# 3D Drawing
# Visibility & Rasterization

CS559 - Spring 2018

Lectures 9-11

March 20-27, 2018

1. Put a 3D primitive in the World
   **Modeling**
2. Figure out what color it should be
   **Shading**
3. Position relative to the Eye
   **Viewing** / Camera Transformation
4. Get rid of stuff behind you/offscreen
   **Clipping**
5. Figure out where it goes on screen
   **Projection** (sometimes called Viewing)
6. Figure out if something else blocks it
   **Visibility** / Occlusion
7. Draw the 2D primitive
   **Rasterization** (convert to Pixels)

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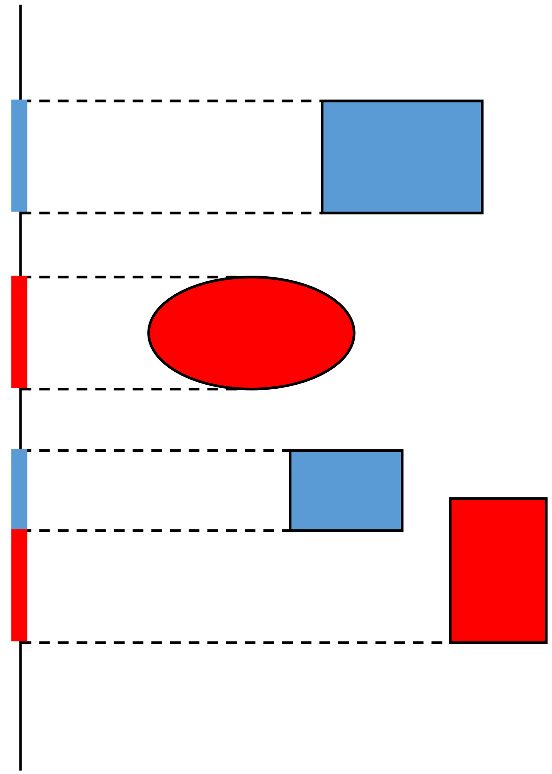
# Orthographic Projection

Projection = transformation that reduces dimension

Orthographic = flatten the world onto the film plane



# Perspective Projection

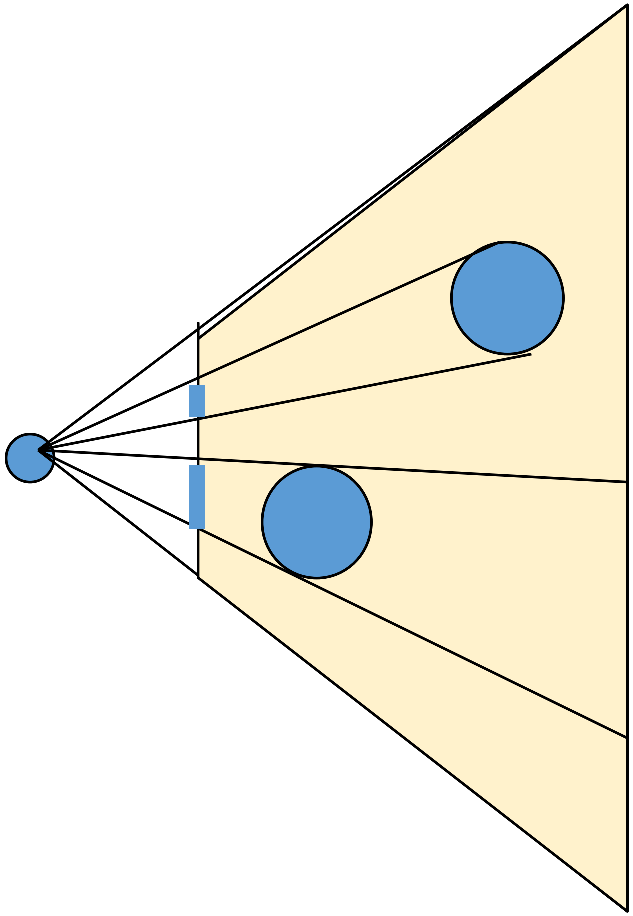
Eye point

Film plane

Frustum

Simplification

- Film plane centered with respect to eye
- Sight down Z axis
  - Can transform world to fit

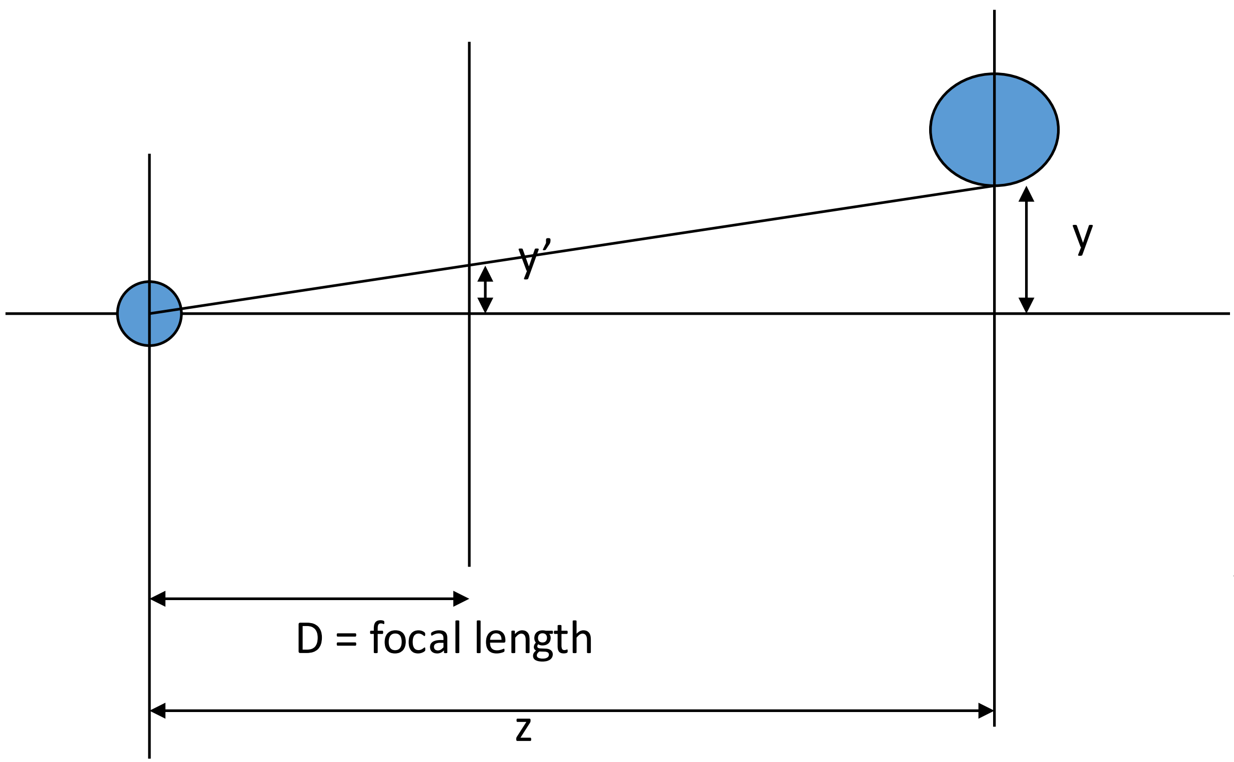


# Basic Perspective

Similar Triangles

Warning = using d for focal length (like book)

F will be “far plane”




$$\frac{y}{z} = \frac{y'}{d}$$

$$y' = \frac{d}{z}y$$

# Use Homogeneous coordinates!

Use divide by w to get perspective divide

Issues with simple version:

- Font / back of viewing volume
- Need to keep some of Z in Z (not flatten)

$$\begin{bmatrix} x' \\ y' \\ z' \\ w' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ z \end{bmatrix} = \begin{bmatrix} x/z \\ y/z \\ z/z = 1 \\ 1 \end{bmatrix}$$

# Simplest Projective Transform

$$\begin{pmatrix} dx \\ dy \\ 1 \\ z \end{pmatrix} = \begin{pmatrix} d & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

After the divide by w…

Note that this is dx/z, dy/z (as we want)

Note that z' is 1/z (we can't keep Z)

Fancier forms scale things correctly

# The real perspective matrix

N = near distance, F = far distance

Z = n put on front plane, z=f put on far plane

$$P = \begin{pmatrix} n & 0 & 0 & 0 \\ 0 & n & 0 & 0 \\ 0 & 0 & n+f & -fn \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

# Shirley's Perspective Matrix

After we do the divide, we get an unusual thing for z – it preserves order, keeps n&f

$$\mathbf{Px} = \mathbf{P}\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x\frac{n}{z} \\ y\frac{n}{z} \\ n + f - \frac{fn}{z} \\ 1 \end{bmatrix}$$

# The TWGL perspective matrix

perspective(fov, aspect, zNear, zFar)
→ {Mat4}

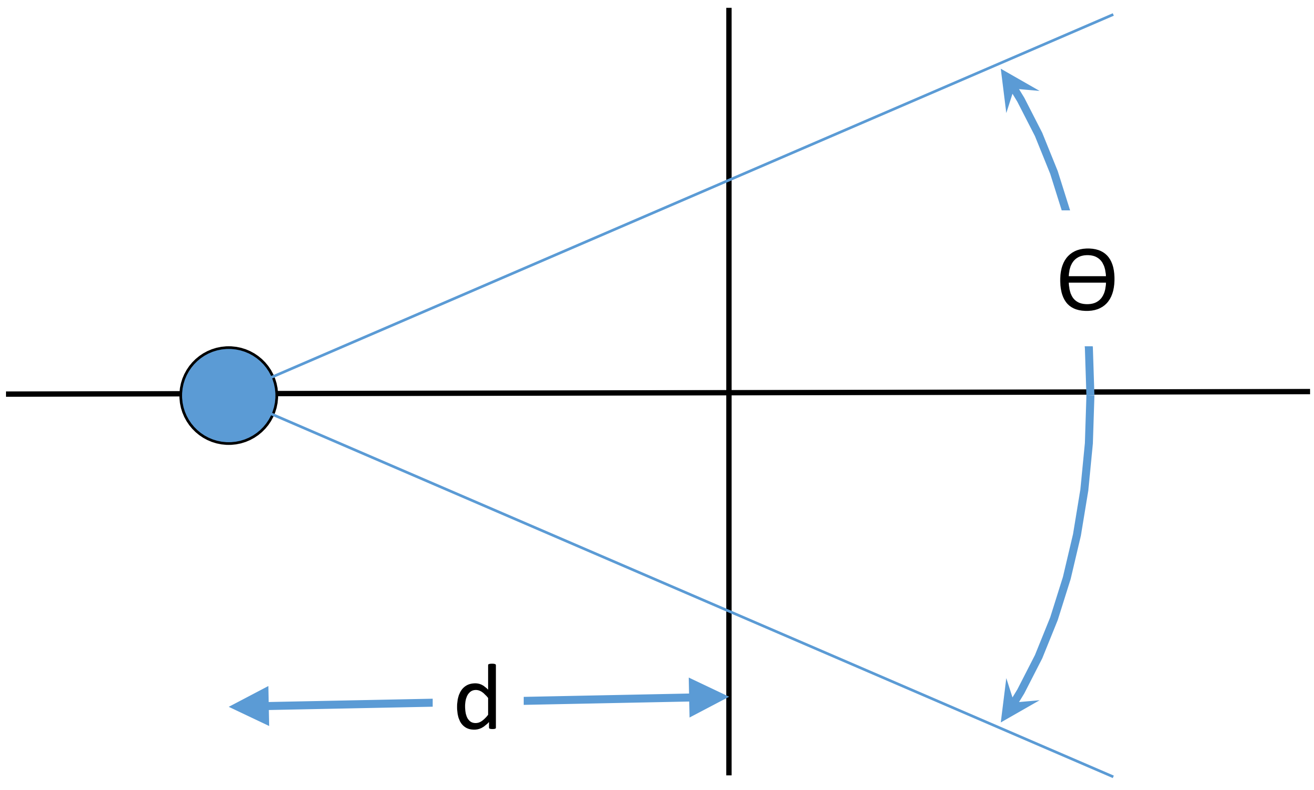
**fov** = field of view (specify focal length)

**aspect** ratio (witdth of image)

assuming height is 1

**[-zNear,-zFar]** remapped to **[-1,+1]**

# Field of View



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# Visibility:
# What objects do you see?

What objects are offscreen?

- To avoid drawing them
- (generally called clipping)

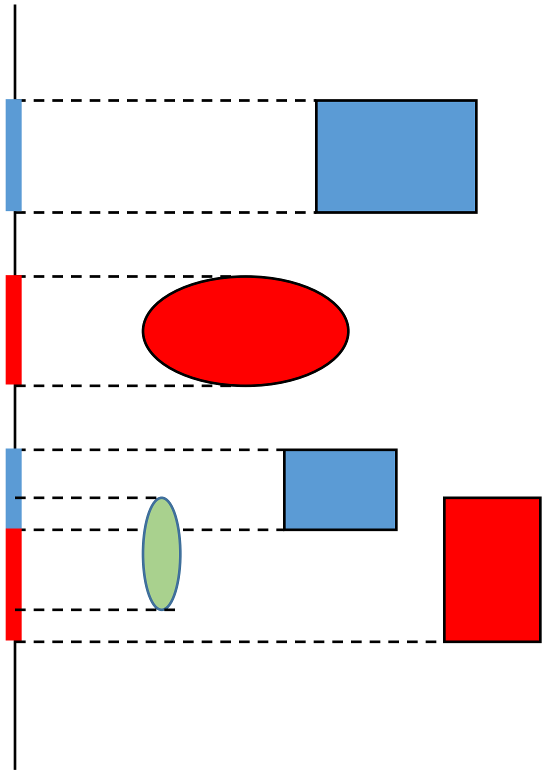
What objects are blocked?

- Need to make things look **solid**

Assumes we have “filled” primitives

- Triangles, not lines

# Now we're in Screen Coordinates with depth



# Bad ideas...

Last drawn wins

sometimes object in back

what you seen depends on ...

Wireframe (nothing blocks anything)

hard to see what's going on if complex

# How to make objects solid

Physically-Based

Analytic Geometry

Object-space methods (order)

Image-space methods (store per pixel)

# Painter's Algorithm

Order the objects

Draw stuff in back first

Stuff in front blocks stuff in back

# Simple version

Pick 1 point for each triangle

Sort by this one point

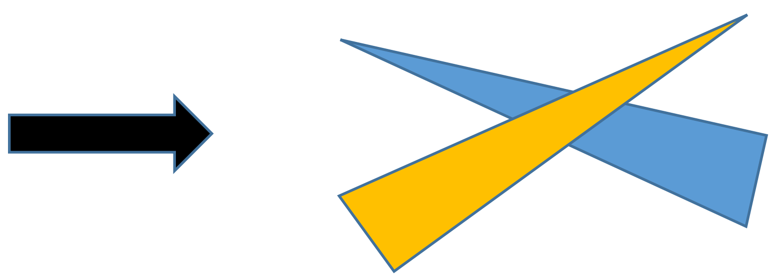
(this is OK for P4)

# What about triangles that … Intersect? Overlap?

Need to divide triangles that intersect

(if you want to get it right)

A triangle can be in front of and behind



# Downsides of Painters Algorithm

Need to sort

    O(n log n)

    need all triangles (not immediate)

Dealing with intersections = lots of triangles

Need to resort when the camera moves

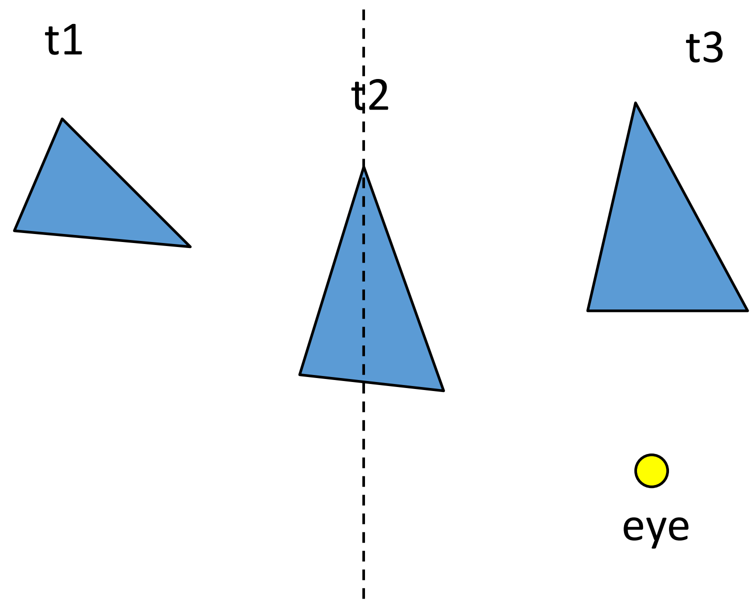
# Binary Space Partitions

Fancy data structure to help painters algorithm

Stores order from any viewpoint

A plane (one of the triangles) divides other triangles

Things on same side as eye get drawn last




T2 divides into groups
T3 is on same side of eye

# Using a BSP tree

Recursively divide up triangles

Traverse entire tree
- Draw farther from eye subtree
- Draw root
- Draw closer to eye subtree

Always O(n) to traverse
- (since we explore all nodes)
- No need to worry about it being balanced

# Building a BSP tree

Each triangle must divide other triangles
- Cut triangles if need be

Goal in building tree: minimize cuts

# Painters Problem 2: Overdraw

All triangles get drawn

Even if something else will cover it

Depth Complexity = # of things at each pixel

Inefficient, uses lots of memory bandwidth

# Z-Buffer

An **image space** approach

Hardware visibility solution

Throw memory at the problem

Every pixel stores color and **depth**

# Z-buffer algorithm

Clear all pixels to “farthest value” (-inf)

```
for each triangle
    for each pixel
        if new Z > old Z:  // in front
            write new color and Z
```

# Simple

The only change to triangle drawing:

test Z before writing pixels

writeColor(@pixel) becomes:

readZ(@pixel)

test

writeZandColor(@pixel)

# Notice...

Order of triangles *usually* doesn't matter

Except…

- If the Z is equal, we have a tie
- We can decide if first or last wins
- Either way, order matters

Z-Fighting

# Z-Fighting

Z Equal? Order matters

Z Really close?

random numerical errors cause flips

# Z-Resolution

Remember – we don't have real Z

we have 1/Z (bunches resolution)

Old days: integer Z-buffer was a problem

Nowadays: floating point Z-buffers

Z-resolution less of an issue

Keep near and far close

# Transparent Objects

Draw object in back

Draw transparent object in front

But…

Draw transparent object in front

~~Draw object in back~~ (Z-buffer prevents)

# Overdraw

Still drawing all objects – even unseen

Can save writes if front objects first

Early z-test...

- Avoid computing pixel color if
    - it will fail z-test

# Using the Z buffer

Give polygons in any order (except...)

Use a Z-Buffer to store depth at each pixel

Things that can go wrong:

- Near and far planes matter
- Culling tricks can be problematic
- You may need to turn the Z-buffer on
- Don't forget to clear the Z-Buffer!

# Culling

**Quickly** determine that things cannot be seen – and avoid drawing them

Must be faster to rule things out than to draw them

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# A Quick Word on Shading (for P4)

Color of triangle depends...

