirical model to calculate illumination at a point on a surface

Phong Shading

- Linearly interpolate the vertex normals
  - Compute lighting equations at each pixel
  - Can use specular component

$$I_{total} = k_a I_{ambient} + \sum_{i=1}^{\#lights} I_i \left(k_d (\mathbf{n} \cdot \mathbf{l_i}) + k_s (\mathbf{v} \cdot \mathbf{r_i})^{n_{shiny}} \right)$$



remember: normals used in diffuse and specular terms

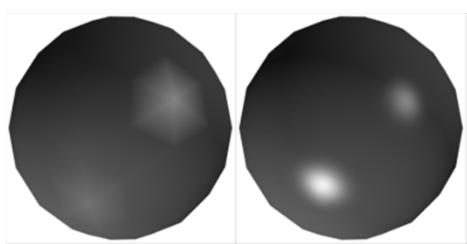
discontinuity in normal's rate of change harder to detect

Phong Shading Difficulties

- Computationally expensive
  - Per-pixel vector normalization and lighting computation!
  - Floating point operations required
- Lighting after perspective projection
  - Messes up the angles between vectors
  - Have to keep eye-space vectors around
- No direct support in standard rendering pipeline
  - But can be simulated with texture mapping, procedural shading hardware (see later)

Shading Artifacts: Silhouettes

- Polygonal silhouettes remain



Gouraud *Phong*