

CSCE 441 Computer Graphics

scan conversion of lines

- horizontal, vertical lines are easy
- for general lines, assume $0 < slope < 1$ (flat to diagonal)
 - you can transform any line to fit this
- naive algorithm would just use floating point and round off
 - floating point is sometimes slow (especially back when not every computer did it in hardware)
- slope from two points:

$$m = \frac{y_H - y_L}{x_H - x_L} a$$

- $s \frac{a}{b}$
- intercept from two points: $b = y_L - m * x_L$
- **Simple Algorithm**
 - start from (xL, yL) and draw to (xH, yH)
 - * where $xL < xH$
 - ```
def draw_line(xL, yL, xH, yH):
 x, y = (xL, yL)
 for i in range(0, xH - xL):
 draw_pixel(x, round(y))
 x = x + 1
 y = m * x + b # simplifies to
 y = y + m
```

- problem: uses floating point math
- problem: rounding

- **Midpoint Algorithm**
  - given a point, we just need to know whether we will move right or up and right on the next step (N or NE)
  - we can simplify this to whether the actual line travels above or below the point  $(x + 1, y + 1/2)$ 
    - \* so we derive formula from  $y = m * x + b$
  - formula:  $f(x, y) = c * x + d * y + e$ 
    - \*  $c = yL - yH$
    - \*  $d = xL - xH$
    - \*  $e = b * (xL - xH)$
    - \*  $f(x, y) = 0$ :  $(x, y)$  is on the line
    - \*  $f(x, y) < 0$ :  $(x, y)$  below line
    - \*  $f(x, y) > 0$ :  $(x, y)$  above line
  - don't want to recalculate formula at every step, so do it iteratively
    - \* that is, use  $f(x + 1, y + 1/2)$  to calculate  $f(x + 2, y + 1/2)$  or  $f(x + 2, y + 3/2)$  depending on right or up-right choice last time
  - went right last time, now calculate  $f(x + 2, y + 1/2)$

- \*  $f(x + 2, y + 1/2) = c + f(x + 1, y + 1/2)$
- went up-right last time, now calculate  $f(x + 2, y + 1/2)$ 
  - \*  $f(x + 2, y + 3/2) = c + d + f(x + 1, y + 1/2)$
- starting value:  $f(x + 1, y + 1/2) = f(xL, yL) + c + (1/2)d = c + (1/2)d$ 
  - \* we can eliminate  $f(xL, yL)$  because we know it is on the line
  - \* furthermore, we can use  $f(x + 1, y + 1/2) = 2 * c + d$  because multiplying by 2 does not change the sign of  $f$ . Also, this saves an expensive division
- full algorithm:
 

```
def midpoint_algorithm_line(xL, yL, xH, yH):
 x = xL
 y = yL
 d = xH - xL
 c = yL - yH
 sum = 2*c + d
 draw_pixel(x,y)
 while x < xH:
 if sum < 0:
 sum += 2*d
 y += 1
 x += 1
 sum += 2*c
 draw_pixel(x,y)
```
- pro:
  - \* only integer operations
  - \* extends to other kinds of shapes, just need formula to tell if inside/outside shape (called implicit formula)
- same as Bresenham's algorithm (more common algorithm)

## scan conversion of polygons

- to deal with overlap, we do not draw the top and right of a polygon
  - this means artifacts are possible. This doesn't really matter since pixels are very small
- rectangles (aligned with axes) are easy
- scan line: one row of pixels
- general polygons: basic idea (**scanline method**)
  - intersect scan lines with edges of polygon
  - this means you must keep track of which edges intersect with which scan lines
    - \* this is easy to do: just look at the y coordinate
  - consecutive scan lines will usually intersect with a similar set of edges
    - \* so we can use coherence to speed stuff up
  - we can throw out horizontal lines. They are implicitly represented by

- start and end, connecting to the other edges
  - data structures
    - \* edge: maxY, currentX, xIncr (increment)
      - calculate these from the two points
      - xIncr is inverse of slope, but you can't calculate the slope and invert it, because divide by 0
      - maxY: y value of higher point
      - currentX: x value of lower point
    - \* active edge table
      - has entry for every scanline on the screen
      - initialize with edges by indexing by minY of edge
    - \* active edge list
      - stores edges that intersect with the current scan line being processed
      - edges must always be sorted by current x value
  - at each step of the algorithm, you must update the active edge list
    - \* remove edges where maxY is less than or equal to the current scan line
      - less or equal because we don't draw the top and right of the polygon
    - \* add edges from the current scan line to the edge list
    - \* sort all edges by currentX
  - then draw the scan line
    - \* take pairs of edges and fill in between their currentX values
      - do not include the right point (because we don't draw the top and right of the polygon)
    - \* if you ever have an odd number of edges in the active edge list, you made a mistake
  - disadvantages
    - \* does not handle long, thin polygons well
    - \* incremental updates are not suitable for massively parallel GPUs
- boundary fill
  - draw the boundary of the polygon, then fill in interior
    - \* fill in interior wherever it is not the same color as you are drawing
  - need to be sure filling can't escape out from an edge or corner
  - need to be able to choose arbitrary interior point to start from
- flood fill
  - starting at point, recursively replace one color with another
  - paint bucket tool