Color per triangle (OK for P4)

Color per vertex

Color per pixel

# Lighting basics

To simulate light, we need to know where the triangle is in the world

Global Effects (other objects)

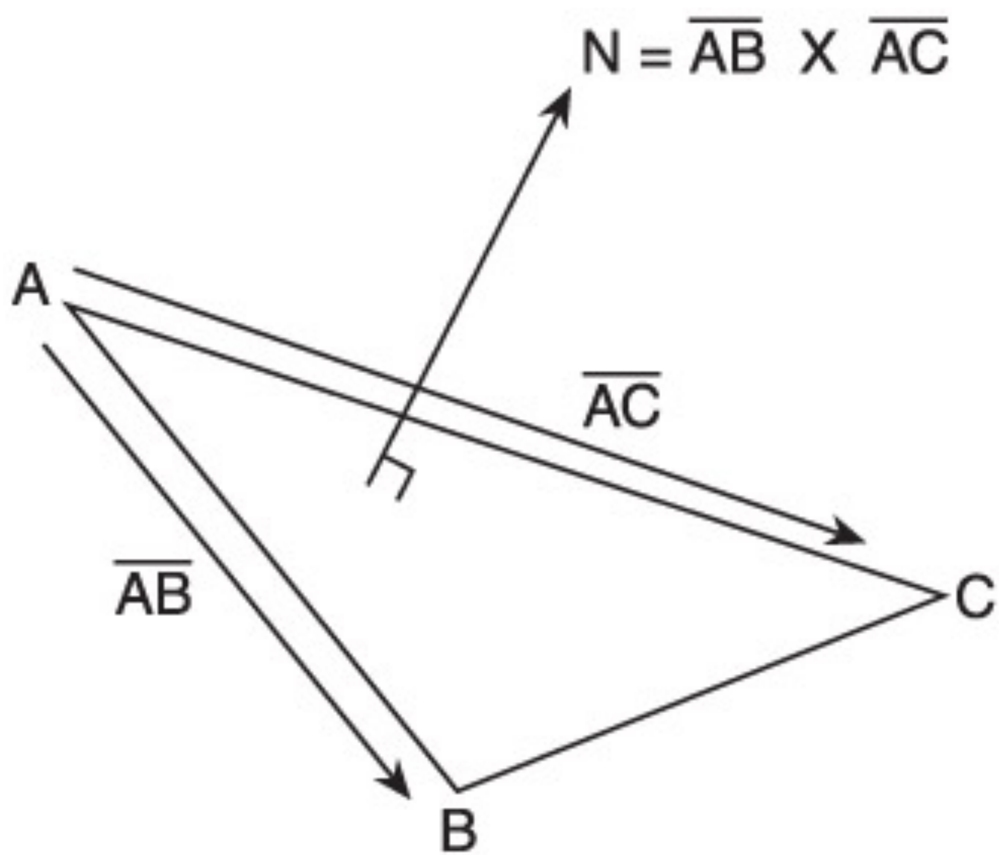
reflections, shadows, …

Local Effects (how the light bounces off)

shininess, facing the light, …

# Local Geometry

Normal Vector – sticks "out" of the triangle



# Transforming Normal Vectors

Transform triangle, re-compute the normal

or...

Normal is transformed by the

inverse transpose of the transform

If the triangle is transformed by M

The normal is tranformed by $(M^{-1})^T$

# Inverse Transpose?

Yes – ask me offline for detailed proof

(the book just asserts it as fact)

For a rotation, the inverse is the transpose

$$M = (M^{-1})^T$$

But only for rotations ...

# What can I use a normal vector for?

Simplest lighting: Diffuse Shading

If surface is pointing towards light, it gets more light

brightness ~= N • L

N = unit normal vector

L = unit light direction vector

# Simple things for P4

High noon…

$$C' = \left( \tfrac{1}{2} + \tfrac{1}{2}\, N \bullet [0,1,0] \right) C$$

Top and bottom…

$$C' = \left( \tfrac{1}{2} + \tfrac{1}{2}\, \mathrm{abs}(N \bullet [0,1,0]) \right) C$$

Make sure N is a unit vector!

# Program 4

Just like P3 (transform points) but…

1. Draw Triangles (solids)
2. Compute Normals (and shade)
3. Store triangles in a list and sort
   Painter’s Algorithm Visibility

# What coordinate system to compute lighting in?

Window (Screen)

Normals lost

Normalized Device – [-1 1]

Projection loses normals

Camera / Eye

Camera space is OK

World

World space is good

Object . . .

Lights attached to objects?

Local

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# Where are we going next...

We've made a graphics pipeline

Triangles travel through steps...
get turned into shaded pixels

How do we use the hardware to make this go fast...

# Rasterization

Figure out which pixels a primitive “covers”

Turns primitives into pixels

# Rasterization

Let the low-level library take care of it

Let the hardware take care of it

Writing it in software is different than hardware

Writing it today (with cheap floating point) is different than a few years ago

# Rasterization

Input:

primitive (in screen coords)

Output

list of pixels “covered”

# What primitives

Points

Lines

Triangles

Generally build other things from those

Approximate curves

# Rasterizing Points

Easy! 1 pixel – and we know where

Issues:

- What if we want different sizes?
  - (points smaller than a pixel?)
- Discretization?
  - (pixels are an integer grid)

# Welcome to the world of Aliasing

The real world is (effectively) continuous

Our models are continuous

Our displays are discrete

This is a deep problem – we'll come back

# Do I care about Aliasing?

Jaggies

Crawlies

Things not moving smoothly

Can't make small things

Can't put things where you want

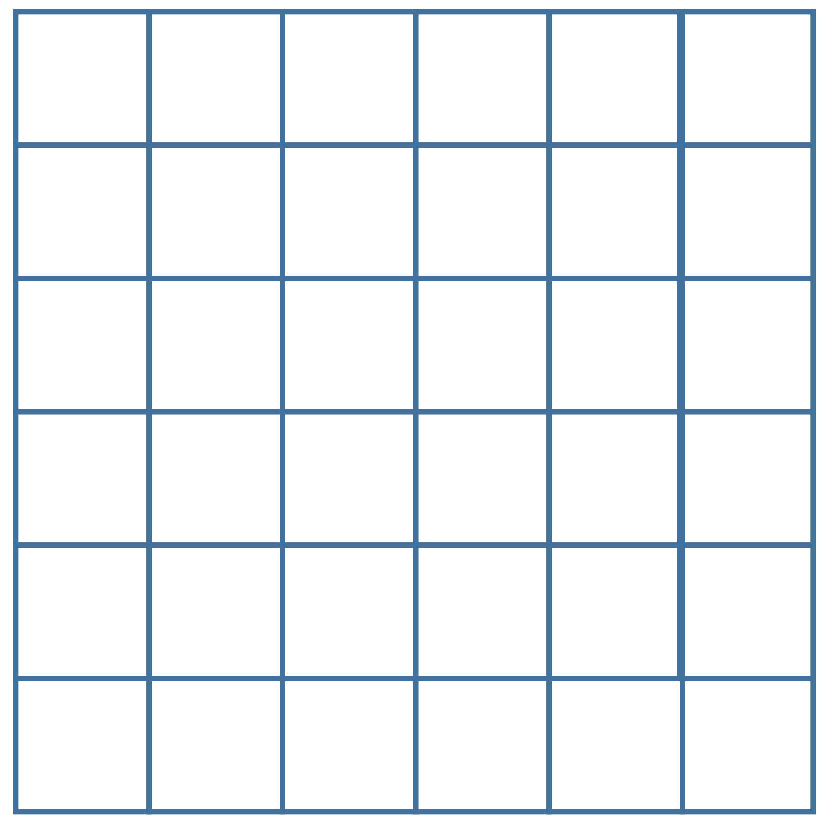
Errors add up to weird patterns

(or, simply, **Yes**)

# Preview: Dealing with Aliasing

Little Square Model

- Not preferred
- Simpler to start



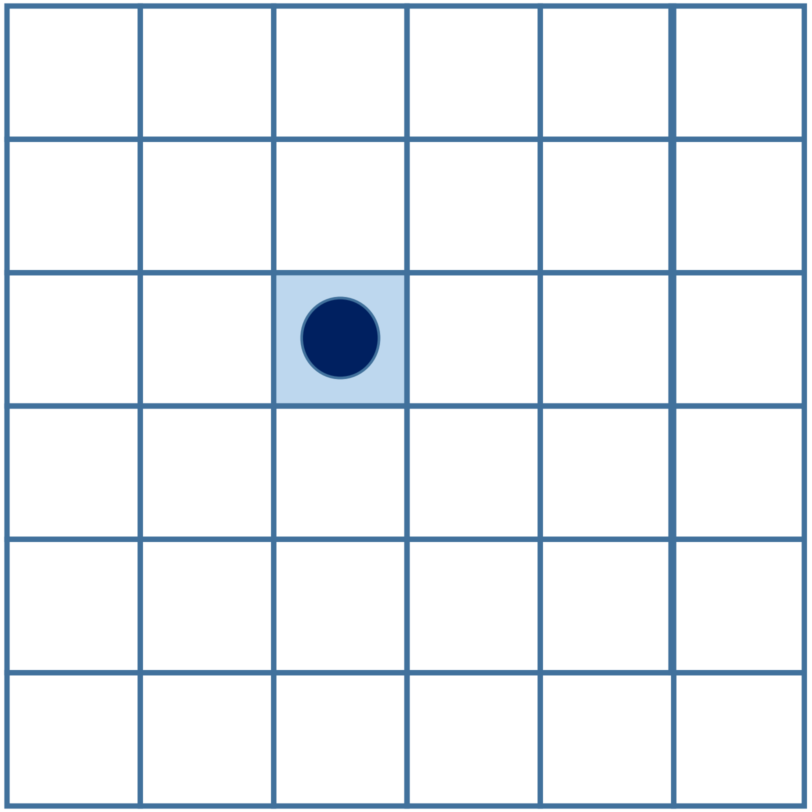
# Preview: Dealing with Aliasing

Simple Drawing

Pick the:

Nearest pixel (center)

Fill the pixel



# Preview: Dealing with Aliasing

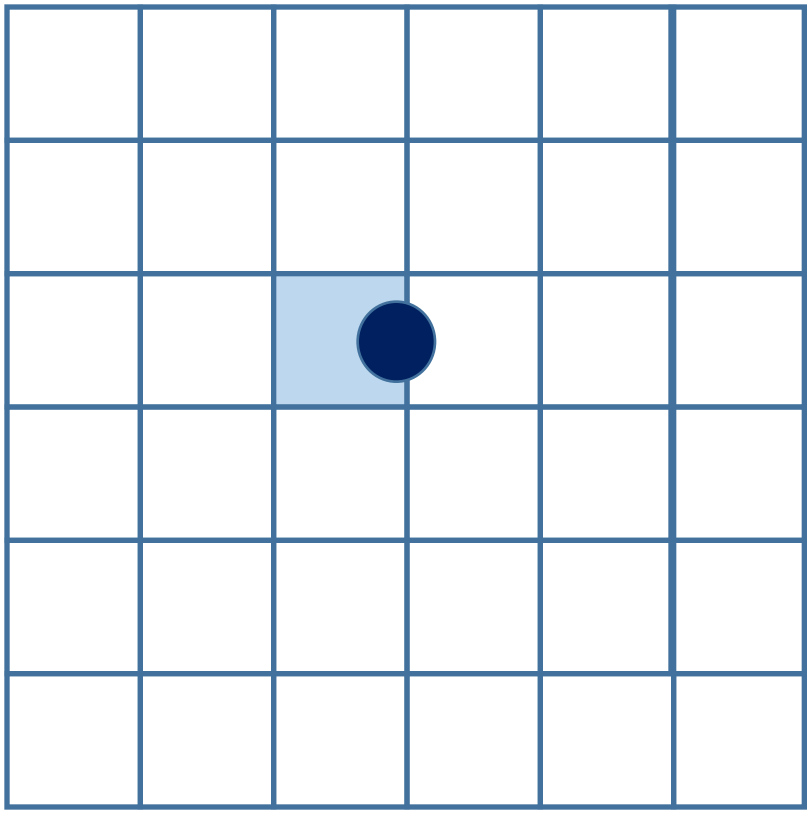
Simple Drawing

Pick the:

~~Nearest pixel (center)~~

(cover multiple pixels)

Fill the pixel



# Preview: Dealing with Aliasing

Simple Drawing

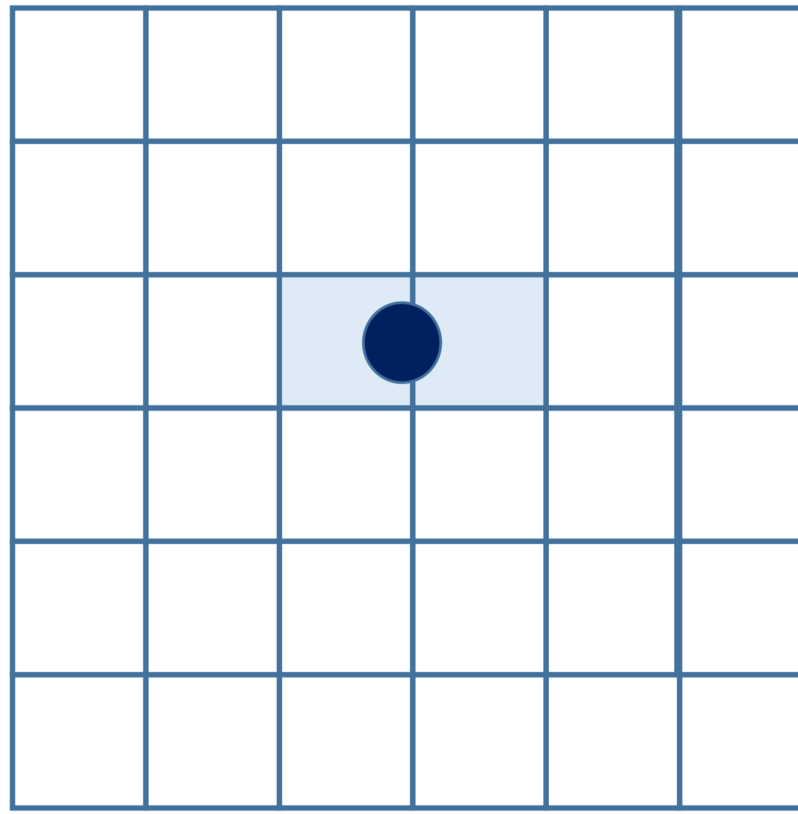
Pick the:

~~Nearest pixel (center)~~

(cover multiple pixels)

~~Fill the pixel~~

(partially fill pixel)



# Dealing with Aliasing?

**Simple:**

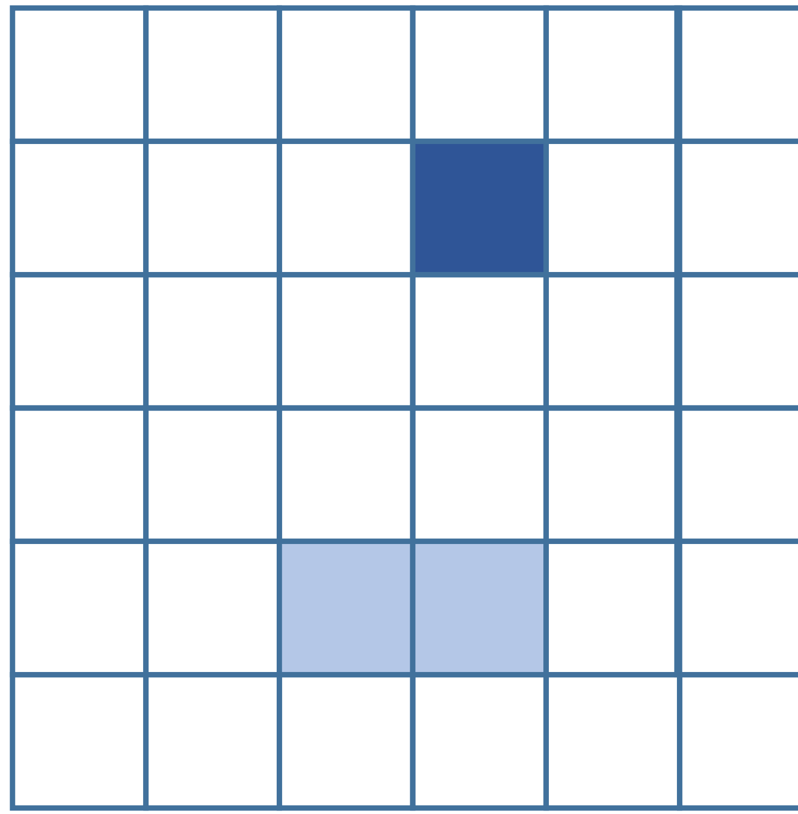
Aliased (jaggies, ...)

Crisp

**Anti-Aliased:**

Less aliased

Blurry



# Other Anti-Aliasing Issues

Z-Buffer is a binary choice

Partially filling can be a problem

Depends on lots of other stuff

Really elegant math! Good theory!

# Lines

**Historical:**

Vector graphics hardware

Simulate with “new” pixel-based (CRT)

**Brezenham’s Algorithm (1960s)**

Integer only line drawing

No divisions

# Today?

Floating point is cheap
Division isn't too expensive

Make lines into degenerate triangles

# 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

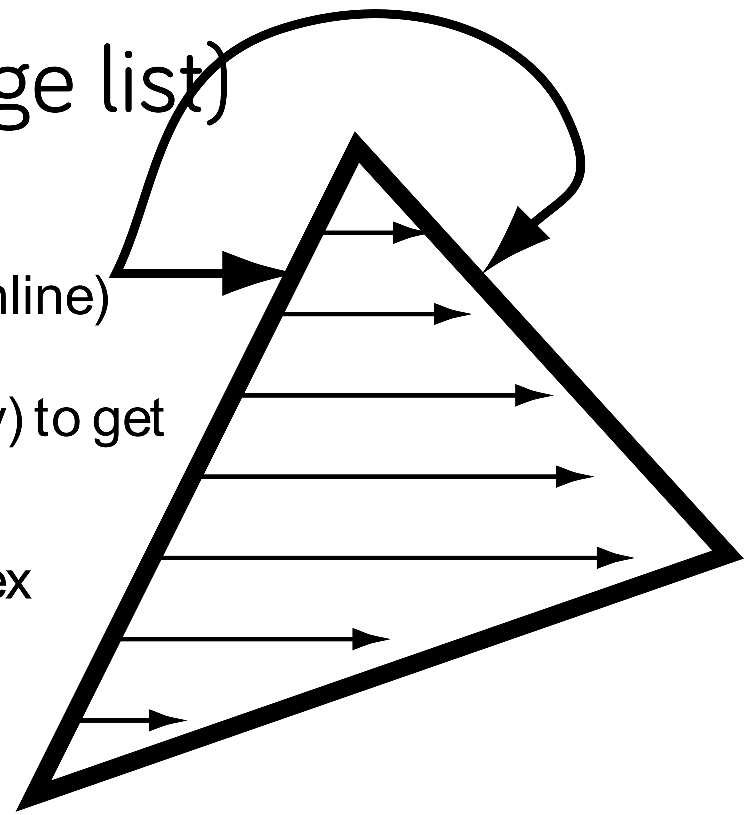
Idea:

- Scan top to bottom
- “walk edges” (active edge list)
- Scan left to right

Active Edges (for this scanline)

Brezenham’s Alg (or equiv) to get begin/end

Change active list at vertex



# 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

# How does the hardware do it?
# (or did it last I learned about it)

Find a box around the triangle

For each pixel in the box

- compute the barycentric coordinates
- check if they are inside the triangle

Do pixels in parallel (in hardware)

- otherwise, really wasteful

Barycentric coordinates are useful

# Barycentric Coordinates

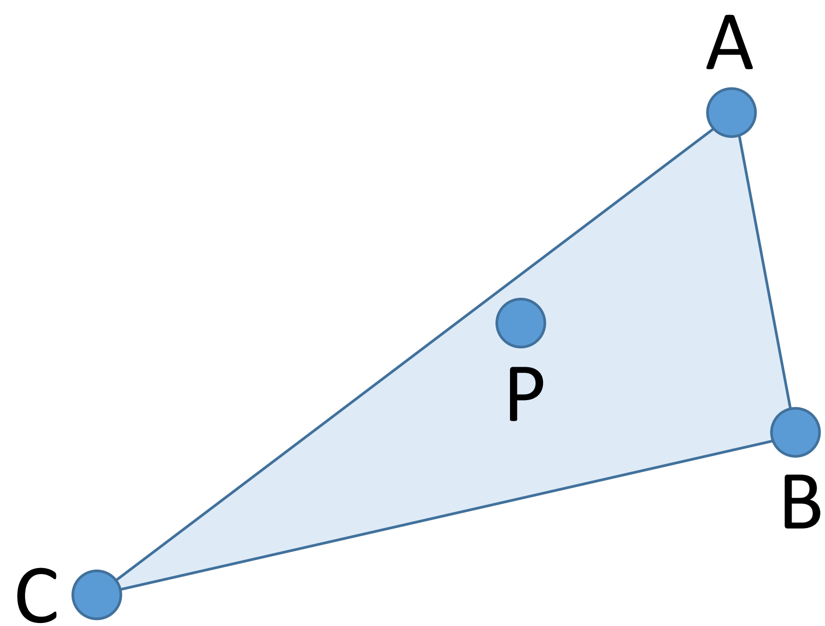
Any point in the plane is a convex combination of the vertices of the triangle

