University of British Columbia
CPSC 314 Computer Graphics
Jan-Apr 2010

Tamara Munzner

## Vision/Color II, Rasterization

## Week 6, Mon Feb 8

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2010

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Department of Computer Science
Undergraduate Events

**Events this week**

**Schlumberger Info Session**
Date: Mon., Feb 8
Time: 5:30 pm
Location: HENN Rm 201

**Finding a Summer Job or Internship Info Session**
Date: Wed., Feb 10
Time: 12 pm
Location: X836

**Masters of Digital Media Program Info Session**
Date: Thurs., Feb 11
Time: 12:30 – 1:30 pm
Location: DMP 201

**Reminder: Co-op Deadline**
Date: Fri., Feb 12
Submit application to Fiona at Rm X241 by 4:30 pm



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## News

- TA office hours in lab for P2/H2 questions this week
  - Mon 3-5 (Shailen)
  - Tue 3:30-5 (Kai)
  - Wed 3-5 (Shailen)
  - Thu 3-5 (Kai)
  - Fri 2-4 (Garrett)
- again - start **now**, do not put off until late in break!



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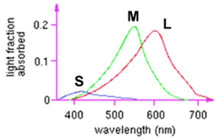
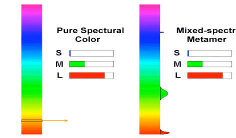
## Review: Trichromacy and Metamers

- three types of cones
- color is combination of cone stimuli
  - metamer: identically perceived color caused by very different spectra



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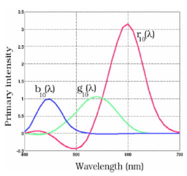
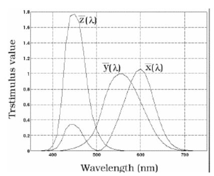
## Review: Measured vs. CIE Color Spaces




- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes
- transformed basis
  - "imaginary" lights
  - all positive, unit area
  - Y is luminance



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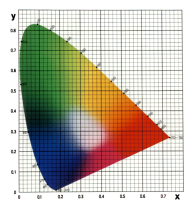
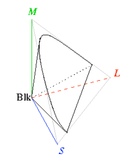
## Review: Chromaticity Diagram

- plane of equal brightness showing chromaticity





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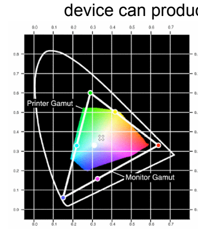
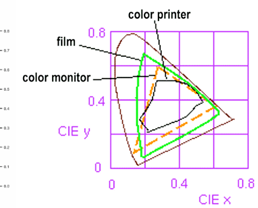
## Device Color Gamuts

- gamut is polygon, device primaries at corners
  - defines reproducible color range
  - X, Y, and Z are hypothetical light sources, no device can produce entire gamut



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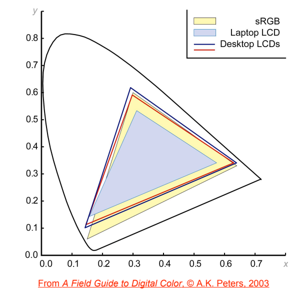
## Display Gamuts




From A Field Guide to Digital Color, © A.K. Peters, 2003



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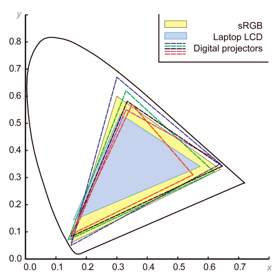
## Projector Gamuts




From A Field Guide to Digital Color, © A.K. Peters, 2003



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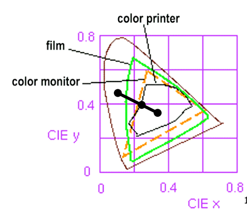
## Gamut Mapping

- how to handle colors outside gamut?
  - one way: construct ray to white point, find closest displayable point within gamut



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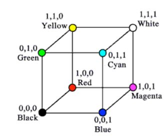
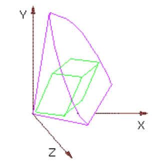
## RGB Color Space (Color Cube)

- define colors with (r, g, b) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric
- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube



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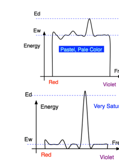
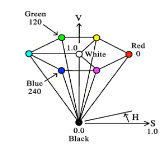
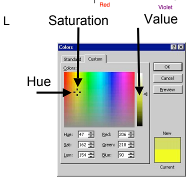
## HSV Color Space