## openGL data CPU to GPU

- openGL can accept data various ways, with different speed impacts
- speed depends on driver implementation

- GPUs only render triangles, and triangles usually share vertexes with other triangles, so saving lots of bandwidth is possible
- fastest is usually vertex buffer objects?
  - stores data directly on GPU?

## clipping lines

- it's not really possible to draw things that are outside of the viewing area
- clipping points is easy (when comparing to rectangular window)
- clipping lines:
  - if both end points are inside window, draw it
- window intersection method:
  - if either or both is outside, intersect line with each window border in sequence
  - $(x_1, y_1), (x_2, y_2)$  intersect with vertical edge at  $x_{right}$ :  
 $y_{intersect} = y_1 + m * (x_{right} - x_1)$ , where  $m = (y_2 - y_1) / (x_2 - x_1)$
  - $(x_1, y_1), (x_2, y_2)$  intersect with horizontal edge at  $y_{bottom}$ :  
 $x_{intersect} = x_1 + (y_{bottom} - y_1) / m$ , where  $m = (y_2 - y_1) / (x_2 - x_1)$
  - all these intersections are costly to compute
    - \* we would like to efficiently handle trivial accepts and trivial rejects
- cohen-sutherland algorithm
  - classify two points  $p_1, p_2$  using 4-bit codes **c0** and **c1**
  - if **c0** & **c1** != 0: trivial reject
    - \* bitwise AND
    - \* both points are outside one of the boundaries
  - if **c0** | **c1** == 0: trivial accept
    - \* bitwise OR
    - \* none of the coordinates of either point is outside any boundary  
 => line is entirely within window
  - otherwise split line until it is a trivial case
  - bits: | **top** | **bottom** | **right** | **left**
    - \* doesn't matter as long as you're consistent? TODO
    - \* you can determine each of these by just comparing one coordinate with the axes
    - \* thus the comparison is fast
  - disadvantages
    - \* repeated clipping is expensive
  - advantages
    - \* considers all possible trivial accept/reject
- laing-barsky algorithm
  - use parametric form of line for clipping
    - \* means that lines are oriented (have a direction)
  - need to classify lines as moving into or out of the window

- since lines are parametric, we will be finding the parameter value of the intersection
  - \* we can put that back into the formula to get the actual point
- parametric lines
  - \*  $x(t) = x_0 + (x_1 - x_0) * t$
  - \*  $y(t) = y_0 + (y_1 - y_0) * t$
  - \*  $0 \leq t \leq 1$
  - \* solve 2d matrix to intersect lines:
 
$$\begin{bmatrix} x_1 - x_0 & x_2 - x_3 \end{bmatrix} \begin{bmatrix} t \\ s \end{bmatrix} = \begin{bmatrix} x_2 - x_0 \\ y_2 - y_0 \end{bmatrix}$$
- algorithm:
  - \* start with  $t$  on range  $[0, 1]$ 
    - this is  $t_{min}, t_{max}$
  - \* iteratively intersect each line with each edge
    - find intersection at  $t$
    - if line is moving in to out:  $t_{max} = \min(t_{max}, t)$
    - else:  $t_{min} = \max(t_{min}, t)$
    - if  $t_{min} > t_{max}$ : reject line
- moving out vs moving in can be determined by looking at coordinates
  - \* different for each boundary
  - \* e.g. for right boundary,  $x_1 < x_2$  is moving in
  - \* does not depend on where either point is, or whether either point is inside/outside window boundary, just relative positions of the points
- disadvantages
  - \* does not consider trivial accept/reject
- advantages
  - \* computation of  $(x, y)$  is done only once at the end
  - \* computation of parametric intersections is fast (only one division)
- note: clipping line and then rounding to integer coordinates may not produce the correct result, due to round-off error
  - can account for this by calculating sum for use in midpoint algorithm

## clipping polygons

- clipping a polygon can change the number of sides it has
  - minimum number of sides is 3 (triangle)
  - maximum number of sides is  $2n + 1$ ? TODO
  - e.g. maximum number of sides of triangle after clipping is 7 sides
- when clipping convex polygons, you could end up with multiple polygons
- sutherland-hodgman clipping
  - clip polygon vs each edge of window individually
  - TODO can this algorithm handle non-rectangular windows?
  - is not guaranteed to handle convex polygons correctly