$P = \alpha A + \beta B + \gamma C$

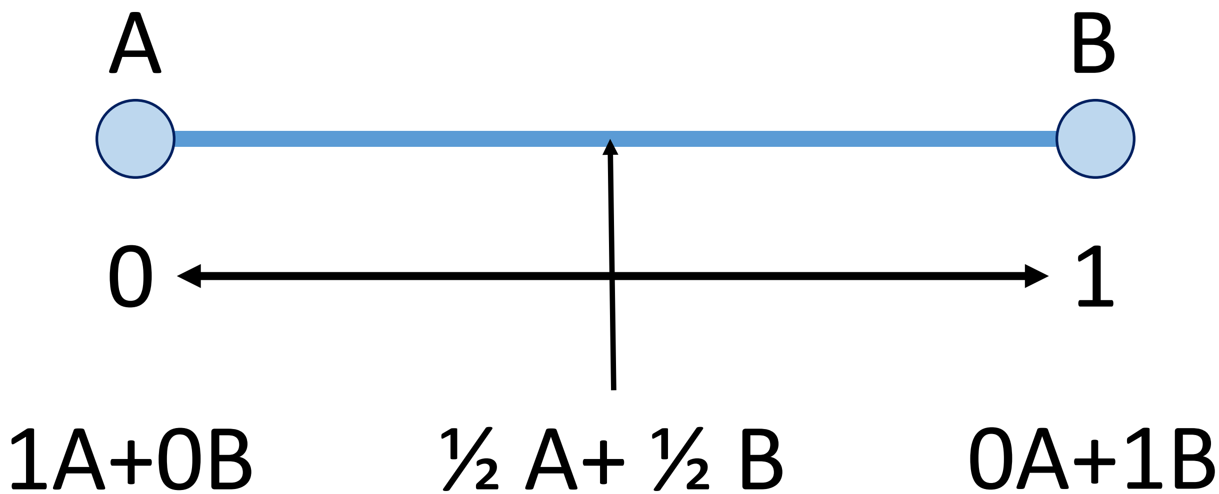
$\alpha + \beta + \gamma = 1$

Inside triangle

$0 <= \alpha, \beta, \gamma <= 1$



# Linear Interpolation




Interpolative coordinate (t)

0<= t <= 1  then in line segment

# Dealing with Aliasing?

**Simple:**

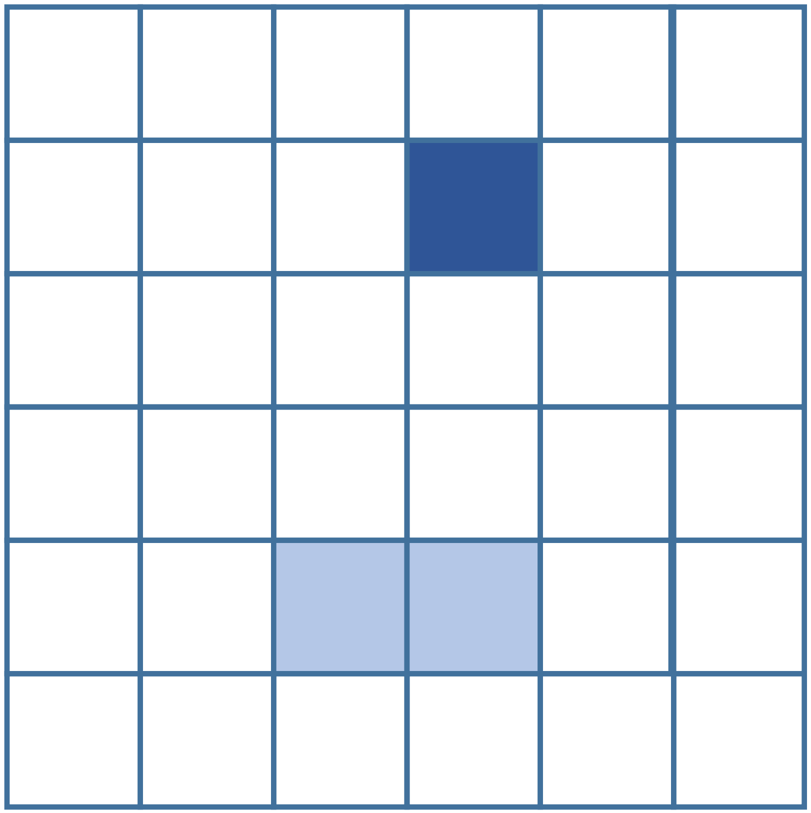
Aliased (jaggies, ...)

Crisp

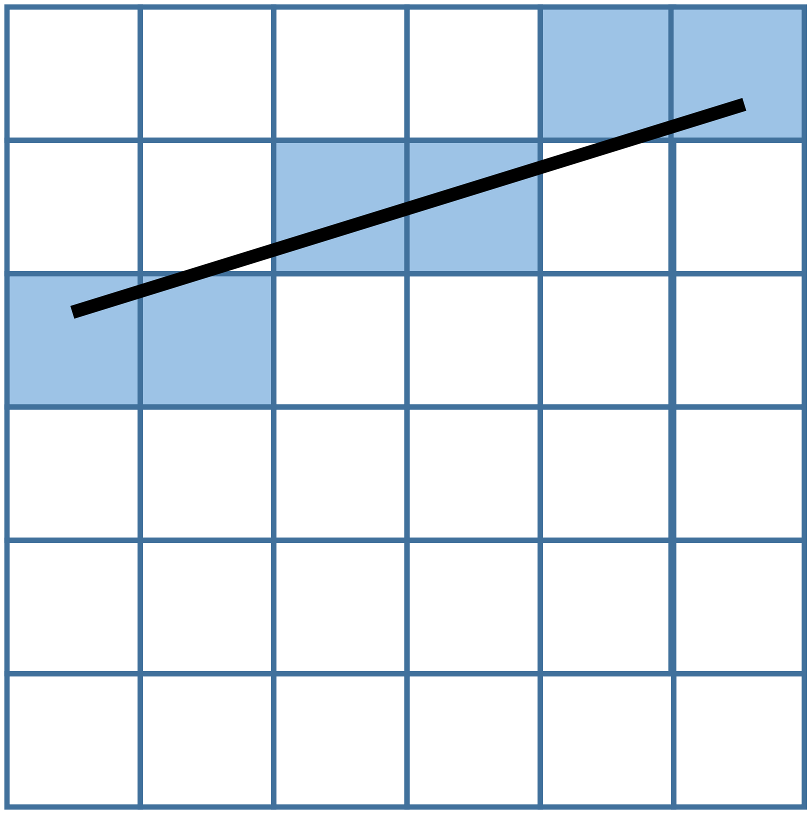
**Anti-Aliased:**

Less aliased

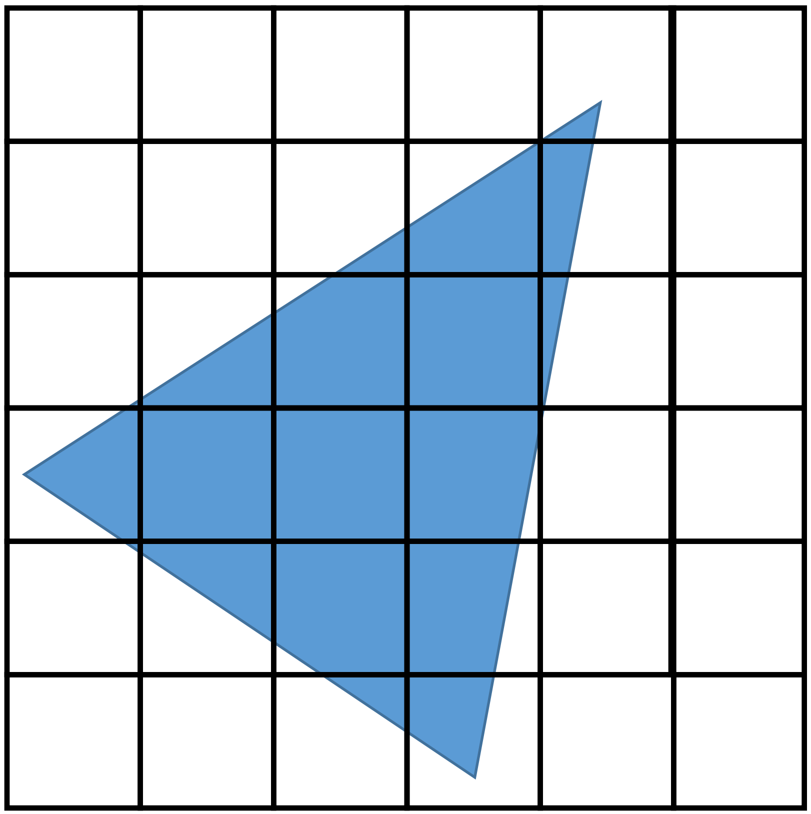
Blurry



# Lines



# Triangles

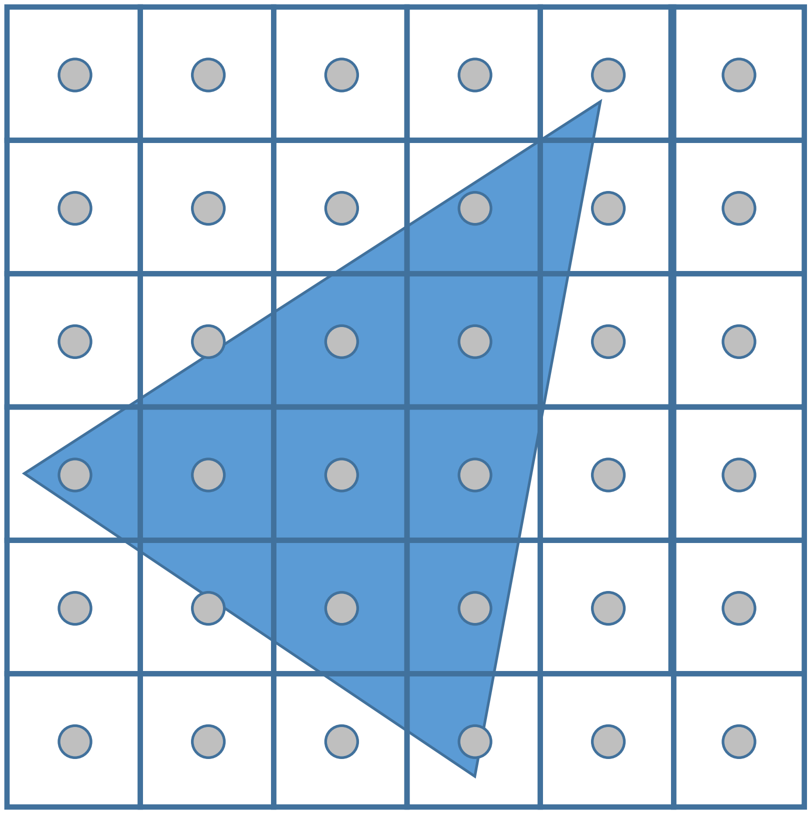


# Hardware Rasterization

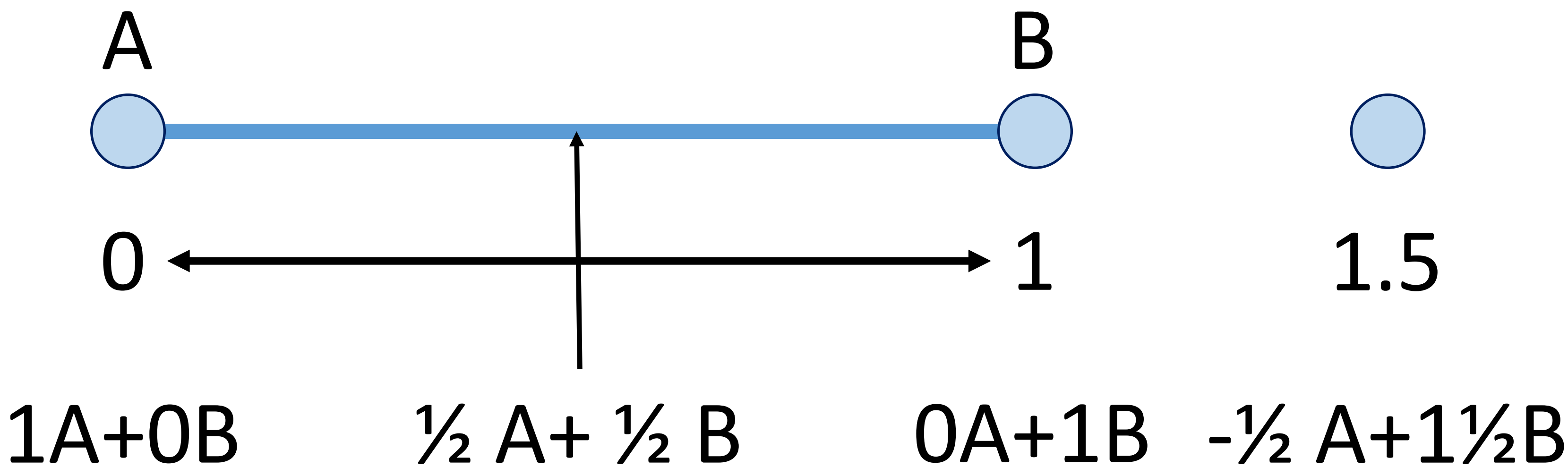
For each point:

Compute barycentric coords

Decide if in or out



# Linear Interpolation
# $P = (1-t)\,A + t\,B$ (t is the coord)




Interpolative coordinate (t) $P = (1-t)\,A + t\,B$

$0 <= t <= 1$ then in line segment

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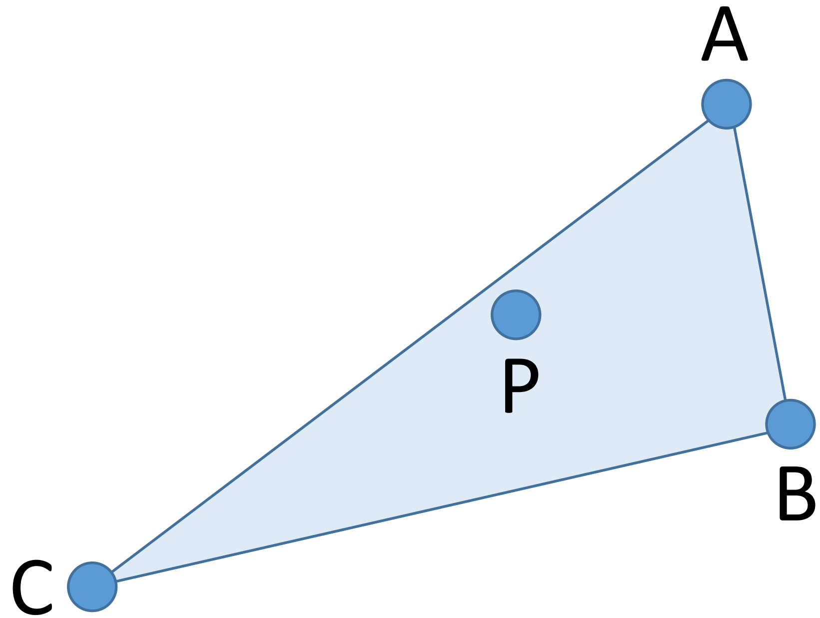


# Barycentric Coords are Useful!

Every point in plane has a coordinate

$(\alpha\ \beta\ \gamma)$ such that: $\alpha + \beta + \gamma = 1$

Easy test inside the triangle

$0 <= \alpha, \beta, \gamma <= 1$

Interpolate values across triangles

$x_p = \alpha\, x_1 + \beta\, x_2 + \gamma\, x_3$

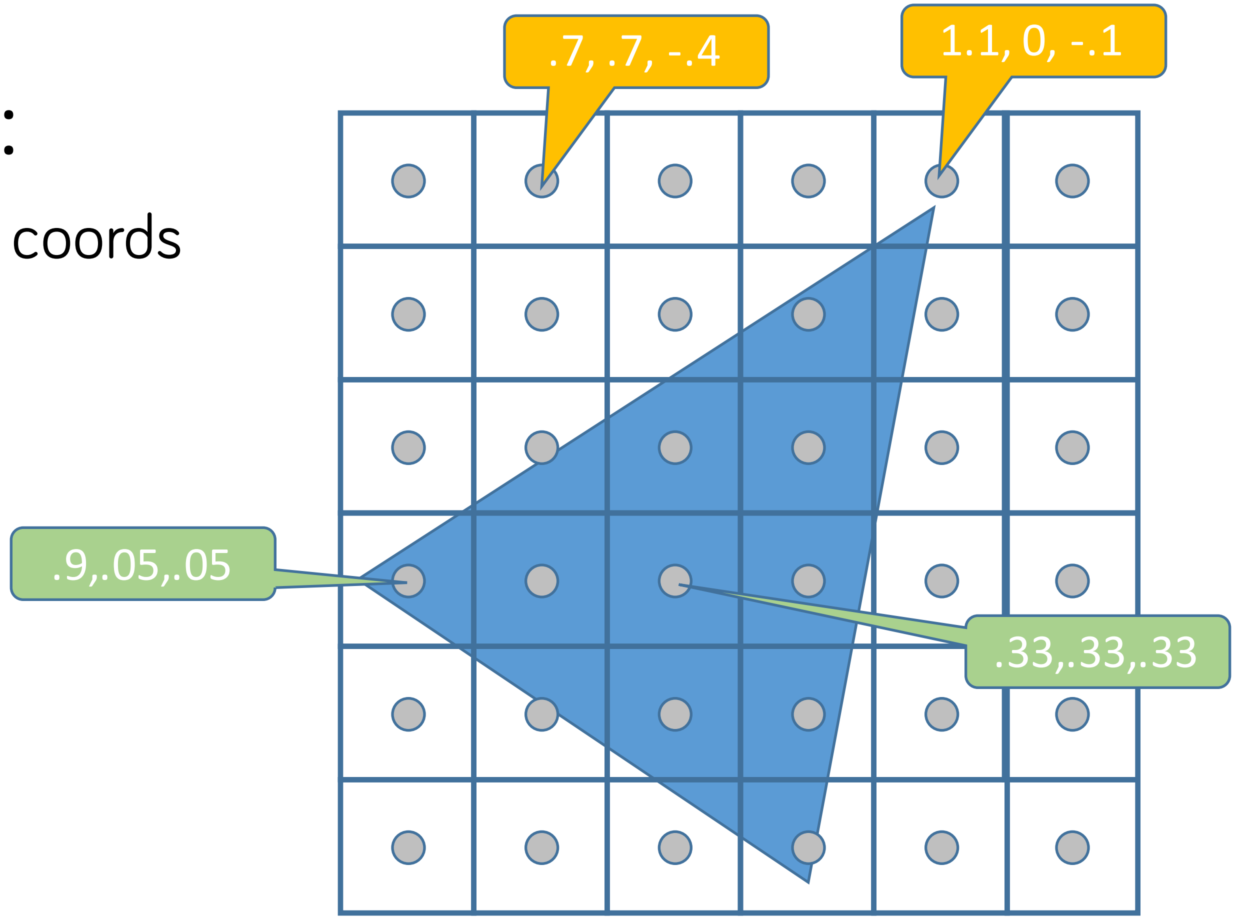
$c_p = \alpha\, c_1 + \beta\, c_2 + \gamma\, c_3$

# Hardware Rasterization

## For each point:

Compute barycentric coords

Decide if in or out



# Wasteful?

Can do all points in parallel

We want the coordinates (coming soon)

Does the right things for touching triangles

- Each point in 1 triangle

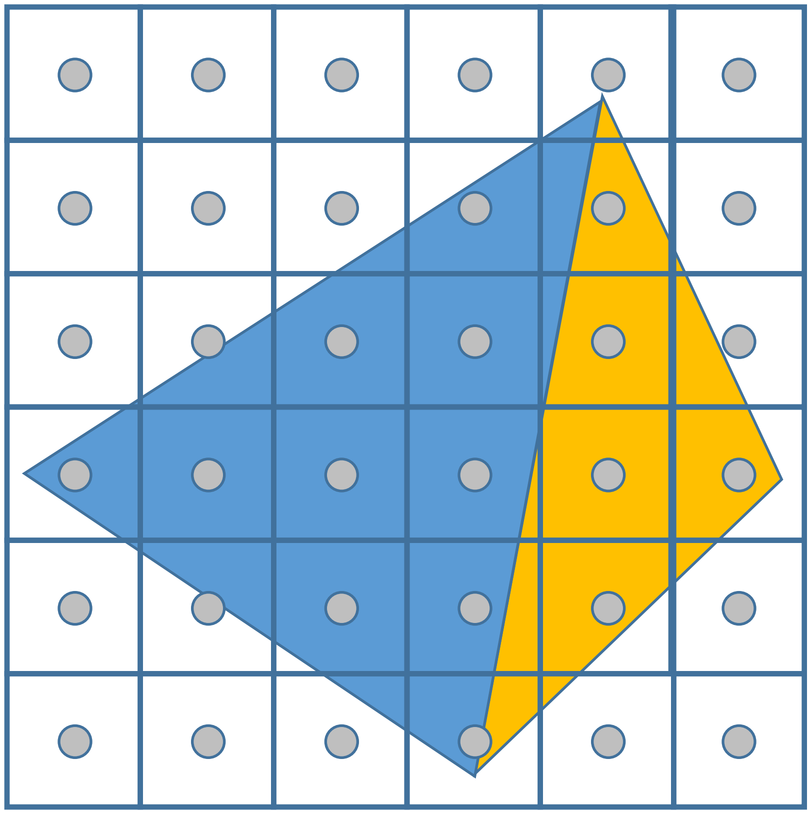
# Hardware Rasterization

Each center point in one triangle

If we choose consistently for “on-the-edge” cases

Over simplified version:

$0 <= a,b,c < 1$



# Note

Triangles are independent

Even in rasterization

(they are independent throughout process)

# The steps of 3D graphics

Model objects (make triangles)

Transform (find point positions)

Shade (lighting– per tri / vertex)

Transform (projection)

Rasterize (figure out pixels)

Shade (per-pixel coloring)

Write pixels (with Z-Buffer test)

# A Pipeline

Triangles are independent

Vertices are independent

Pixels (within triangles) are independent

(caveats about sharing for efficiency)

Don't need to finish 1 before start 2

(might want to preserve finishing order)

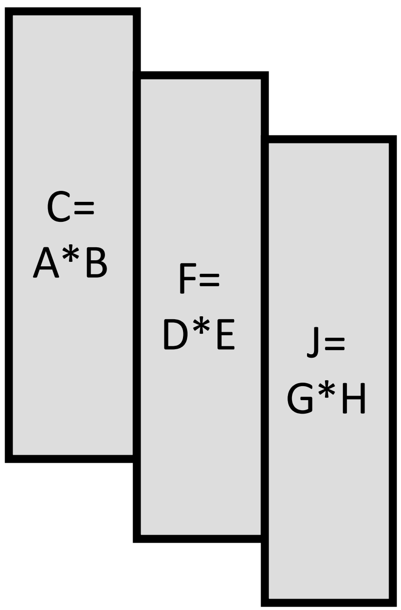
# Pipelining in conventional processors

Start step 2 before step 1 completes

C = A * B

F = D * E

J = G * H



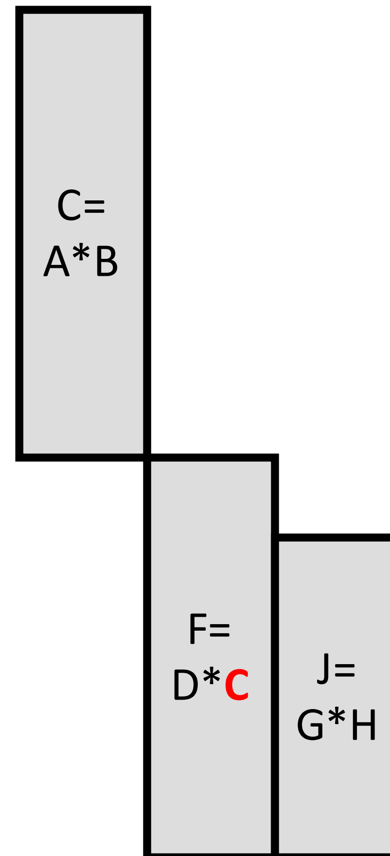

Unless step 2 depends on step 1

Pipe Stall

C = A * B

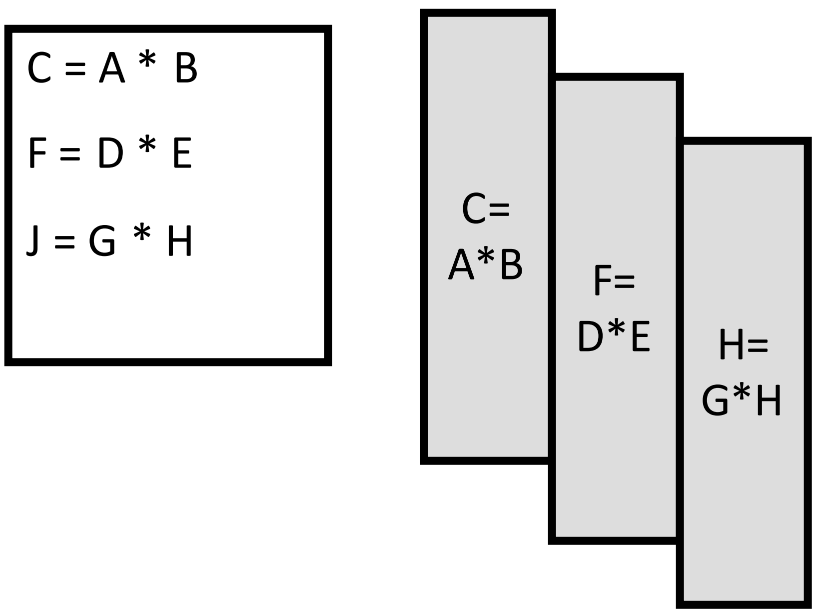
F = D * C

J = G * H



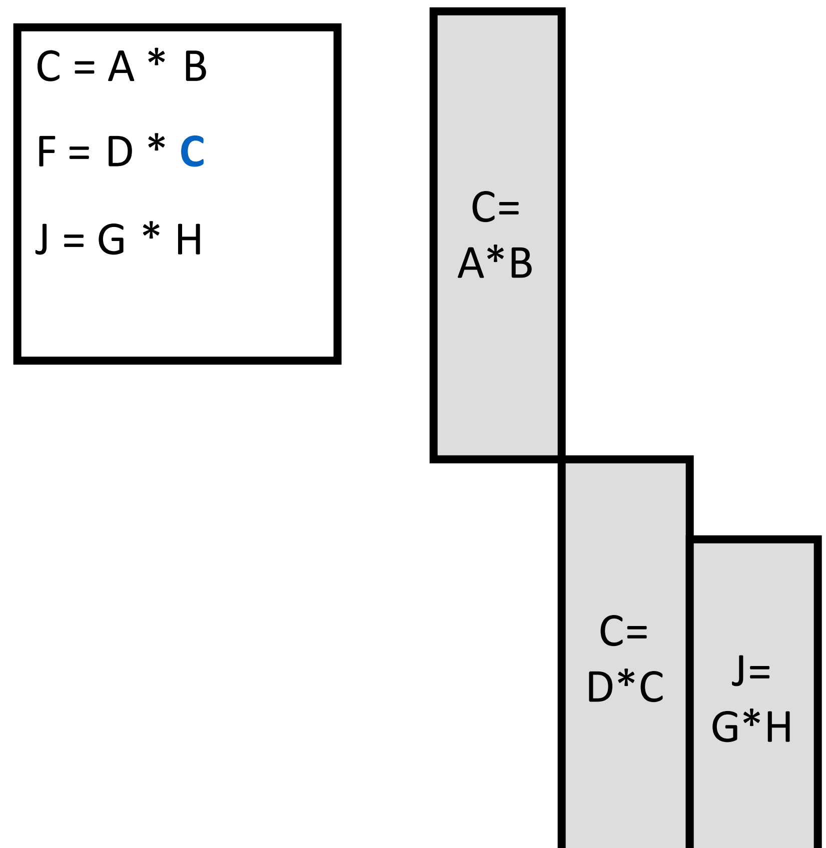
# Triangles are independent!
# No stalls! (no complexity of handling stalls)

Start step 2 before step 1 completes

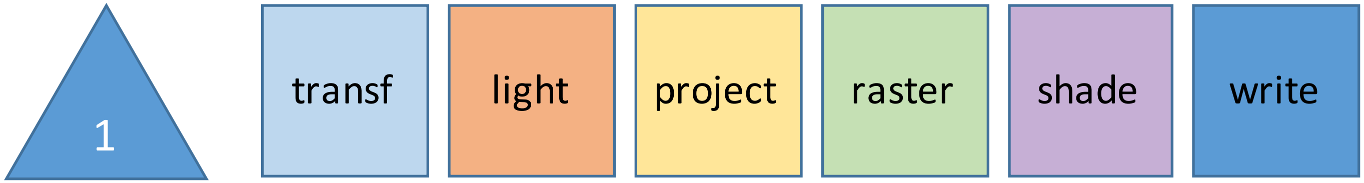



Unless step 2 depends on step 1

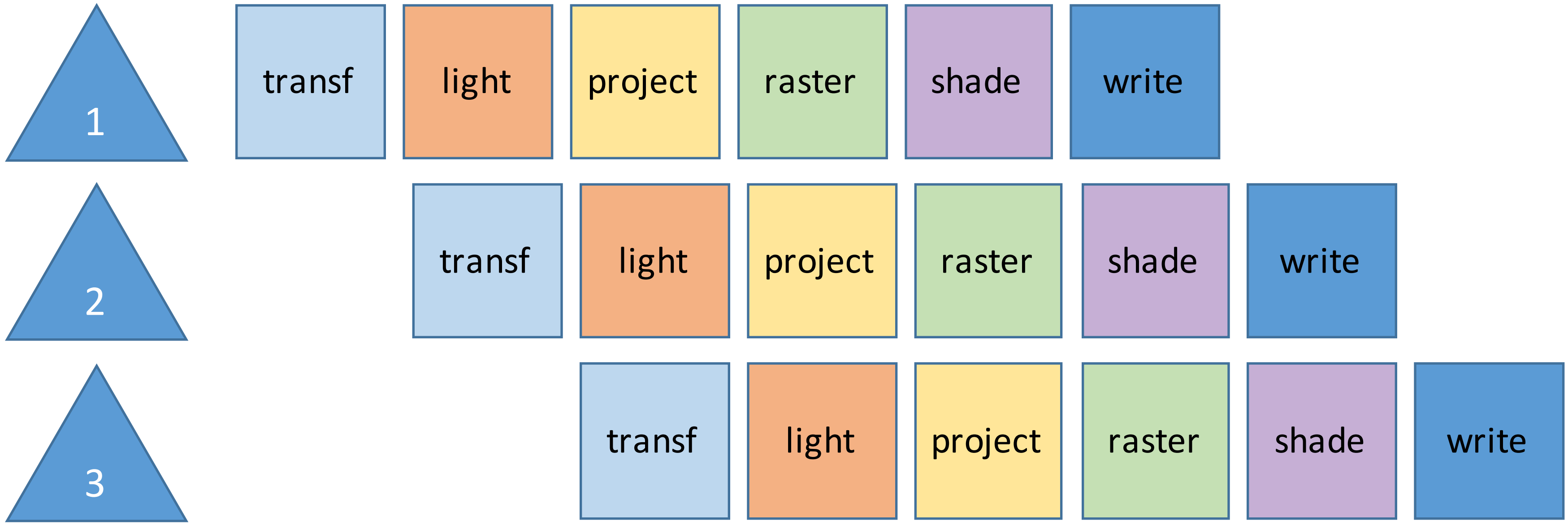
Pipe Stall



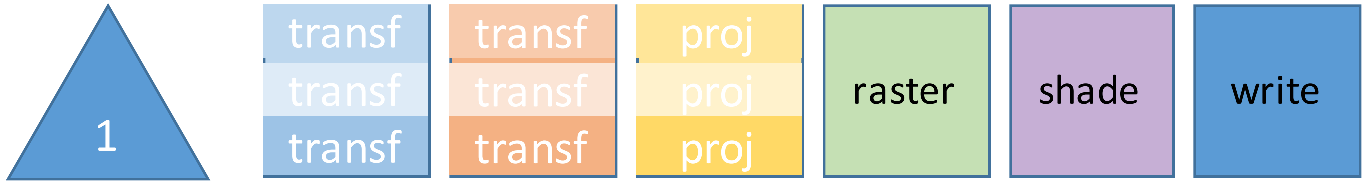
# A Pipeline



# A Pipeline


1
transf
light
project
raster
shade
write
2
transf
light
project
raster
shade
write
3
transf
light
project
raster
shade
write

# Vertices are independent
# Parallelize!



# Parallelization

Vertex operations

- split triangles / re-assemble
- compute **per-vertex** not per-triangle

Pixel (fragment) operations

- lots of potential parallelism
- less predictable

Use queues and caches

# Why do we care?

This is why the hardware can be fast

It requires a specific model
Hardware implements this model

The programming interface is designed for this model. You need to understand it.

# Some History...

Custom Hardware (pre-1980)

rare, each different

Workstation Hardware (early 80s-early 90s)

increasing features, common methods

Consumer Graphics Hardware (mid 90s-)

cheap, eventually feature complete

Programmable Graphics Hardware (2002-)

# Graphics Workstations 1982-199X

Implemented graphics in hardware

Providing a common abstraction set

Fixed function –

it was built into the hardware

# Silicon Graphics (SGI)

Stanford Research Project 1980

Spun-off to SGI (company) 1982

The Geometry Engine

- 4x4 matrix mutiply chip
- approximate division

Raster engine (Z-buffer)

# 1988: The Personal Iris

The 4D-2X0 series

4 processors (240)

Different graphics

1988 – GT/GTX

1990 - VGX

# Why do you care?

It's the first time the abstractions were right

later stuff adds to it

It's where the programming model is from

it was IrisGL before OpenGL

It's the pipeline at it's essense

we'll add to it, not take away

# The Abstractions

Points / Lines / Triangles
Vertices in 4D
Color in 4D  (RGBA = transparency)
Per-Vertex transform (4x4 + divide by w)
Per-Vertex lighting
Color interpolation
Fill Triangle
Z-test (and other tests)
Double buffer (and other buffers)

# What's left to add?

All of this was in software in the 80s

1990 – texture

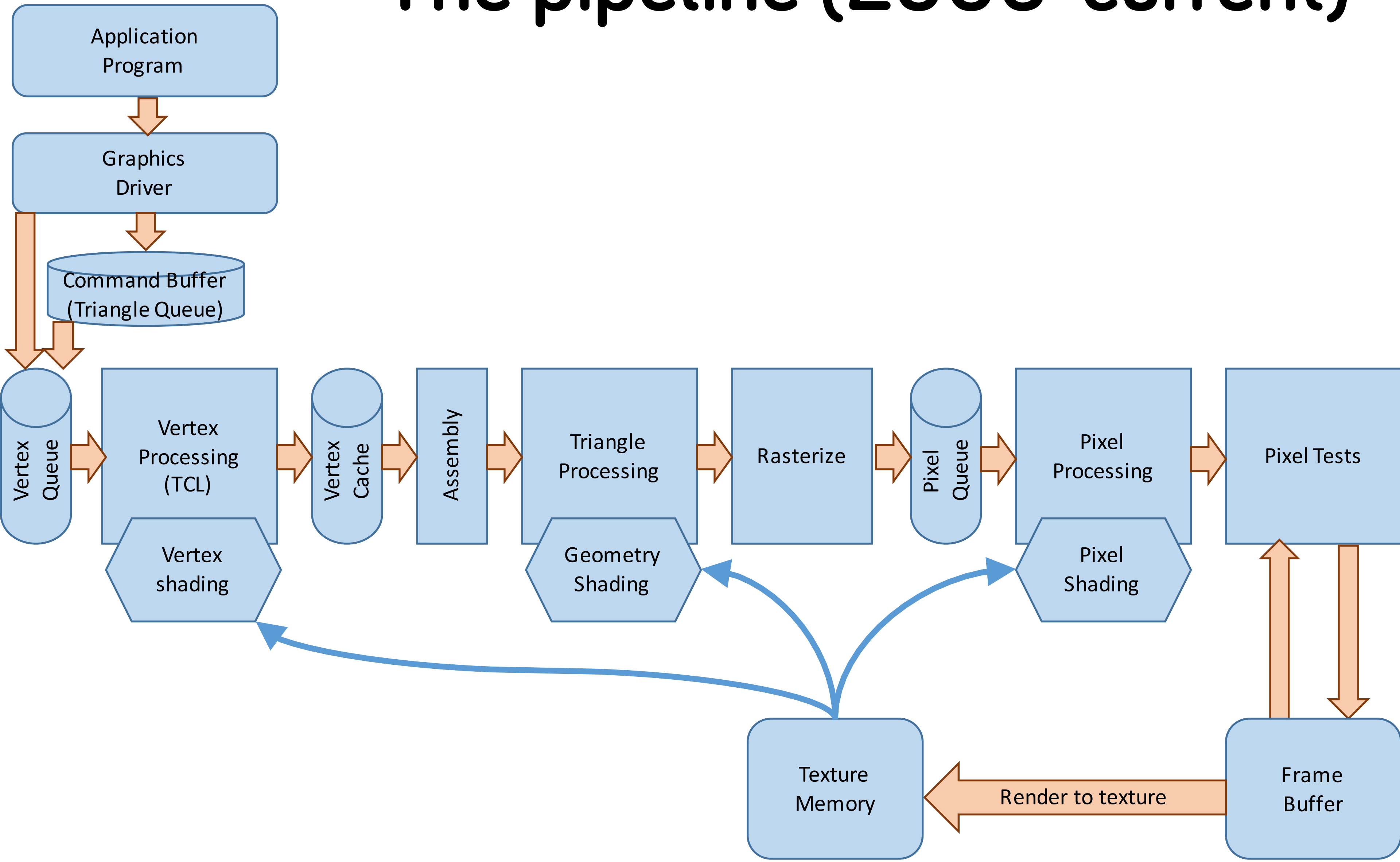
1992 – multi-texture (don't really need)

