Rasterization and Graphics Hardware

CS559 Course Notes

Not for Projection

November 2007, Mike Gleicher

Where does a picture come from?

- Result: image (raster)
- Input 2D/3D model of the world

- Rendering
  - term usually applied to whole scene
  - Implication of caring about quality
- Rasterization
  - term usually applied to individual primitives

Not just about fancy 3D!

- Rendering fonts
  - Really want it to look good
  - Have to do a lot of it
  - Complex shapes
  - Complex aliasing issues (since things are small)

Rendering/Rasterization

- Do the whole scene at once
  - Collect everything
- Do each primitive at a time

- Different algorithms and tradeoffs

When do we care?

- Rasterization
- Usually done by low-level
  - OS / Graphics Library / Hardware
  - Hardware implementations counter-intuitive
    - Modern hardware doesn't work anything like what you'd expect

- High quality rendering
- Really high-quality 2D rendering
- Understanding of how to best use hardware

The simplest case: Points

- Not all that interesting – but good for bringing up aliasing issues

Drawing Points

- What is a point?
  - Position – without any extent
  - Can't see it – since it has no extent, need to give it some
- Position requires co-ordinate system
  - Consider these in more depth later
- How does a point relate to a sampled world?
  - Points at samples?
  - Pick closest sample?
  - Give points finite extent and use little square model?
  - Use proper sampling

Sampling a point

- Point is a spike – need to LPF
  - Gives a circle w/roll-off
- Point sample this
- Or…
  - Samples look in circular (kernel shaped) regions around their position
- But, we can actually record a unique "splat" for any individual point

Anti-Aliasing

- Anti-Aliasing is about avoiding aliasing
  - once you've aliased, you've lost
- Draw in a way that is more precise
  - E.g. points spread out over regions
- Not always better
  - Lose contrast, might not look even if gamma is wrong, might need to go to binary display, …

Line drawing

- Was really important, now, not so important
- Let us replace expensive vector displays with cheap raster ones
- Modern hardware does it differently
  - Actually, doesn't draw lines, draws small, filled polygons
- Historically significant algorithms
- Good for considering issues

Line Drawing (2)

- Consider the integer version
  - (x1,y1) -> (x2,y2) are integers
  - Not anti-aliased (binary decision on pixels)
- Naïve strawman version:
  - Y = mx + b

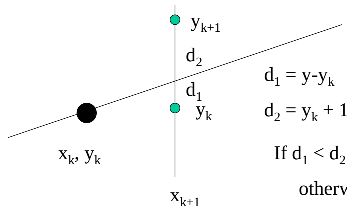
```
For x = x1 to x2
   y = mx + b
   set(x,y)
```

- Problems:
  - Too much math (floating point)
  - gaps

Brezenham's algorithm (and variants)

- Consider only 1 octant (get others by symmetry)
  - 0 >= m > = 1
- Loop over x pixels
  - Guaruntees 1 per column
- For each pixel, either move up 1 or not
  - If you plotted x,y then choose either x+1,y or x+1,y+1
  - Trick: how to decide which one easily
  - Same method works for circles (just need different test)
- Decision variable
  - Implicit equation for line (d=0 means on the line)

Midpoint method



$d_1 = y - y_k$

$d_2 = y_k + 1 - y$

If $d_1 < d_2$ pick y_k

otherwise pick y_k+1

If d_1-d_2 < 0 pick y_k

^^^--- Δd

Derivation

Δ d = $d_1 - d_2$

Δ d = $(y-y_k) - (y_k+1-y)$

$y = m(x_k+1) + b$

$\Delta d = 2\,(m\,(x_k+1) + b) - 2\,y_k - 1$

$m = \Delta y / \Delta x$

Multiply both sides by Δx (since we know its positive)

$\Delta d \Delta x = 2\Delta y\, x_k + 2\Delta y + 2b\Delta x - 2\Delta x\, y_k - \Delta x$

$P_k = \Delta d \Delta x = 2\Delta\, y\, x_k + 2\Delta x\, y_k + c$

$c = 2\Delta y + \Delta x(2b - 1)$

(all the stuff that doesn't depend on k)