- \* does not split into multiple polygons
  - \* but usually looks about right
- output is mixture of old/new vertexes
  - \* will be exactly old vertexes if polygon was entirely inside the window
  - \* will be only new vertexes if all vertexes were outside the window (but not necessarily all edges)
- process each side of the rectangular window separately
  - \* and also, process each edge in polygon iteratively
- 4 cases for an edge from S to E:
  - \* S and E both outside: no output
  - \* S and E both inside: output only E
  - \* S inside, E outside: compute intersection with border, and output that
  - \* S outside, E inside: output intersection with border, and output E
- output of one intersection is used as input for next intersection
  - \* you can kind of do these in parallel, with the partial output from the previous stage
    - pipeline
  - \* then you need a end-of-polygon marker, and you need to use that along with the first edge to make the last edge
- weiler-atherton algorithm
  - general intersection between any two kinds of polygons
  - handles non-convex polygons
    - \* thus can output more than one polygon for a single input polygon
  - not as efficient as sutherland-hodgman
    - \* all those intersections are expensive
    - \* difficult to parallelize
  - algorithm
    - \* start at point on polygon
    - \* follow polygon edges counterclockwise until an edge crosses out of the window
    - \* follow window edges from the intersection point until the polygon intersects again
    - \* now that part is a polygon. Go back to the first intersection point and follow the polygon until it re-enters the window, and find more polygons

## transformations in 2D

- coordinates
  - need point of origin (0,0) and axes (x and y)
  - we want to define transformations generally, without need for coordi-

- nates
  - but hardware uses coordinates, so we must use them eventually
- dot product
  - product of magnitudes and cosine of angle between
    - \* or sum of product of coordinates along each axes
  - when dot product is 0, vectors are perpendicular
- 2d cross product
  - the cross product we normally think of only makes sense in 3d
  - our 2d cross product is just a vector of same magnitude, perpendicular to original
  - unary operation
  - represented by  $v$  superscript perpendicular-sign
  - $vp = (-v.y, v.x)$
  - $v$  dot product with ( $v$  cross product) == 0
- there are two kinds of transformations
  - conformal:
    - \* preserves angles
    - \* translation, rotation, uniform scaling
  - affine
    - \* can be represented by matrix multiplication
    - \* TODO is affine transform a superset of conformal transform?
    - \* translation, rotation, uniform/non-uniform scaling, shear
- translation
  - add a vector to every point
- uniform scaling
  - scale about a point (about an origin) by a scale factor
  - the point (origin) about which you scale will be unaffected by the scaling
  - the farther something is from the point (origin), the more it's position will change
- non-uniform scaling
  - same as uniform scaling, but you now have a vector that you're scaling along
  - so take the vector from transform-origin to point, find parallel to transform vector, and scale that
  - scaling along a vector is not the same as scaling along the x and y components of that vector separately
- rotation
  - $q$  = vector from transform-origin to p
  - new point is transform-origin + linear combination of  $q$  and  $q$ -cross determined by sin and cos of theta
- shear
  - not the same as non-uniform scaling
  - move point in direction of  $v$ , proportional to distance to o perpendicular to  $v$
- reflection

- TODO do we need to know this?
- matrix representation
  - compact
  - allows multiple transforms to be composed to single matrix (efficient)
  - if you have 3 points and those 3 points after some transformation, you can solve for the transformation
    - \* TODO assuming it is an affine transform?
    - \* TODO do we need to know how to solve that on the exam?
- TODO how much of the transformation equations do we need to know?

## fractals and iterated function systems

- affine transform fractal is defined by set of contractive transformations
- contractive transform: transform  $F$  is contractive if for any two compact sets  $X1, X2$ , the distance between them is less after transforming them
  - that is,  $D(F(X1), F(X2)) < D(X1, X2)$
- hausdroff distance:
  - if two sets are equal, their distance is 0
  - distance of a,b is same as distance b,a
  - hausdroff distance is the maximum distance of a point in one set to the closest point in the other
- attractor: shape that fractal approaches after a large (ideally infinite) number of iterations
  - if transforms are contractive, attractor is independent of starting point(s)
- fractal tennis:
  - algorithm to draw fractal by randomly applying transforms to the same point
    - \* but need to iterate point for a few hundred iterations first to get it into the attractor
  - resulting fractal is not perfect
  - can be made better by weighting fractal transform random choice by area
    - \* difficult to calculate the area of a transform (TODO do you just guess?)
- condensation set: basically a thing you add in at every iteration
  - allows shape to build on itself
- fractal dimension
  - like spatial dimension, but for fractals
  - $dim = -\log(\#transformations)/\log(scale\ factor)$
- fractal curves can have infinite length but enclose finite surface area
  - and that's fine
  - fractal paint bucket would not work because paint atoms have finite size