- more intuitive color space for people
  - H = Hue
    - dominant wavelength, "color"
  - S = Saturation
    - how far from grey/white
  - V = Value
    - how far from black/white
    - also: brightness B, intensity I, lightness L





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## HSI/HSV and RGB

- HSV/HSI conversion from RGB not expressible in matrix
  - H=hue same in both
  - V=value is max, I=intensity is average

$$H = \cos^{-1}\left[\frac{\frac{1}{2}[(R-G)+(R-B)]}{\sqrt{(R-G)^2+(R-B)(G-B)}}\right] \quad \text{if } (B > G),\quad H = 360 - H$$

HSI: $S = 1 - \dfrac{\min(R,G,B)}{I}$ $\quad I = \dfrac{R+G+B}{3}$

HSV: $S = 1 - \dfrac{\min(R,G,B)}{V}$ $\quad V = \max(R,G,B)$



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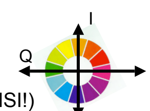
## YIQ Color Space




- color model used for color TV
  - Y is luminance (same as CIE)
  - I & Q are color (not same I as HSI!)
  - using Y backwards compatible for B/W TVs
  - conversion from RGB is linear
    - expressible with matrix multiply

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- green is much lighter than red, and red lighter than blue



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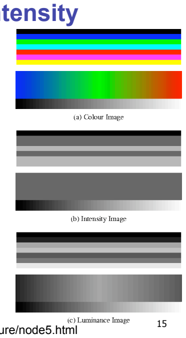
## Luminance vs. Intensity

- luminance
  - Y of YIQ
  - 0.299R + 0.587G + 0.114B
  - captures important factor
- intensity/brightness
  - I/V/B of HSI/HSV/HSB
  - 0.333R + 0.333G + 0.333B
  - not perceptually based



(a) Colour Image

(b) Intensity Image

(c) Luminance Image

www.csse.uwa.edu.au/~robyn/Visioncourse/colour/lecture/node5.html



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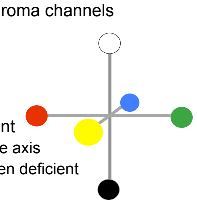
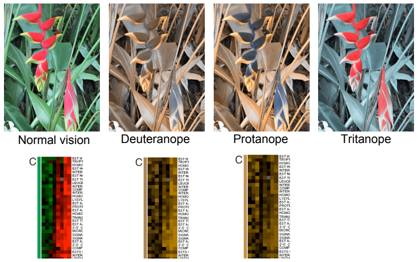
## Opponent Color

- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
- first level encoding
  - linear combination of LMS
  - before optic nerve
  - basis for perception
  - "color blind" = color deficient
    - degraded/no acuity on one axis
    - 8%-10% men are red/green deficient



## vischeck.com

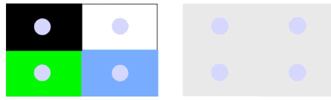
- simulates color vision deficiencies






## Color/Lightness Constancy

- color perception depends on surrounding
  - colors in close proximity
    - simultaneous contrast effect



  - illumination under which the scene is viewed



## Color/Lightness Constancy

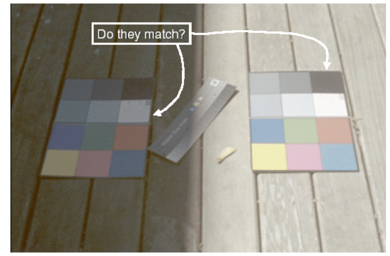



Image courtesy of John McCann



## Color/Lightness Constancy

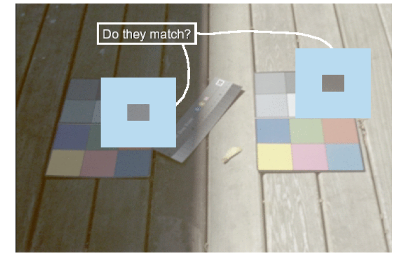
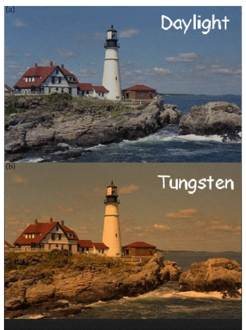



Image courtesy of John McCann



## Color Constancy

- automatic “white balance” from change in illumination
- vast amount of processing behind the scenes!
- colorimetry vs. perception




From Color Appearance Models, fig 8-1

## Stroop Effect

- red
- blue
- orange
- purple
- green



## Stroop Effect

- blue
- green
- purple
- red
- orange

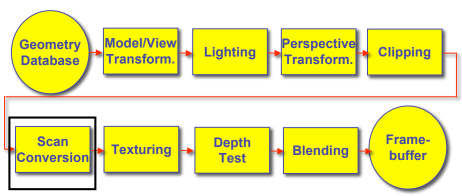
- interplay between cognition and perception