Incremental Algorithm

- Suppose we know p_k – what is p_{k+1} ?
- $p_{k+1} = p_k + 2\Delta y - 2\Delta x\,(y_{k+1} - y_k)$
  - Since $x_{k+1} = x_k+1$
- And $y_{k+1} - y_k$ is either 1 or 0, depending on p_k

Brezenham's Algorithm

- P_k = 2 \Delta y + x
- $Y = y_1$
- For $X = x_1$ to x_2
  - Set X,Y
  - If $P_k < 0$
  - Y += 1
  - P_k += 2 Δ y – 2 Δ x
  - Else: P_k += 2Δ y

Why is this cool?

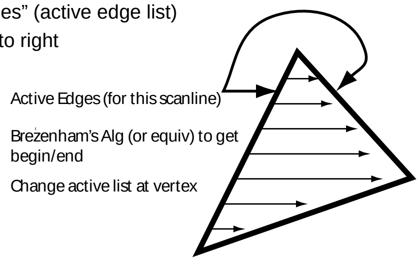
- No division!
- No floating point!
- No gaps!
- Extends to circles
- But…
  - Jaggies
  - Lines get thinner as they approach 45 degrees
  - Can't do thick primitives

Triangles (Polygons)

- The really important primitive
- Determine which pixels are covered
  - Also do interpolation (UV, color, W, depth)
- Scan conversion
  - Generically used as a term for rasterization
  - An old algorithm that isn't used by hardware
- Not to be confused with Scanline rendering
  - Related, but deals with whole scenes

Scan Conversion Algorithm

- Idea:
  - Scan top to bottom
  - "walk edges" (active edge list)
  - Scan left to right



Scan-Conversion

- Cool
  - Simple operations, very simple inner loops
  - Works for arbitrary polygons (active list management tough)
  - No floating point (except for interpolation of values)
- Downsides
  - Very serial (pixel at a time) / can't parallelize
  - Inner loop bottle neck if lots of computation per pixel

Modern Rasterization (in hardware)

- Generate pixel candidates
- Compute barycentric coords for each pixel
- Decide whether or not its inside triangle

- Why?
  - Easier for hardware
  - Parallel (each pixel somewhat independent)
  - Need barycentric coords for interpolation
  - Breaks work into even sized chunks
    - (regular tiles / groups of pixels)

What is scanline algorithm?

- Not scan conversion algorithm

- Keep all polygons – sort by Y value on screen, then by X
- Scan across each line of image – keep track of what polygons each pixel covers

- Why?
  - Image-space algorithm
  - One line Z-buffer (1 pixel Z-Buffer)
  - Makes anti-aliasing easier (know all polys that affect pixel)
  - Done by software renderers (that aren't ray tracers)

The whole process: graphics pipeline

- Primitives (triangles) in – frame buffer writes out
  - Actually, any memory that we store images modified
- Software does the same steps

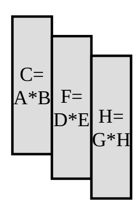
- Why pipeline?
  - Do step 1, then step 2, …
  - Can have one object in each step
  - Steps don't depend on each other too much

- Paralellism mainly in hardware

Pipelining in conventional processors

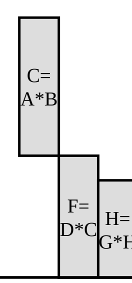
- Start step 2 before step 1 completes

C = A * B
F = D * E
J = G * H



- Unless step 2 depends on step 1
- Pipe Stall

C = A * B
F = D * **C**
J = G * H



Graphics Hardware / Interactive Rendering

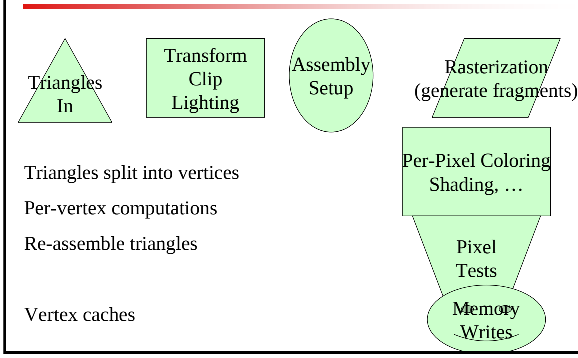
- Key Idea: Set of basic abstractions
  – Z-buffer, texture, triangles, …
- Implement these really well
- Let programmers figure out how to use it to do other things