1998 (2000) – programmable shading

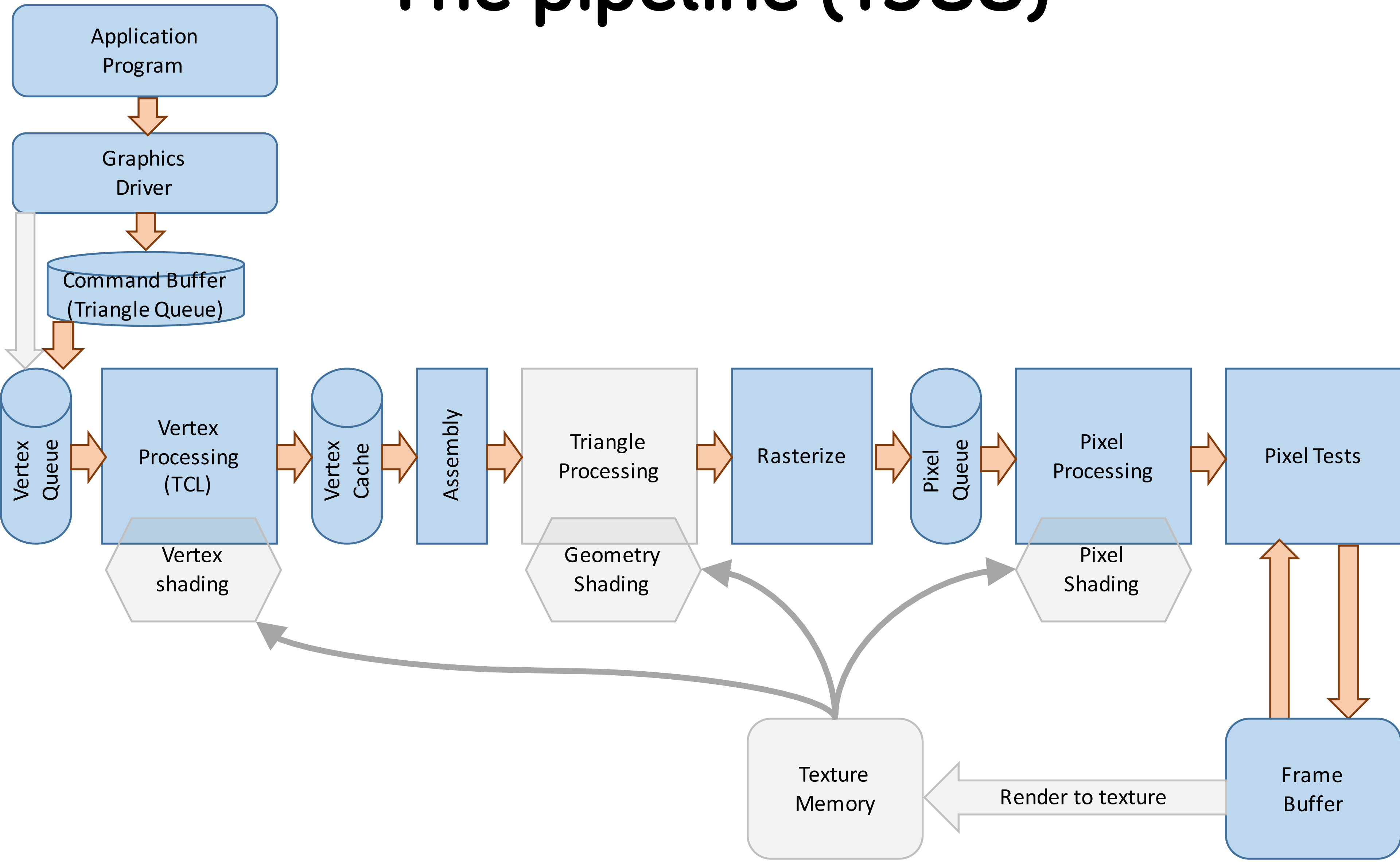
2002 – programmable pipelines

2005 – more programmability

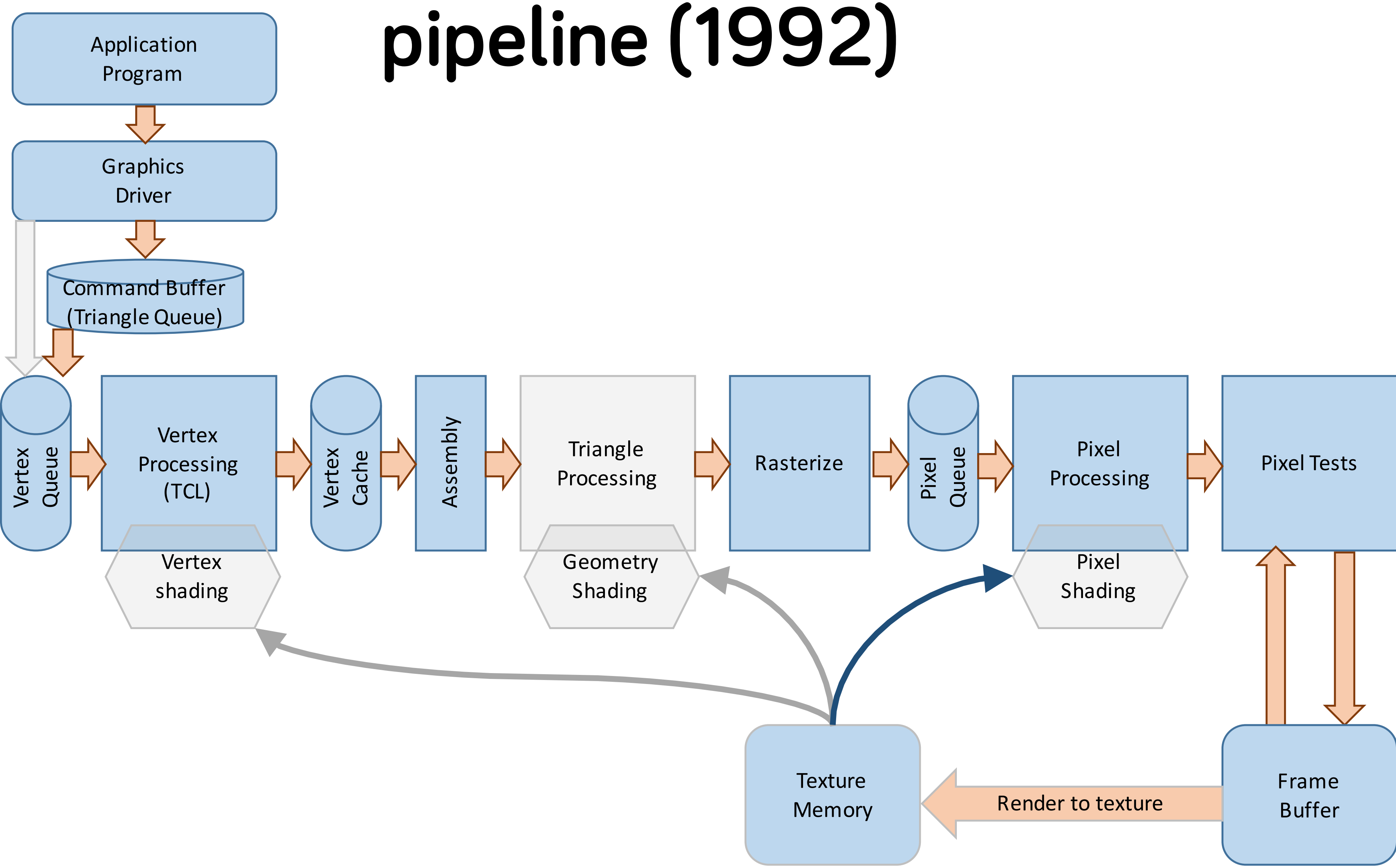
# The pipeline (2006-current)



# The pipeline (1988)



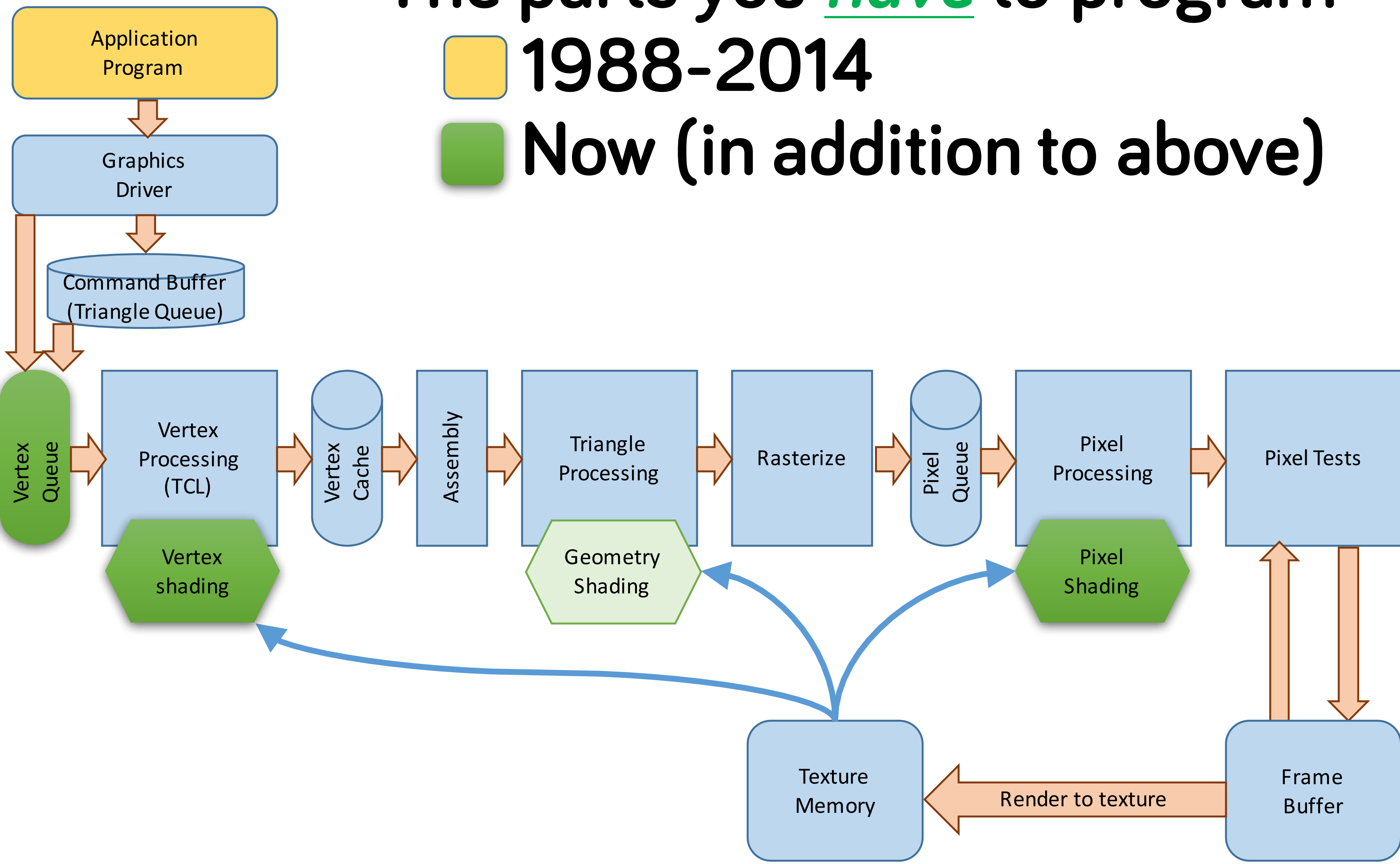
# The full fixed-function pipeline (1992)



# The parts you *have* to program

1988-2014

Now (in addition to above)



# A Triangle’s Journey

# Things to observe as we travel through the pipeline...

What does each stage do?

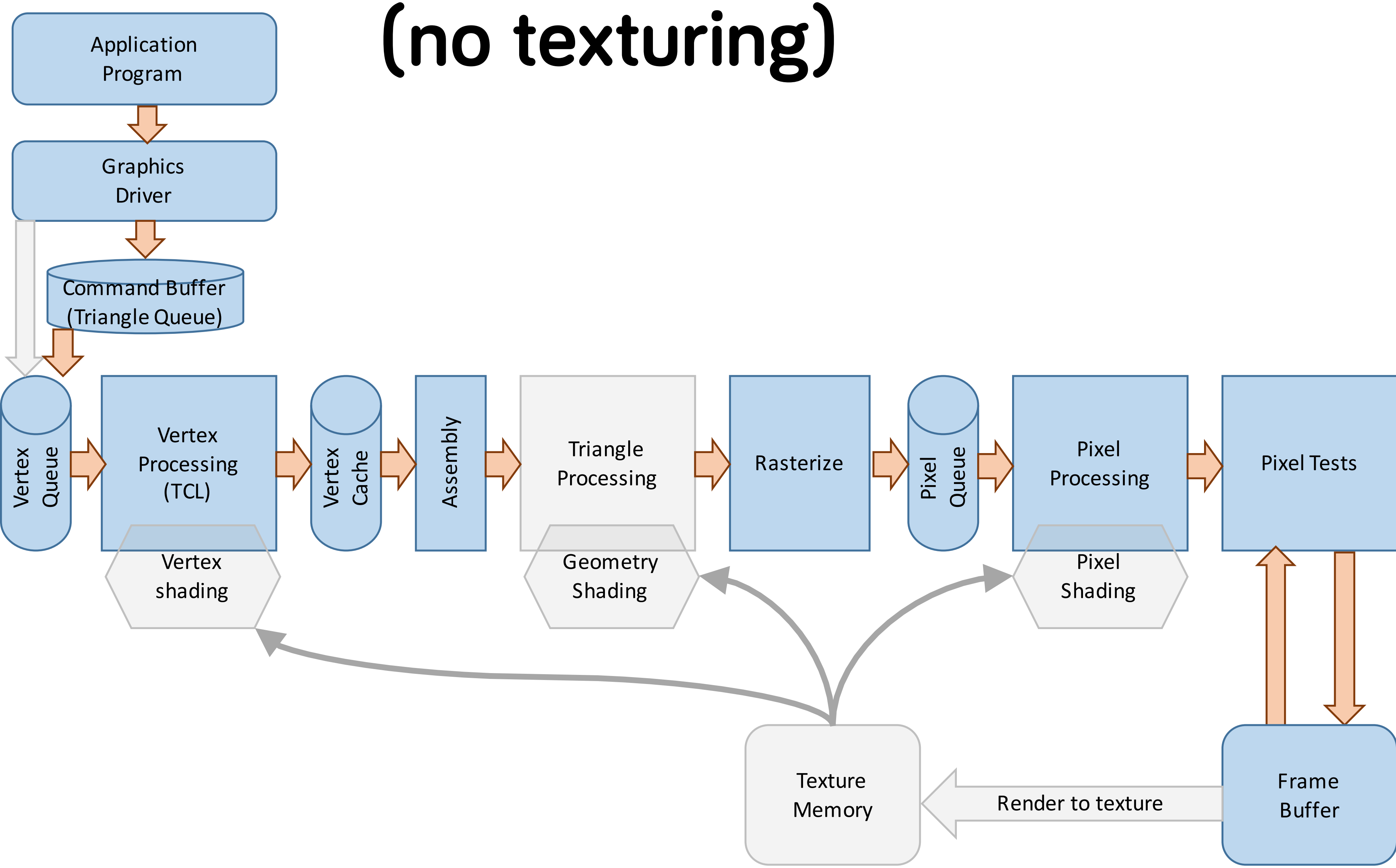
What are its inputs and output?

important for programmability

Why would it be a bottleneck?

and what could we do to avoid it

# The pipeline (1988) (no texturing)



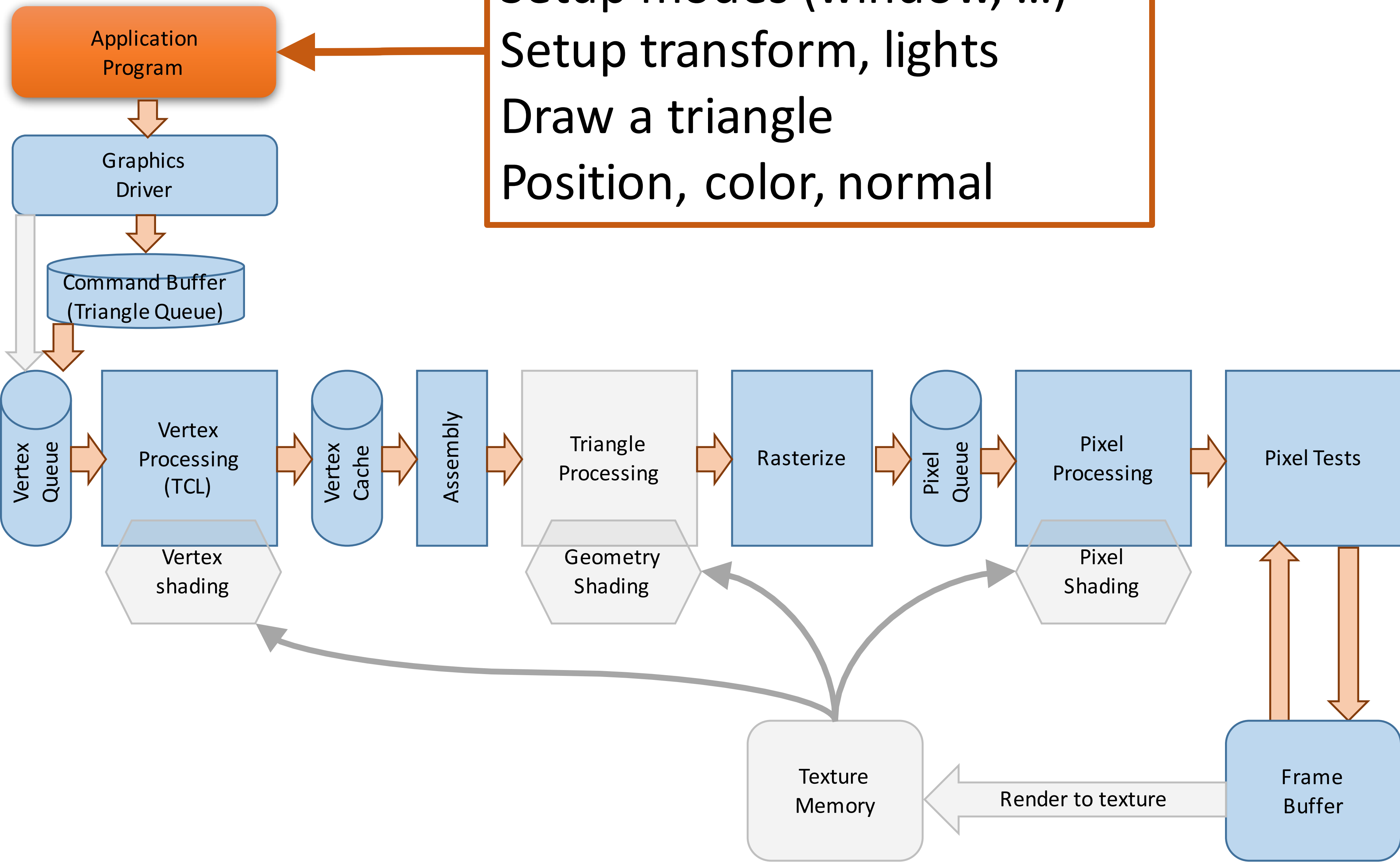
**Start here**

Setup modes (window, …)

Setup transform, lights

Draw a triangle

Position, color, normal



# Drawing a triangle

**Modes** per triangle

- which window, how to fill, use z-buffer, ...

**Data** per-vertex

- position
- normal
- color
- other things (texture coords)