## Rasterization



## Rendering Pipeline





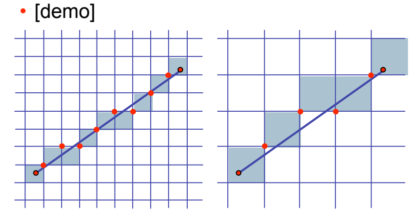

## Scan Conversion - Rasterization

- convert continuous rendering primitives into discrete fragments/pixels
  - lines
    - midpoint/Bresenham
  - triangles
    - flood fill
    - scanline
    - implicit formulation
  - interpolation



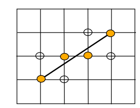
## Scan Conversion

- given vertices in DCS, fill in the pixels
- display coordinates required to provide scale for discretization
  - [demo]





## Basic Line Drawing



$$y = mx + b$$

$$y = \frac{(y_1 - y_0)}{(x_1 - x_0)}(x - x_0) + y_0$$

- goals
  - integer coordinates
  - thinnest line with no gaps
- assume
  - $x_0 < x_1$ slope $0 < {dy}/{dx} < 1$
  - one octant, other cases symmetric
- how can we do this more quickly?

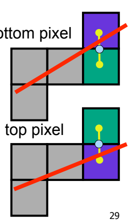
**Line** ( $x_0, y_0, x_1, y_1$ )
begin
float $dx, dy, x, y, slope$;
$dx \Leftarrow x_1 - x_0$;
$dy \Leftarrow y_1 - y_0$;
$slope \Leftarrow {dy}/{dx}$;
$y \Leftarrow y_0$
for $x$ from $x_0$ to $x_1$ do
begin
**PlotPixel** ( $x$, **Round** ($y$) );
$y \Leftarrow y + slope$;
end;
end;

## Midpoint Algorithm

- we're moving horizontally along x direction
  - only two choices: draw at current y value, or move up vertically to y+1?
    - check if midpoint between two possible pixel centers above or below line
- candidates
  - top pixel: (x+1,y+1)
  - bottom pixel: (x+1, y)
- midpoint: (x+1, y+.5)
- check if midpoint above or below line
  - below: pick top pixel
  - above: pick bottom pixel
- key idea behind Bresenham
  - [demo]

above: bottom pixel

below: top pixel





## Making It Fast: Reuse Computation

- midpoint: if f(x+1, y+.5) < 0 then y = y+1
- on previous step evaluated f(x-1, y-.5) or f(x-1, y+.05)
- f(x+1, y) = f(x,y) + ($y_0$-$y_1$)
- f(x+1, y+1) = f(x,y) + ($y_0$- $y_1$) + ($x_1$- $x_0$)

```
y=y0
d = f(x0+1, y0+.5)
for (x=x0; x <= x1; x++) {
  draw(x,y);
  if (d<0) then {
   y = y + 1;
   d = d + (x1 - x0) + (y0 - y1)
  } else {
   d = d + (y0 - y1)
}
```



## Making It Fast: Integer Only

- avoid dealing with non-integer values by doubling both sides

```
y=y0
d = f(x0+1, y0+.5)
for (x=x0; x <= x1; x++)
  {
  draw(x,y);
  if (d<0) then {
   y = y + 1;
   d = d + (x1 - x0) +
           (y0 - y1)
  } else {
   d = d + (y0 - y1)
}
```

```
y=y0
2d = 2*(y0-y1)(x0+1) +
      (x1-x0)(2y0+1) +
      2x0y1 - 2x1y0
for (x=x0; x <= x1; x++) {
  draw(x,y);
  if (d<0) then {
   y = y + 1;
   d = d + 2(x1 - x0) +
           2(y0 - y1)
  } else {
   d = d + 2(y0 - y1)
}
```

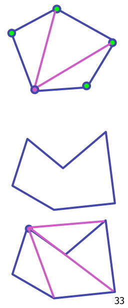


## Rasterizing Polygons/Triangles

- basic surface representation in rendering
- why?
  - lowest common denominator
    - can approximate any surface with arbitrary accuracy
      - all polygons can be broken up into triangles
  - guaranteed to be:
    - planar
    - triangles - convex
  - simple to render
    - can implement in hardware

## Triangulating Polygons

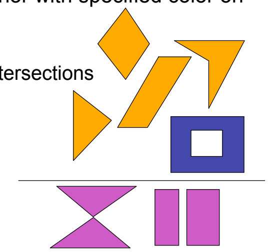
- simple convex polygons
  - trivial to break into triangles
  - pick one vertex, draw lines to all others not immediately adjacent
  - OpenGL supports automatically
    - glBegin(GL_POLYGON) ... glEnd()
- concave or non-simple polygons
  - more effort to break into triangles
  - simple approach may not work
  - OpenGL can support at extra cost
    - gluNewTess(), gluTessCallback(), ...