## transformations in 3D

- very similar to transformations in 2d
- things that are the same:
  - dot product, translation, uniform/non-uniform scaling
- cross product
  - now is binary operator
  - produces third vector that is perpendicular to both input vectors
  - magnitude: product of magnitudes and sine of angle between
    - \* mag represents area of 4-sided polygon formed by the two vectors
  - uses special matrix called  $\underline{\quad}$  (underscore)
    - \*  $v \text{ cross } \underline{\quad} =$  put components of  $v$  in special places
    - \* then  $(v \text{ cross } \underline{\quad}) \text{ cross } w == v \text{ cross } w$
- rotation
  - input: axis to rotate about (specified as point and unit vector), theta to rotate
  - thus you're rotating in the plane that is perpendicular to the axis
  - component of  $q$  parallel to axis does not change, perpendicular component is rotated (in plane)
- mirror image
  - the same as non-uniform scaling with  $a = -1$
  - reflect about plane formed by normal vector  $v$  and point  $o$
- orthogonal projection
  - flatten things straight down onto plane
- perspective transformation
  - flatten things onto plane, but as if seen by an observation point  $e$  (an eye)
  - not defined for vectors (depends on where the vector is how much it gets scaled by)
  - **not an affine transformation!**
  - therefore you need to use the bottom row of the matrix also
  - the final 3d location is found by taking the normal 3d output and dividing by the 4th element (a scalar)
- hierarchical animation
  - split body into components joined by joints
  - each joint has a transformation associated with it, so you can apply the transformations corresponding to what position of components you want, and then render that
- skeletal animation
  - skeleton inside model mesh has hierarchical animation stuff
  - every vertex on mesh has a list of weights of how its position depends on transformations of bones
  - thus allowing mesh to deform like the skeleton does
- OpenGL matrices
  - view, model, projection, viewport

- view: position the camera
- model: position model in world
- projection: flatten world into 2d plane
- viewport: transform projection into window pixel coordinates
- opengl uses ModelView matrix
  - \*  $ModelView = V^{-1}M = T^{-1}R^{-1}M$
  - \* viewer always views from origin
    - TODO looking down negative z axis?
  - \* then you push a matrix for the models so that they're positioned correctly

## color

- human eye
  - cornea, iris, lens, retina
  - center of focus is fovea
  - stuff not in fovea (center of focus) is out of focus
    - \* this is different than blurry
    - \* all of the computer screen is in focus, so it can't perfectly replicate out-of-focus things
  - rods
    - \* brightness only
    - \* best response to blue-green light
    - \* mostly in peripheral, not fovea
    - \* more common than cones (100 million in retina)
  - cones
    - \* captures color
    - \* mostly in fovea, few in peripheral
    - \* far fewer overall than rods (6 million)
  - also at the very middle of your eye, where the optic nerve connects, there is no rods or cones
    - \* called blind spot
    - \* brain smooths this out
  - human vision
    - \* center of focus is highly detailed and in color
    - \* peripheral is black and white and less detail
    - \* in general, we can distinguish change in intensity more than change in color
- intensity/luminance: how much light there is
  - like energy
- brightness: perceived intensity
  - color-dependent? TODO?
  - human eye can notice about 1% change in intensity
  - and it's logarithmic

- gamma correction
  - correct for how humans perceive color
  - combining colors is not linear!
    - \* you need to convert to linear space, mix colors, then convert back
  - gamma correction is meant to model old CRT displays
    - \* new displays do the same thing just for compatibility
- dynamic range
  - dynamic range =  $1/(\text{max intensity})$ , where minimum intensity == 1
  - different than contrast
- contrast
  - maximum vs minimum brightness a display can do *at the same time*
- receptor response
  - eye cones respond to 3 specific wavelengths of light
- CIE XYZ system
  - luminance
  - chromaticism
- chromaticity diagram
  - spectral colors
  - saturation
  - hue
  - non-spectral colors
  - combining colors
  - complimentary colors
  - combining 3 colors
- gamut
  - differing gamuts
  - device gamuts
- color models
  - RGB
  - CMY
  - CMYK
  - YIQ/YUV
  - HSV
  - Lab and Luv
  - color representation

## coloring with limited intensities

- thresholding
- halftone/dithering
  - patterns
- dithering
- error diffusion

## lighting

- global illumination
- local illumination
- reflection models
  - ideal specular
  - ideal diffuse
  - specular
- illumination model
  - ambient, diffuse, specular
- ambient
- diffuse
- lambert's law
- specular
  - finding reflected vector
  - n exponent
- multiple sources
- attenuation
- spot lights
- implementation considerations
- openGL
  - normals
  - create/position lights
  - specify material properties
  - select lighting model