# Per Vertex?

**Modes** per triangle

which window, how to fill, use z-buffer, …

**Data** per-vertex

position

normal ← allow us to make non-flat

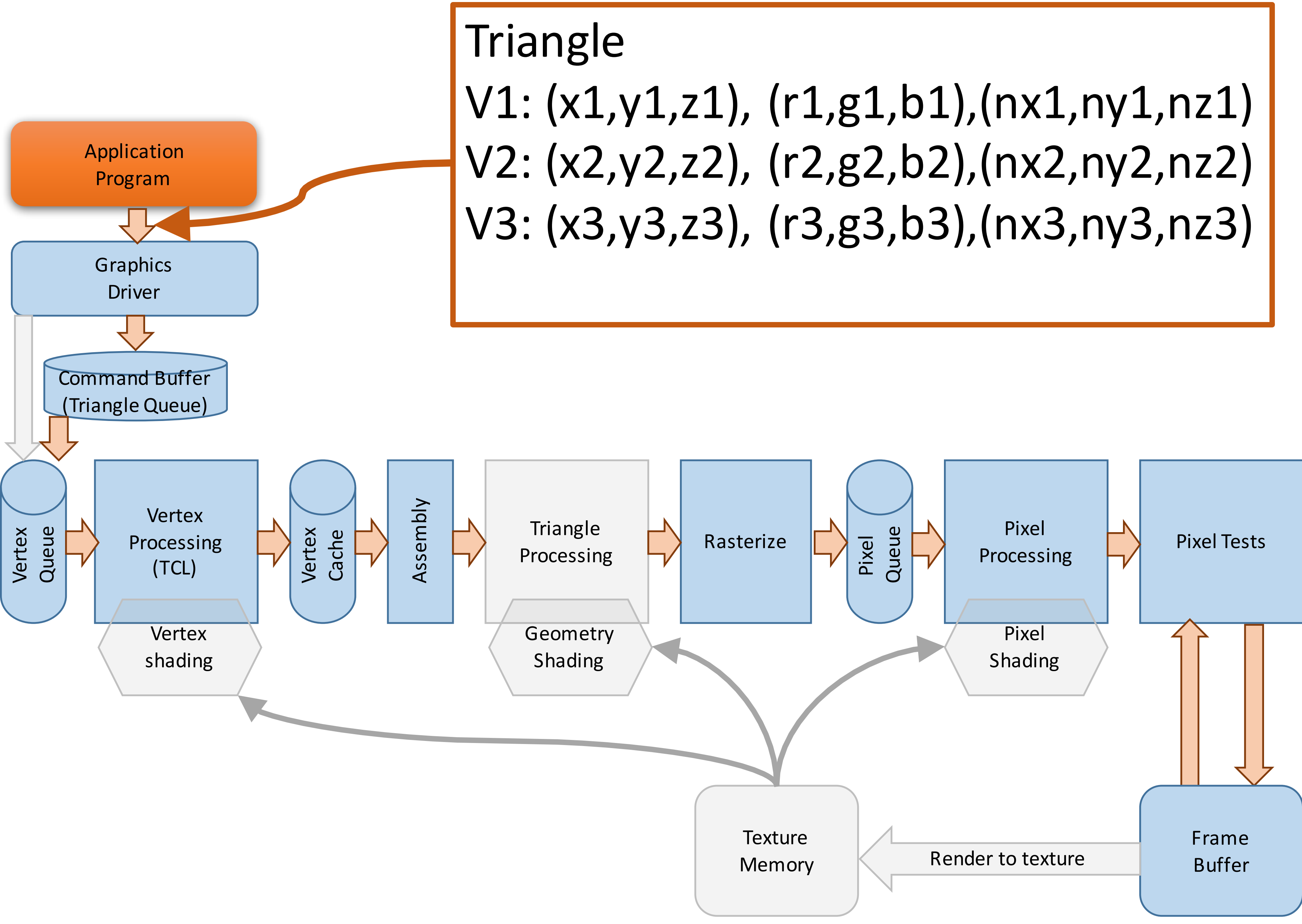
color ← allows us to interpolate

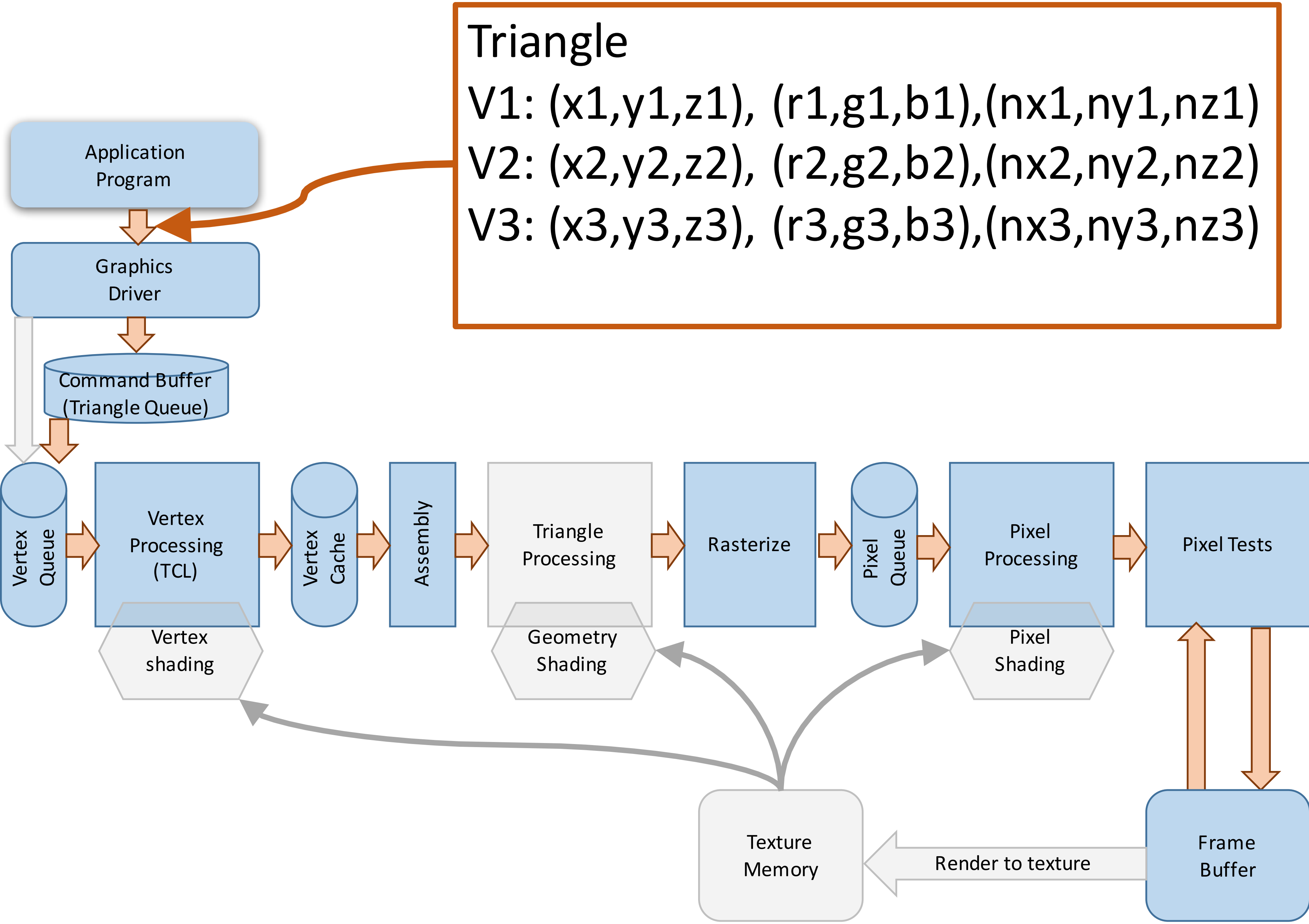
other things (texture coords)

# Per-Vertex not Per-Triangle

Allows sharing vertices between triangles

Or make all the vertices the same
(color, normal, …) to get truly flat


Triangle
V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
V3: (x3,y3,z3), (r3,g3,b3),(nx3,ny3,nz3)
Application Program
Graphics Driver
Command Buffer (Triangle Queue)
Vertex Queue
Vertex Processing (TCL)
Vertex shading
Vertex Cache
Assembly
Triangle Processing
Geometry Shading
Rasterize
Pixel Queue
Pixel Processing
Pixel Shading
Pixel Tests
Texture Memory
Render to texture
Frame Buffer


Triangle
V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
V3: (x3,y3,z3), (r3,g3,b3),(nx3,ny3,nz3)
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Triangle Processing
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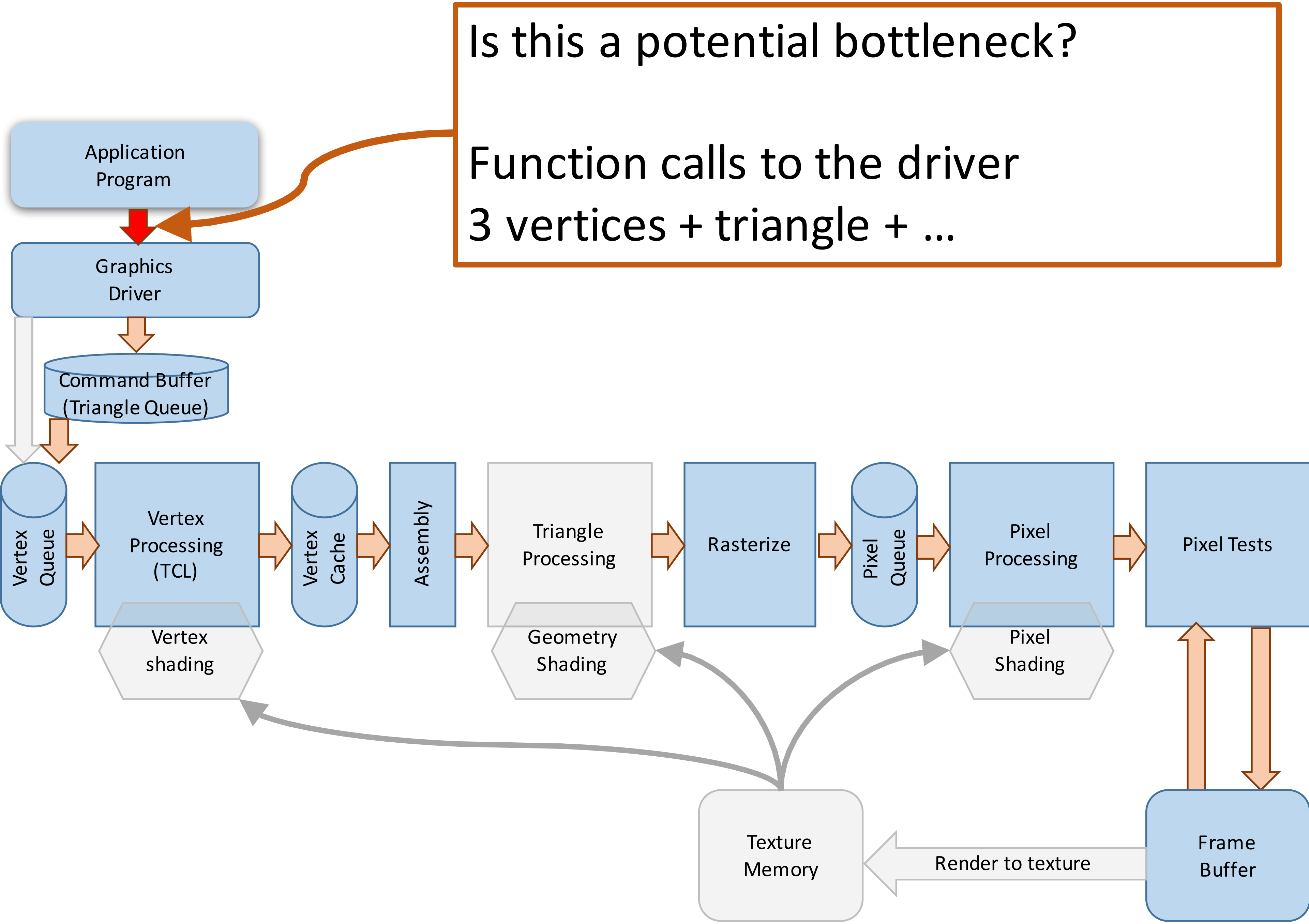
Pixel Queue
Pixel Processing
Pixel Shading
Pixel Tests
Texture Memory
Render to texture
Frame Buffer


Is this a potential bottleneck?
Function calls to the driver
3 vertices + triangle + …
Application Program
Graphics Driver
Command Buffer (Triangle Queue)
Vertex Queue
Vertex Processing (TCL)
Vertex shading
Vertex Cache
Assembly
Triangle Processing
Geometry Shading
Rasterize
Pixel Queue
Pixel Processing
Pixel Shading
Pixel Tests
Texture Memory
Render to texture
Frame Buffer

# Old style OpenGL

```
begin(TRIANGLE);
c3f(r1,g1,b1);
n3f(nx1,ny1,nz1);
v3f(x1,y1,z1);
c3f(r2,g2,b2);
n3f(nx2,ny2,nz2);
v3f(x2,y2,z2);
c3f(r3,g3,b3);
n3f(nx3,ny3,nz3);
v3f(x3,y3,z3);
end(TRIANGLE);
```

11 function calls
35 arguments pushed

Old days:
This is a lot less than the number of pixels!

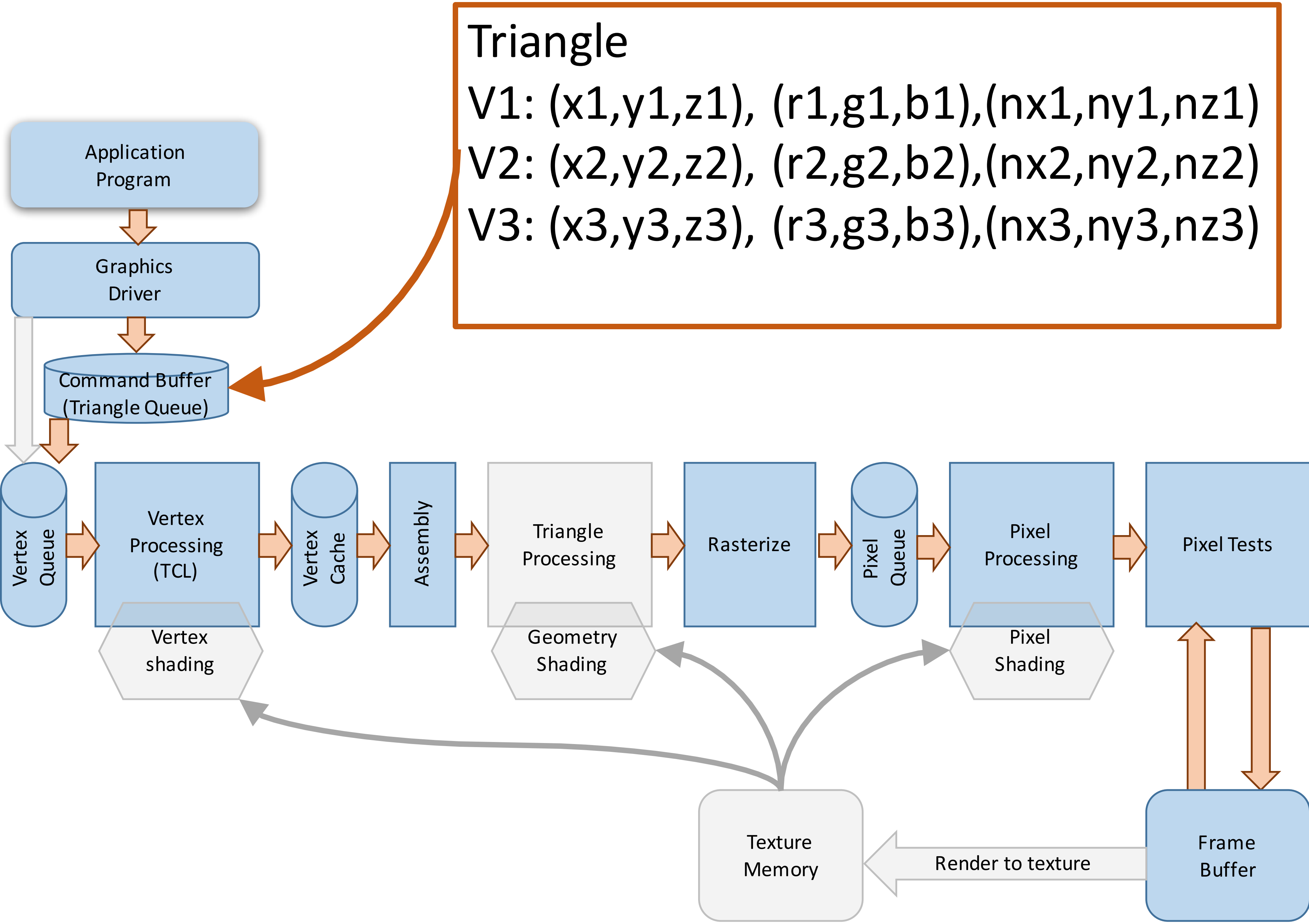
Nowadays:
Just the memory access swamps the process

# Coming Soon...

Block transfers of data

Data for lots of triangles moved as a block

Try to draw groups of triangles


Triangle
V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
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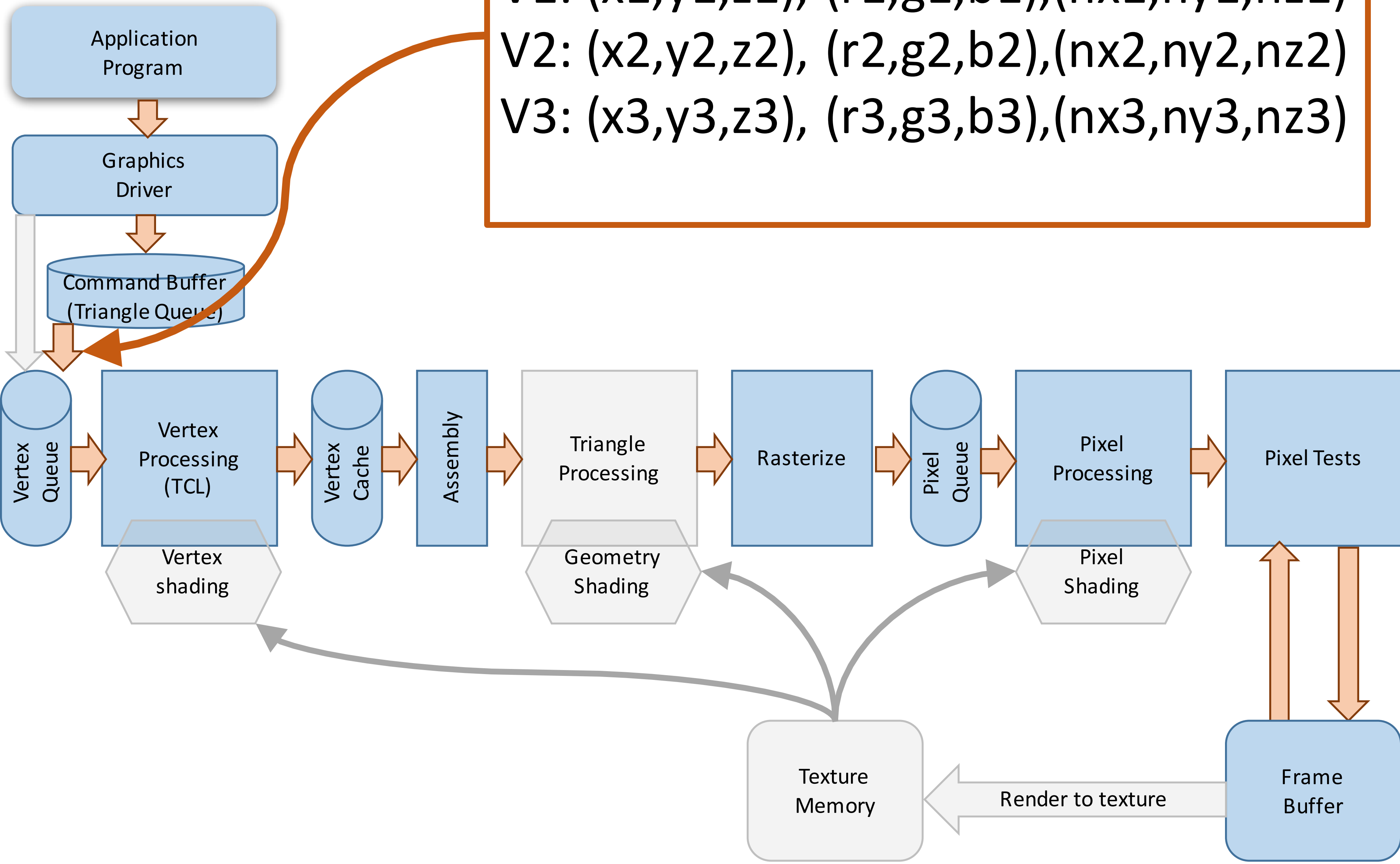
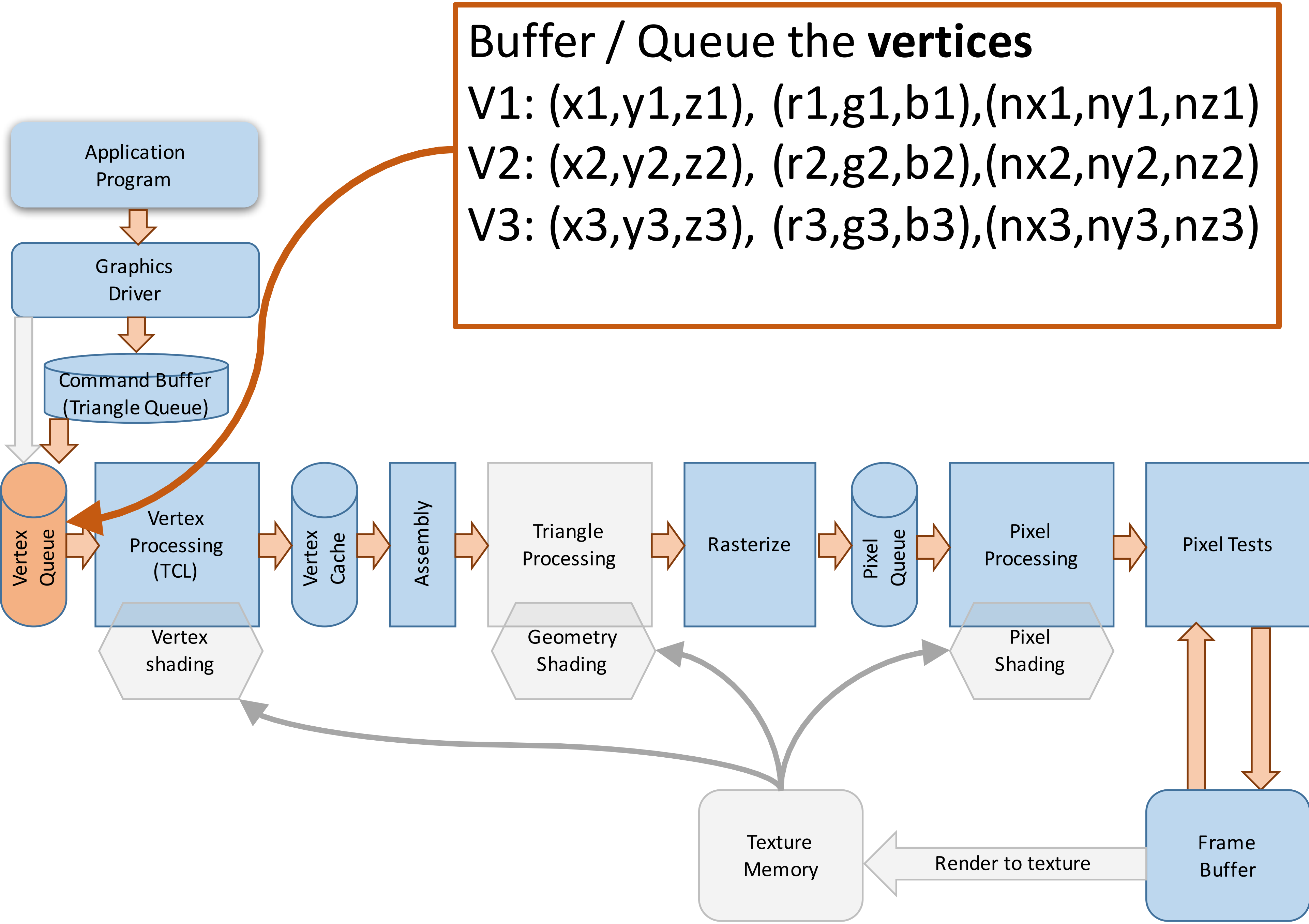
Pixel Queue
Pixel Processing
Pixel Tests
Vertex shading
Geometry Shading
Pixel Shading
Texture Memory
Render to texture
Frame Buffer