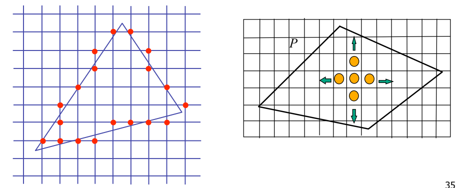
## Problem

- input: closed 2D polygon
- problem: fill its interior with specified color on graphics display
- assumptions
  - simple - no self intersections
  - simply connected
- solutions
  - flood fill
  - edge walking



## Flood Fill

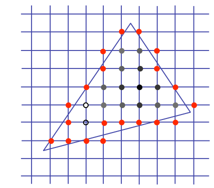
- simple algorithm
  - draw edges of polygon
  - use flood-fill to draw interior






## Flood Fill

- start with seed point
  - recursively set all neighbors until boundary is hit





## Flood Fill

- draw edges
- run:

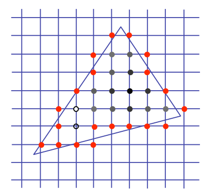
```
FloodFill(Polygon P, int x, int y, Color C)
if not (OnBoundary(x,y,P) or Colored(x,y,C))
begin
    PlotPixel(x,y,C);
    FloodFill(P,x+1,y,C);
    FloodFill(P,x,y+1,C);
    FloodFill(P,x,y-1,C);
    FloodFill(P,x-1,y,C);
end ;
```

- drawbacks?



## Flood Fill Drawbacks

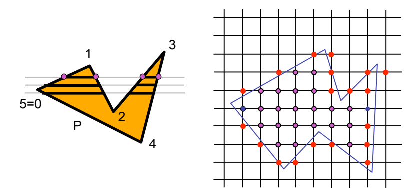
- pixels visited up to 4 times to check if already set
- need per-pixel flag indicating if set already
  - must clear for every polygon!





## Scanline Algorithms

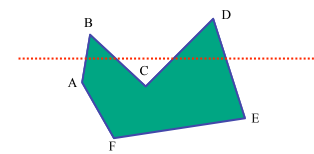
- scanline: a line of pixels in an image
  - set pixels inside polygon boundary along horizontal lines one pixel apart vertically






## General Polygon Rasterization

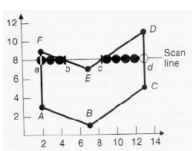
- how do we know whether given pixel on scanline is inside or outside polygon?






## General Polygon Rasterization

- idea: use a parity test

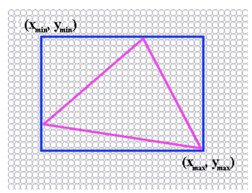



```
for each scanline
    edgeCnt = 0;
    for each pixel on scanline (l to r)
        if (oldpixel->newpixel crosses edge)
            edgeCnt ++;
        // draw the pixel if edgeCnt odd
        if (edgeCnt % 2)
            setPixel(pixel);
```



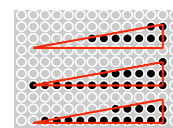
## Making It Fast: Bounding Box

- smaller set of candidate pixels
  - loop over xmin, xmax and ymin,ymax instead of all x, all y

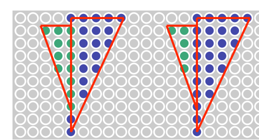



## Triangle Rasterization Issues

- moving slivers



- shared edge ordering





## Triangle Rasterization Issues

- *exactly which pixels should be lit?*
  - pixels with centers inside triangle edges
- *what about pixels exactly on edge?*
  - draw them: order of triangles matters (it shouldn't)
  - don't draw them: gaps possible between triangles
- need a consistent (if arbitrary) rule
  - example: draw pixels on left or top edge, but not on right or bottom edge
  - example: check if triangle on same side of edge as offscreen point



## Interpolation



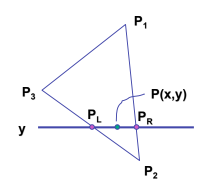
## Interpolation During Scan Conversion

- drawing pixels in polygon requires interpolating many values between vertices
  - r,g,b colour components
    - use for shading
  - z values
  - u,v texture coordinates
  - $N_x, N_y, N_z$ surface normals
- equivalent methods (for triangles)
  - bilinear interpolation
  - barycentric coordinates