- Expand abstractions based on what people figure out to do

History of Hardware

- 1980s – first workstation 3D hardware (SGI)
- 1990s – extension of abstraction set
  – Texture mapping, compositing, multi-buffering
- 1990s – first PC graphics hardware
  – Low end (Apple's white magic project)
  – High end (3D solutions – expensive)
- 2000s – consumer graphics hardware
  – Driven by gaming market
  – Extensive use of the abstractions
- 2002++ - programmable graphics hardware
  – Better abstractions, generality, use as GP processor

Basic Graphics Pipeline



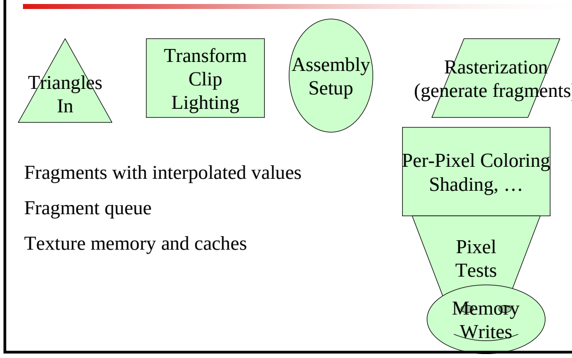
Triangles split into vertices

Per-vertex computations

Re-assemble triangles

Vertex caches

Basic Graphics Pipeline



Fragments with interpolated values

Fragment queue

Texture memory and caches

What's a fragment

- It will be a pixel when it grows up

- Pixel = place on screen
- Fragment = makes up a pixel
  – Maybe won't make it to the screen
  – Maybe combined to make a pixel (anti-aliasing)

- Position in the final image is known
  – (e.g. which pixel it contributes to)

Per-Pixel Coloring

- Interpolation (handled by rasterization)
- Texture lookup / blending
- Per-Pixel Lighting (if its allowed)

- Arbitrary programs (we'll get to that later)

Per-Fragment operations

- Stencil test
- Window clipping
- Other things

- Z-testing
  - Note this is late (lots of work done and thrown away)
  - Could do Z-test earlier (maybe)

Memory writes

- Need to do read/modify (for z-buffer / stencil)
- Useful for color as well:
  - Alpha blending
  - Multi-pass operations

Basics of graphics performance

- Where is the bottleneck?
  - Getting triangles into the pipeline
  - Transforming the verices
  - Rasterization
  - Doing the per-pixel operations
  - Getting texture for per-pixel operations
  - Reading/writing to memory
- Different systems have different bottlenecks
  - And the bottlenecks are moving

The Fixed-Function Pipeline

- We know what each block does
  - Vertex
    - Projection matrix, divide by Z, Phong lighting (per vertex)
    - Color, UV, Z, W, per vertex
  - Fragment
    - Interpolate colors
    - Look up textures – blend (and apply over interpolated lighting)

- Want more (per-pixel lighting, normal maps),…
  - But which one to put in hardware
  - All of them! (make it flexible and programmable)

Vertex Processor

- What comes in?
  - Vertex info (position, normal, assigned color&UV)
  - State information (matrices, lighting, …)
- What goes out
  - Vertex info – just now in screen space

- All the per-vertex operations do is change the values around!

Fragment Processor

- What comes in
  - Info about fragment
    - Interpolated from vertices
    - Position XY (can't be changed, since it's the "identity" of the fragment)
    - Other properties Z,W, UV, Color
  - State information (lighting, bound textures, …)
- What goes out
  - Info about fragment (mainly color, but also new Z/W)

- Can't really change X/Y

Programming the pipeline

- Write “little” functions for each
- Remember what each can “do” (inputs and outputs)

- Each gets applied a lot
  - To every vertex
  - To every fragment
- But applied in parallel (so it can be fast)