## Bilinear Interpolation

- interpolate quantity along $L$ and $R$ edges, as a function of $y$
  - then interpolate quantity as a function of $x$

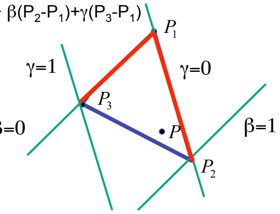




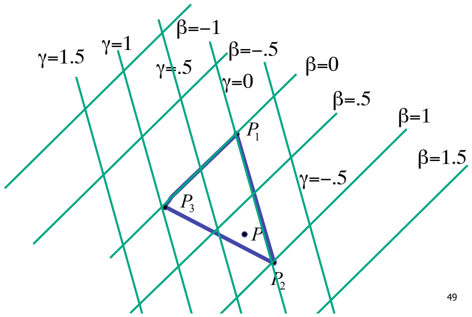

## Barycentric Coordinates

- non-orthogonal coordinate system based on triangle itself
  - origin: $P_1$, basis vectors: $(P_2-P_1)$ and $(P_3-P_1)$

$P = P_1 + \beta(P_2-P_1)+\gamma(P_3-P_1)$



## Barycentric Coordinates





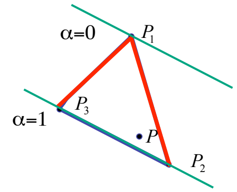

## Barycentric Coordinates

- non-orthogonal coordinate system based on triangle itself
  - origin: $P_1$, basis vectors: $(P_2-P_1)$ and $(P_3-P_1)$

$P = P_1 + \beta(P_2-P_1)+\gamma(P_3-P_1)$

$P = (1-\beta-\gamma)P_1 + \beta P_2+\gamma P_3$

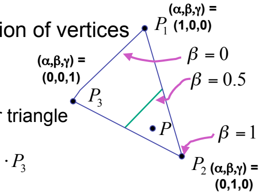
$P = \alpha P_1 + \beta P_2+\gamma P_3$






## Using Barycentric Coordinates

- weighted combination of vertices
  - smooth mixing
  - speedup
    - compute once per triangle



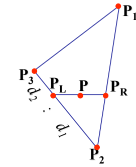

$$\begin{cases} P = \alpha \cdot P_1 + \beta \cdot P_2 + \gamma \cdot P_3 \\ \alpha + \beta + \gamma = 1 \\ 0 \le \alpha, \beta, \gamma \le 1 \text{ for points inside triangle} \end{cases}$$

"convex combination of points"



## Deriving Barycentric From Bilinear

- from bilinear interpolation of point P on scanline




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

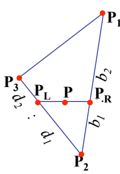
$$= (1 - \frac{d_1}{d_1+d_2})P_2 + \frac{d_1}{d_1+d_2}P_3 =$$

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



## Deriving Barycentric From Bilineaer

- similarly




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

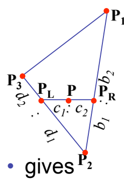
$$= (1 - \frac{b_1}{b_1+b_2})P_2 + \frac{b_1}{b_1+b_2}P_1 =$$

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



## Deriving Barycentric From Bilinear

- combining




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

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

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

- gives

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



## Deriving Barycentric From Bilinear

- thus $P = \alpha P_1 + \beta P_2 + \gamma P_3$ with

$$\alpha = \frac{c_1}{c_1+c_2}\frac{b_1}{b_1+b_2}$$

$$\beta = \frac{c_2}{c_1+c_2}\frac{d_2}{d_1+d_2} + \frac{c_1}{c_1+c_2}\frac{b_2}{b_1+b_2}$$

$$\gamma = \frac{c_2}{c_1+c_2}\frac{d_1}{d_1+d_2}$$

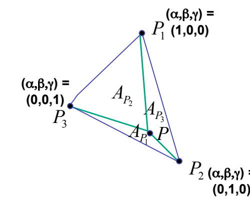
- can verify barycentric properties

$$\alpha + \beta + \gamma = 1, \qquad 0 \le \alpha, \beta, \gamma \le 1$$



## Computing Barycentric Coordinates

- 2D triangle area
  - half of parallelogram area
    - from cross product




$A = A_{P1} + A_{P2} + A_{P3}$

$\alpha = A_{P1}/A$

$\beta = A_{P2}/A$

$\gamma = A_{P3}/A$