Split up triangles into **vertices**

V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
V3: (x3,y3,z3), (r3,g3,b3),(nx3,ny3,nz3)





Buffer / Queue the **vertices**
V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
V3: (x3,y3,z3), (r3,g3,b3),(nx3,ny3,nz3)
Application Program
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Command Buffer (Triangle Queue)
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Pixel Processing
Pixel Tests
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Geometry Shading
Pixel Shading
Texture Memory
Render to texture
Frame Buffer

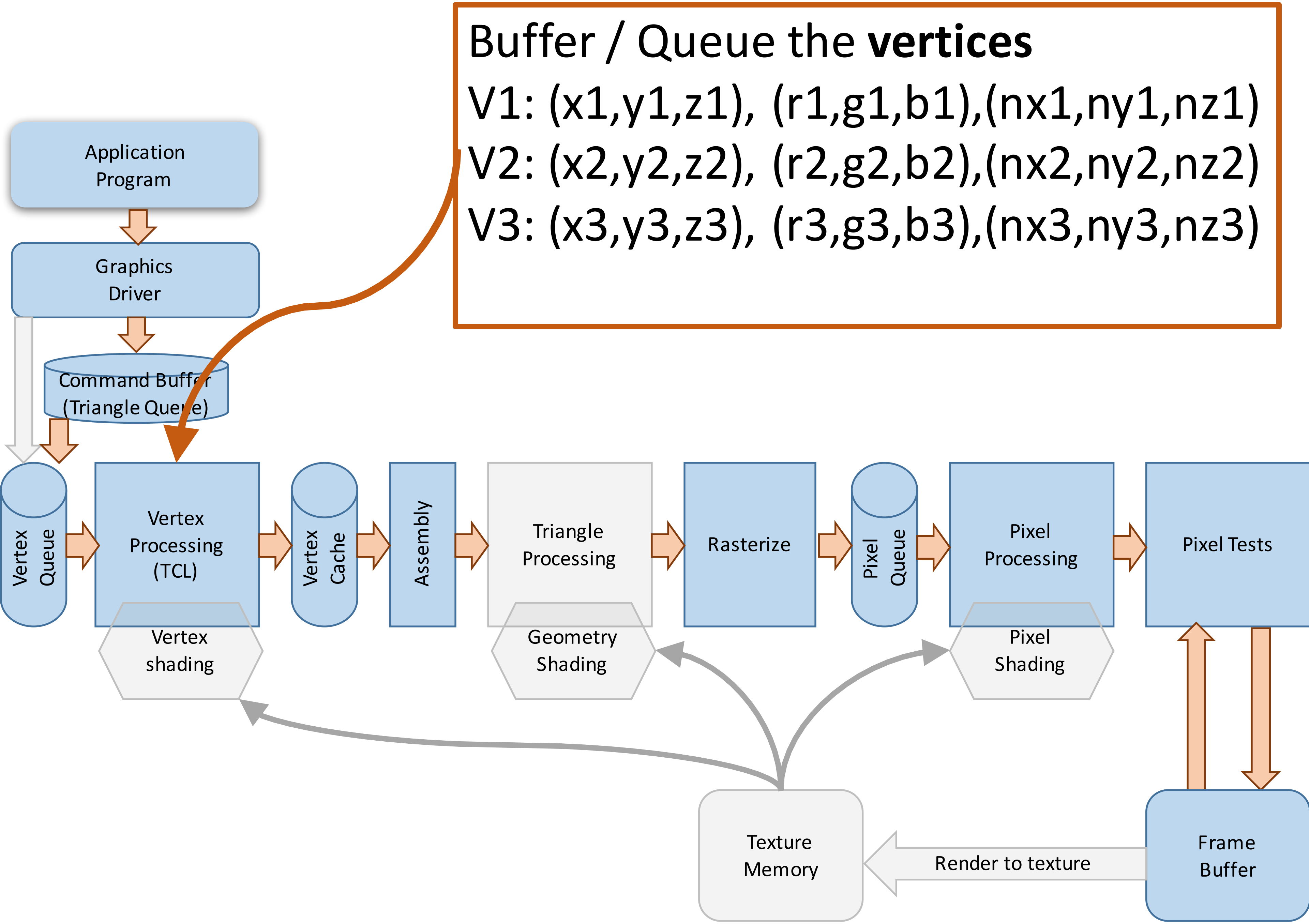
# Buffering Vertices

Old Days:

- Vertex processing expensive
- Try to maximize re-use
- Process once an use for many triangles

Nowadays

- Getting vertex to hardware is expensive
- Process vertices in parallel


Buffer / Queue the **vertices**
V1: (x1,y1,z1), (r1,g1,b1),(nx1,ny1,nz1)
V2: (x2,y2,z2), (r2,g2,b2),(nx2,ny2,nz2)
V3: (x3,y3,z3), (r3,g3,b3),(nx3,ny3,nz3)
Application Program
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Command Buffer (Triangle Queue)
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Vertex Cache
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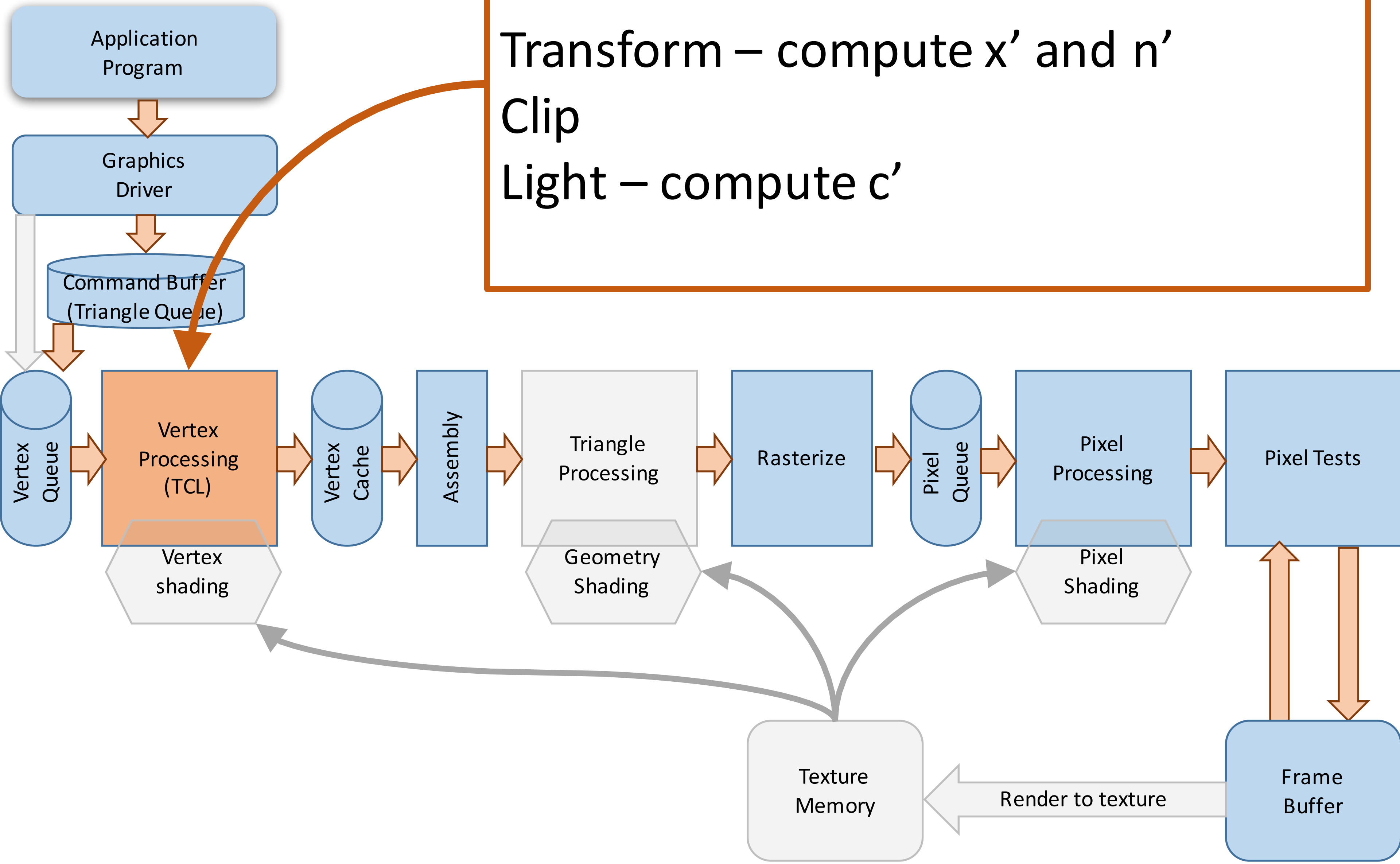
Pixel Processing
Pixel Tests
Vertex shading
Geometry Shading
Pixel Shading
Texture Memory
Render to texture
Frame Buffer

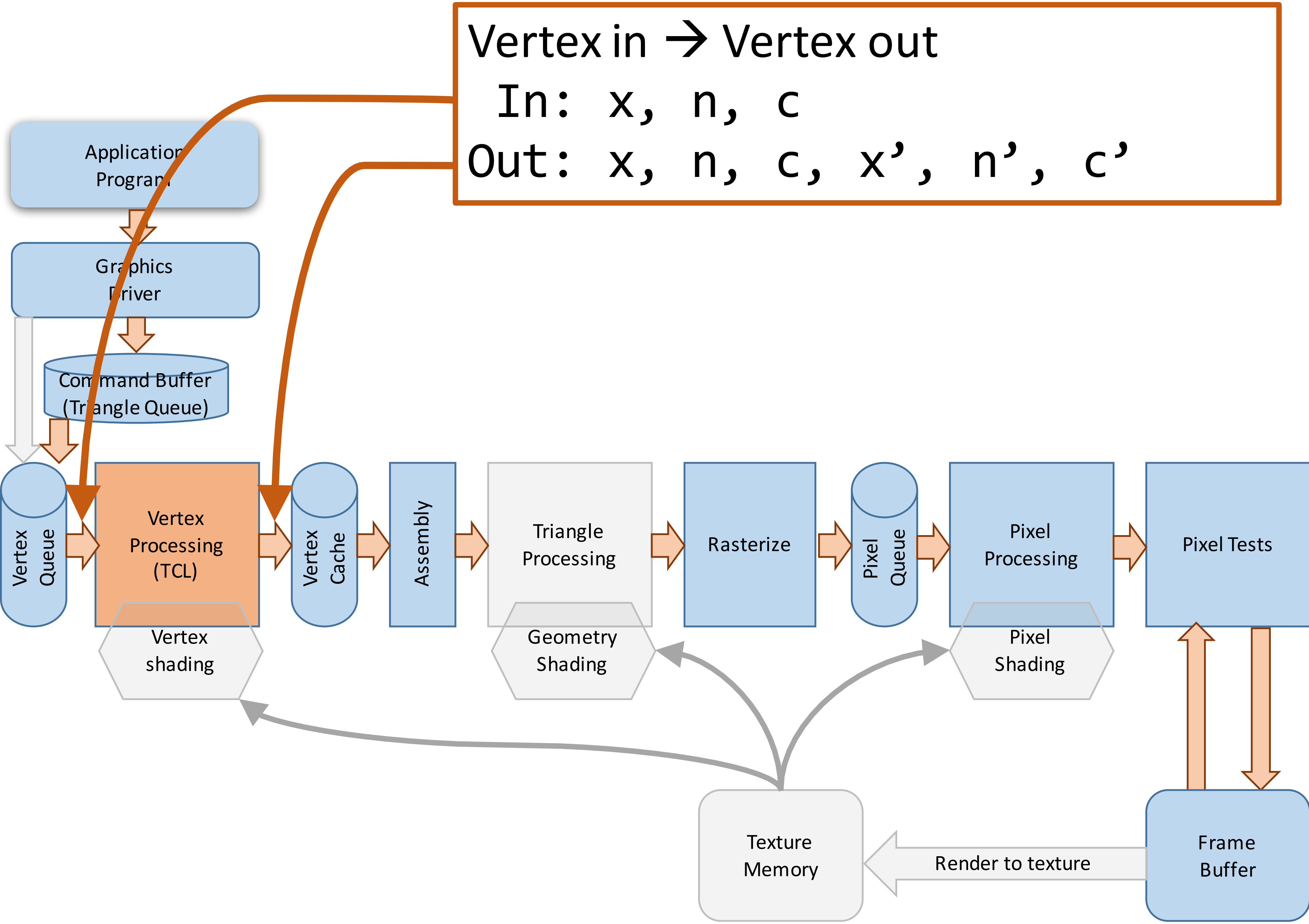
Process each vertex independently

Transform – compute x’ and n’

Clip

Light – compute c’




Vertex in → Vertex out
In: x, n, c
Out: x, n, c, x', n', c'
Application Program
Graphics Driver
Command Buffer (Triangle Queue)
Vertex Queue
Vertex Processing (TCL)
Vertex shading
Vertex Cache
Assembly
Triangle Processing
Geometry Shading
Rasterize
Pixel Queue
Pixel Processing
Pixel Shading
Pixel Tests
Texture Memory
Render to texture
Frame Buffer

# Vertex Processing

Just adds information to vertices

Computes transformation

screen space positons, normals

Computes “lighting”

new colors

(in the old days, clipping done here hence TCL)

# Vertex Processing: Each vertex is independent

Inputs are:

- vertex information for **this vertex**
- any “global” information
  - current transform, lighting, …

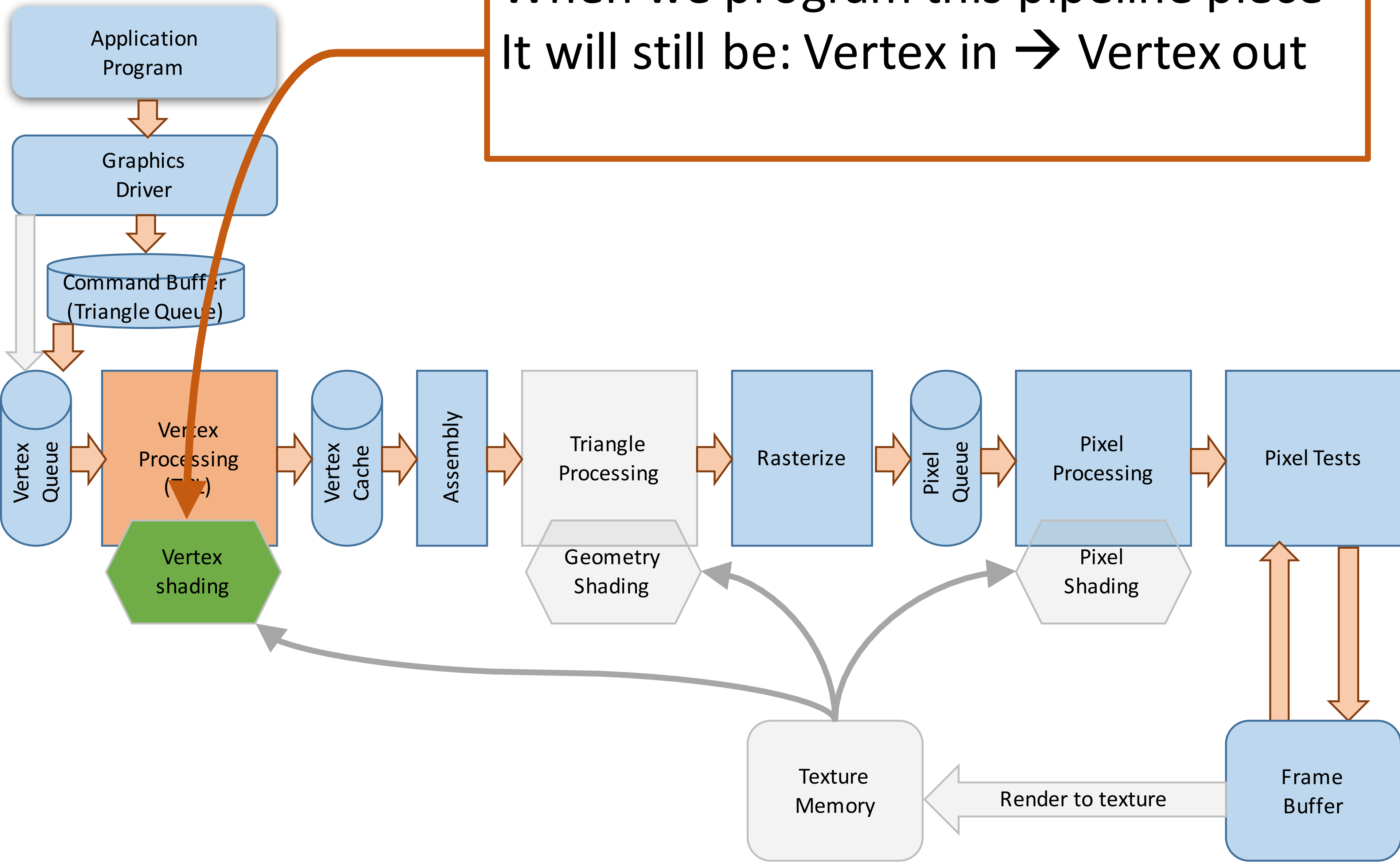
Outputs are:

- vertex information for **this vertex**

Looking ahead…

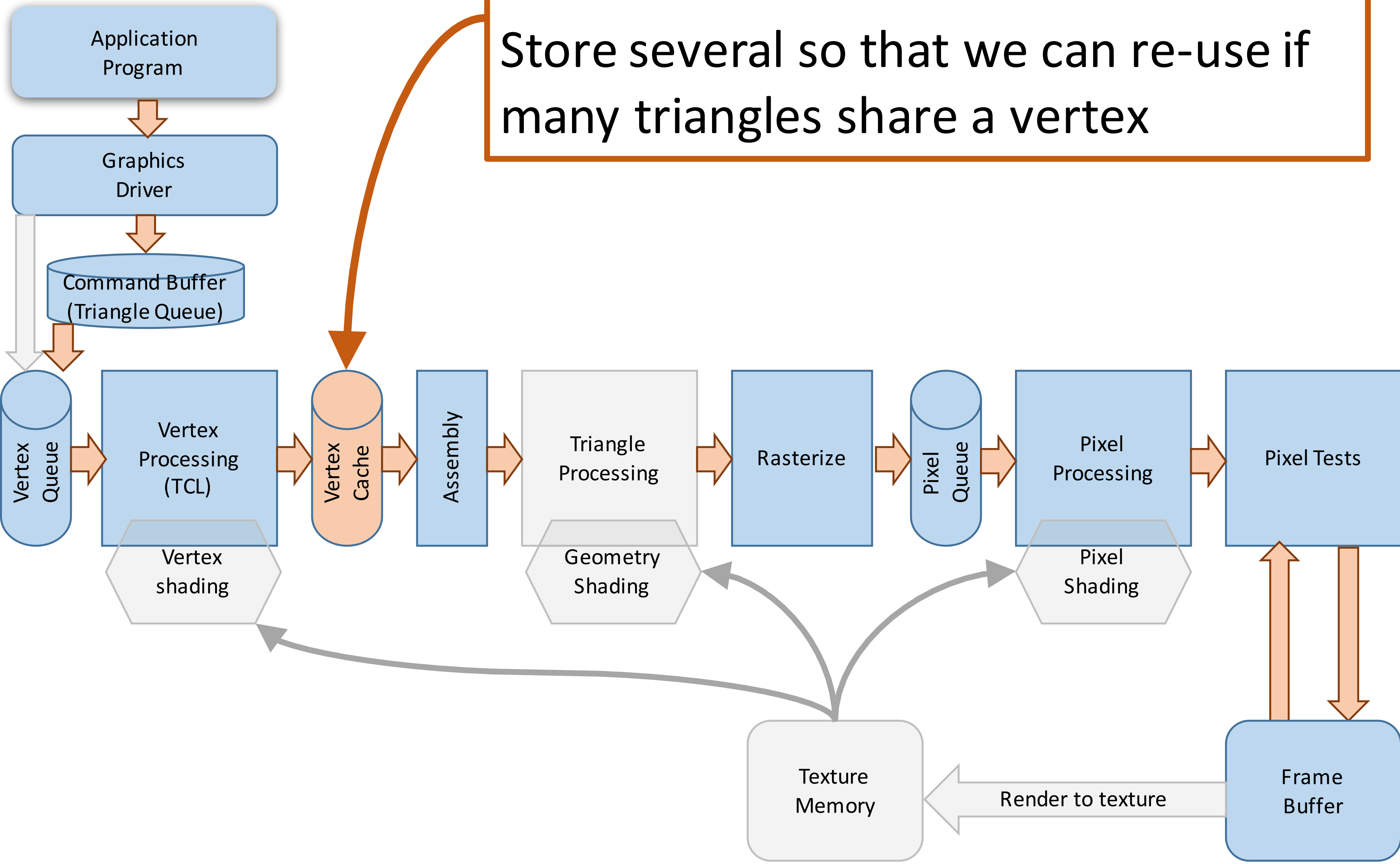
When we program this pipeline piece

It will still be: Vertex in → Vertex out



Store processed vertices in a **cache**

Store several so that we can re-use if many triangles share a vertex



# Vertex Caching

Old days:

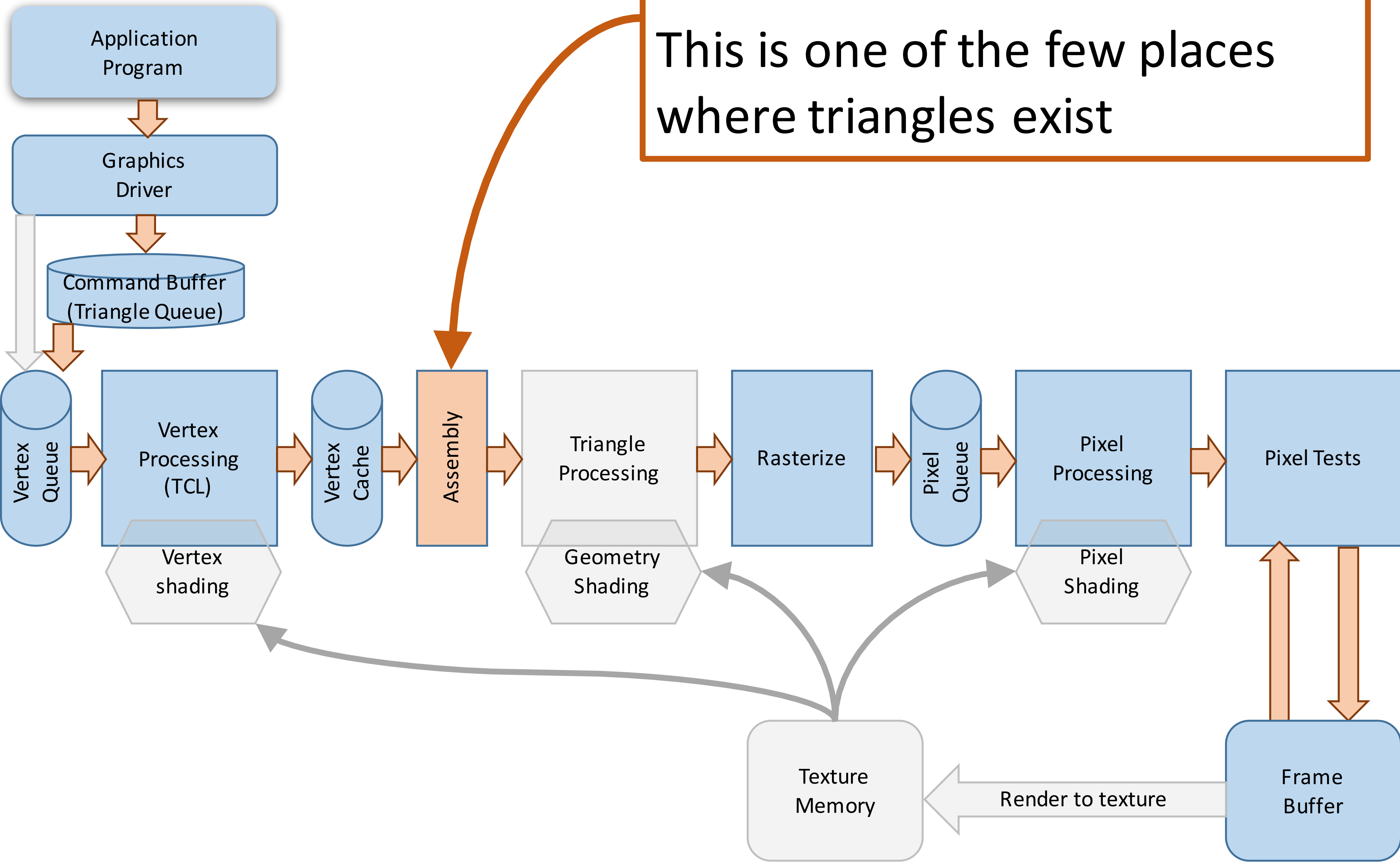
Big deal, important for performance

Now:

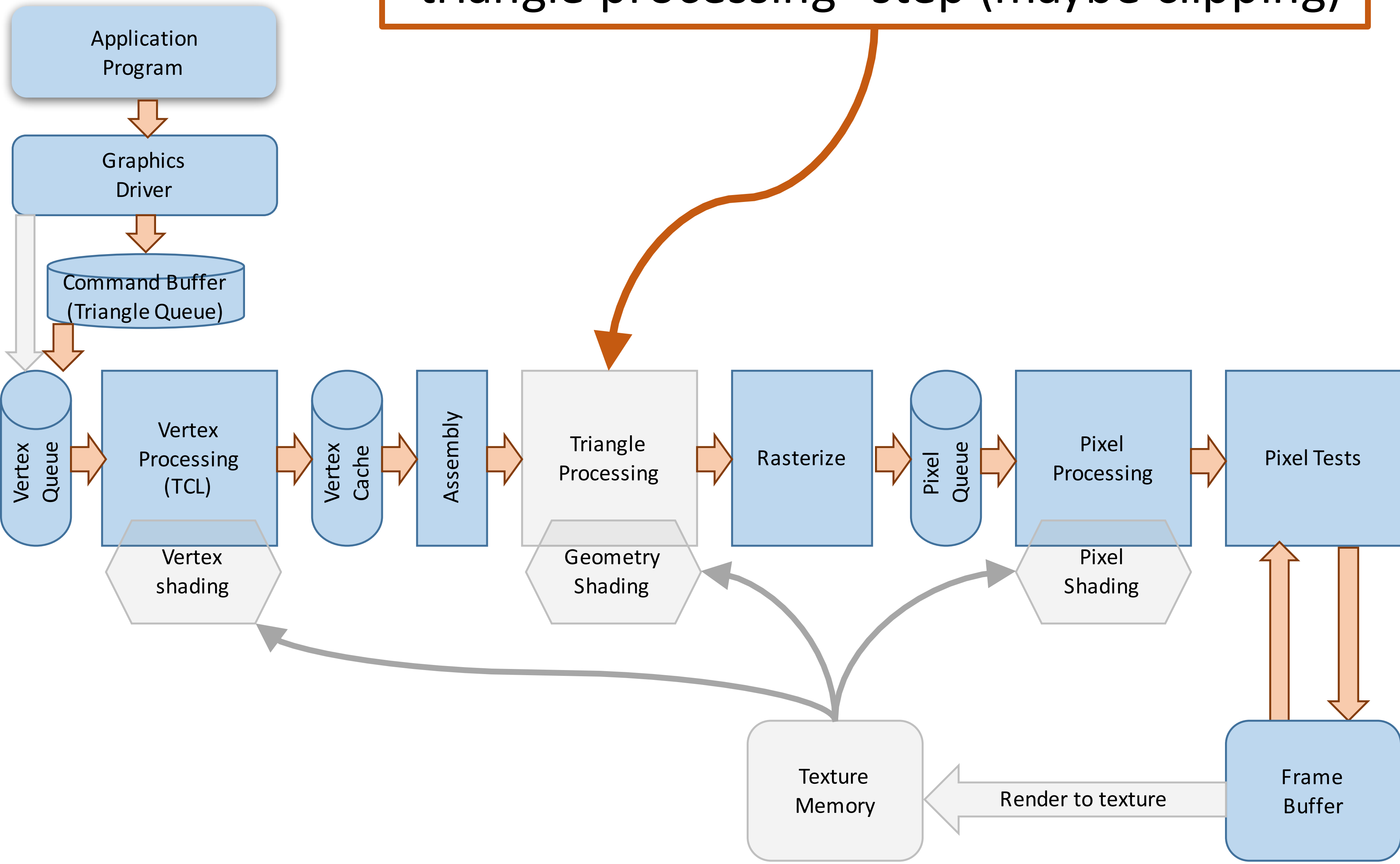
Not even sure that it's always done

Put triangles back together

This is one of the few places where triangles exist



In the fixed-function pipeline, there is no "triangle processing" step (maybe clipping)

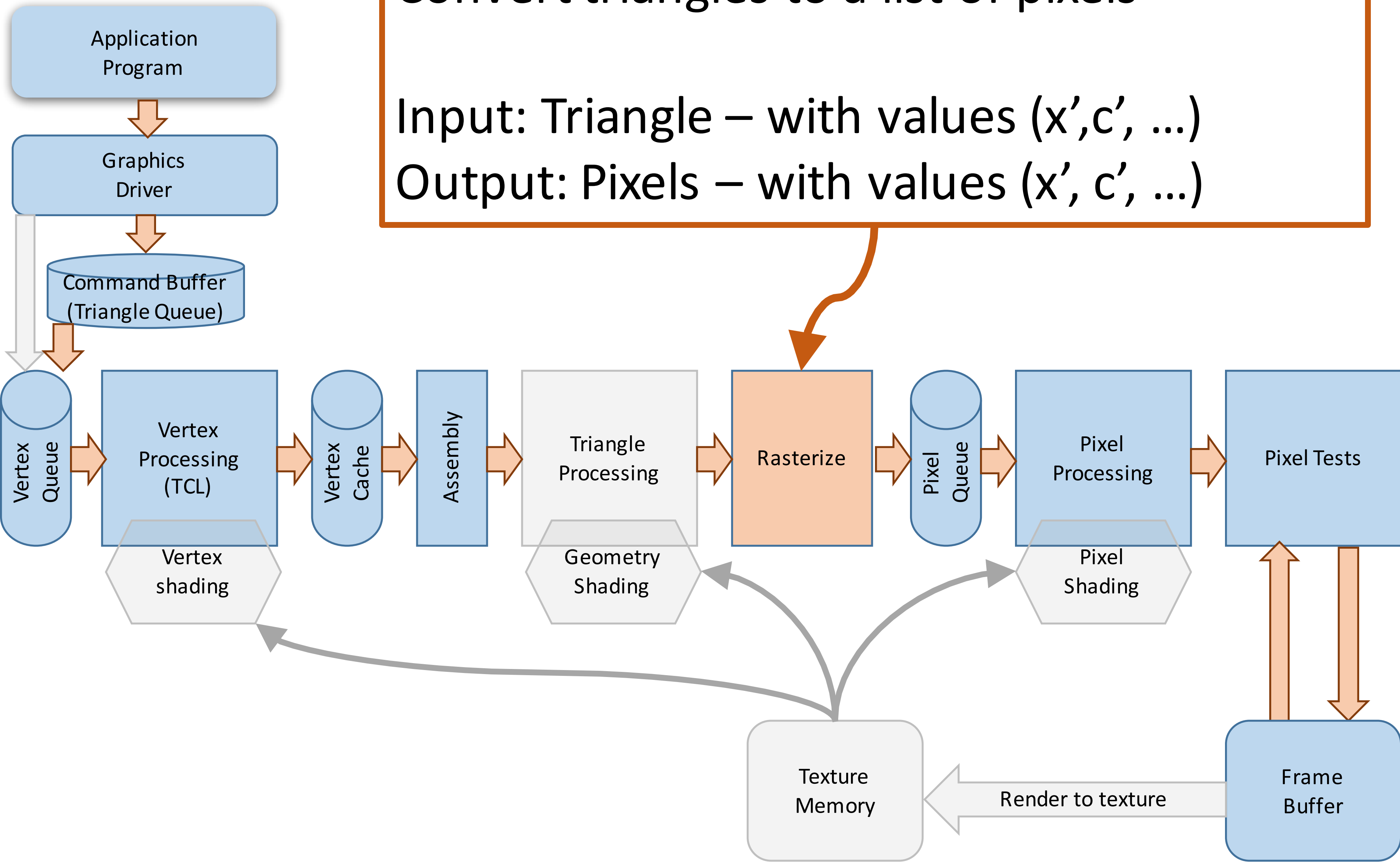


Rasterizer:

Convert triangles to a list of pixels

Input: Triangle – with values (x',c', …)

Output: Pixels – with values (x', c', …)



# Pixels or Fragments

I am using the terms interchangably

(actually, today I am using pixel)

**Technically...**

Pixel = a dot on the screen

Fragment = a dot on a triangle

might not become a pixel (fails z-test)

might only be part of a pixel

# Where do pixel values come from?

Each vertex has values

Each pixel comes from 3 vertices

Pixels interpolate their vertices' values

Barycentric interpolation

All values (in a pixel) are interpolated

# Each triangle is separate

Careful processing of edges so no cracks

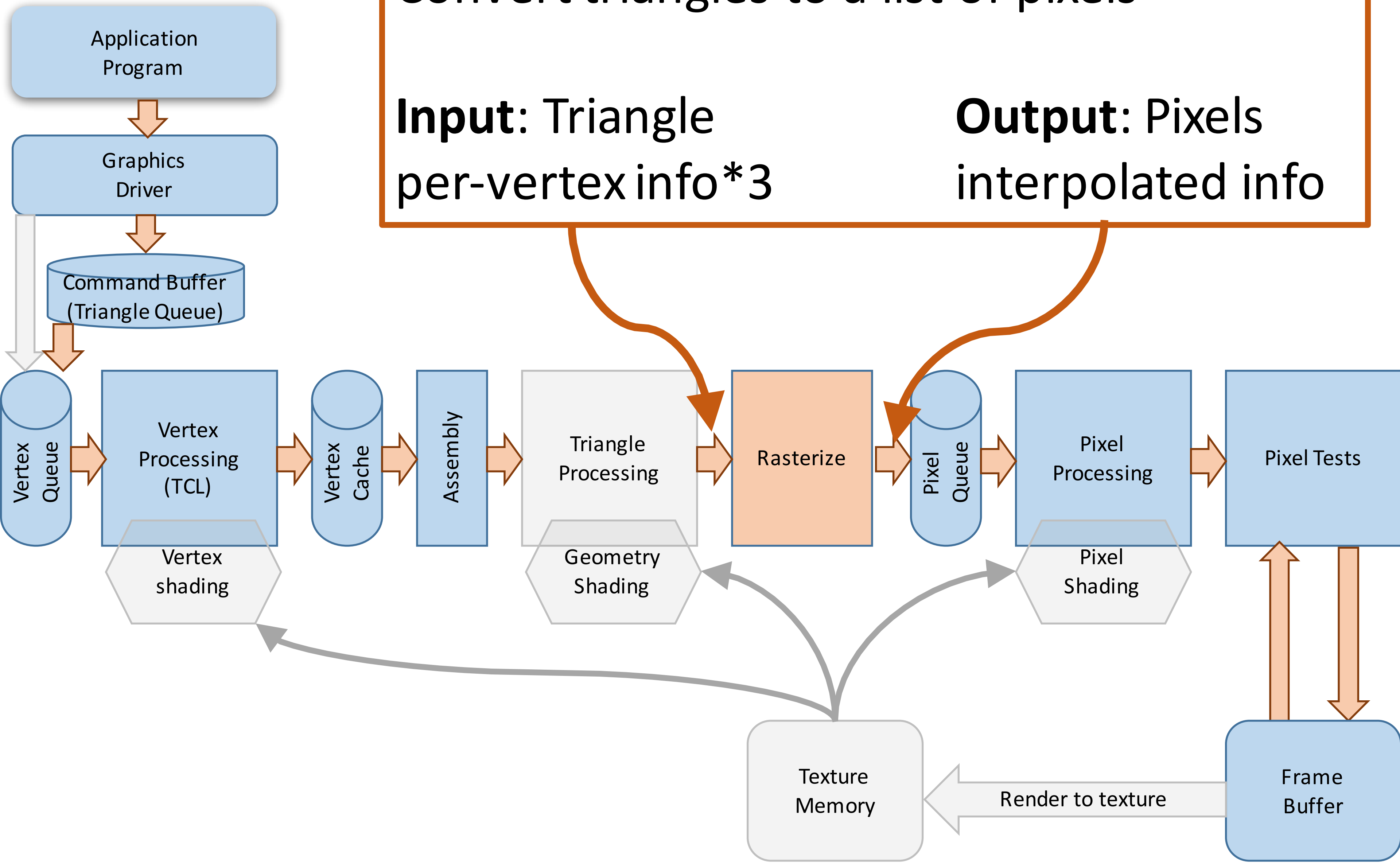
1 triangle → many pixels

Rasterizer:

Convert triangles to a list of pixels

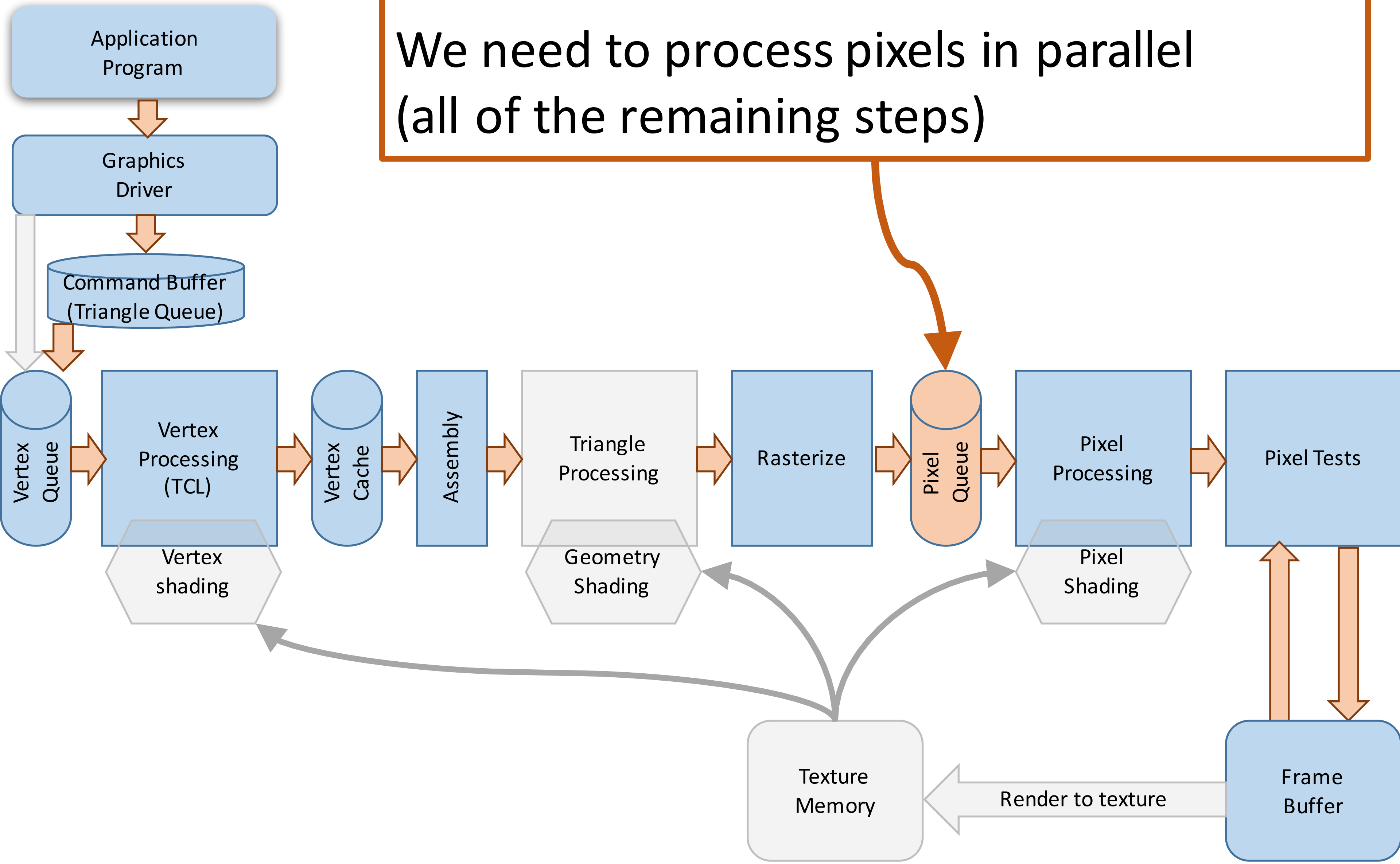
**Input**: Triangle per-vertex info*3

**Output**: Pixels interpolated info



Each triangle can make lots of pixels

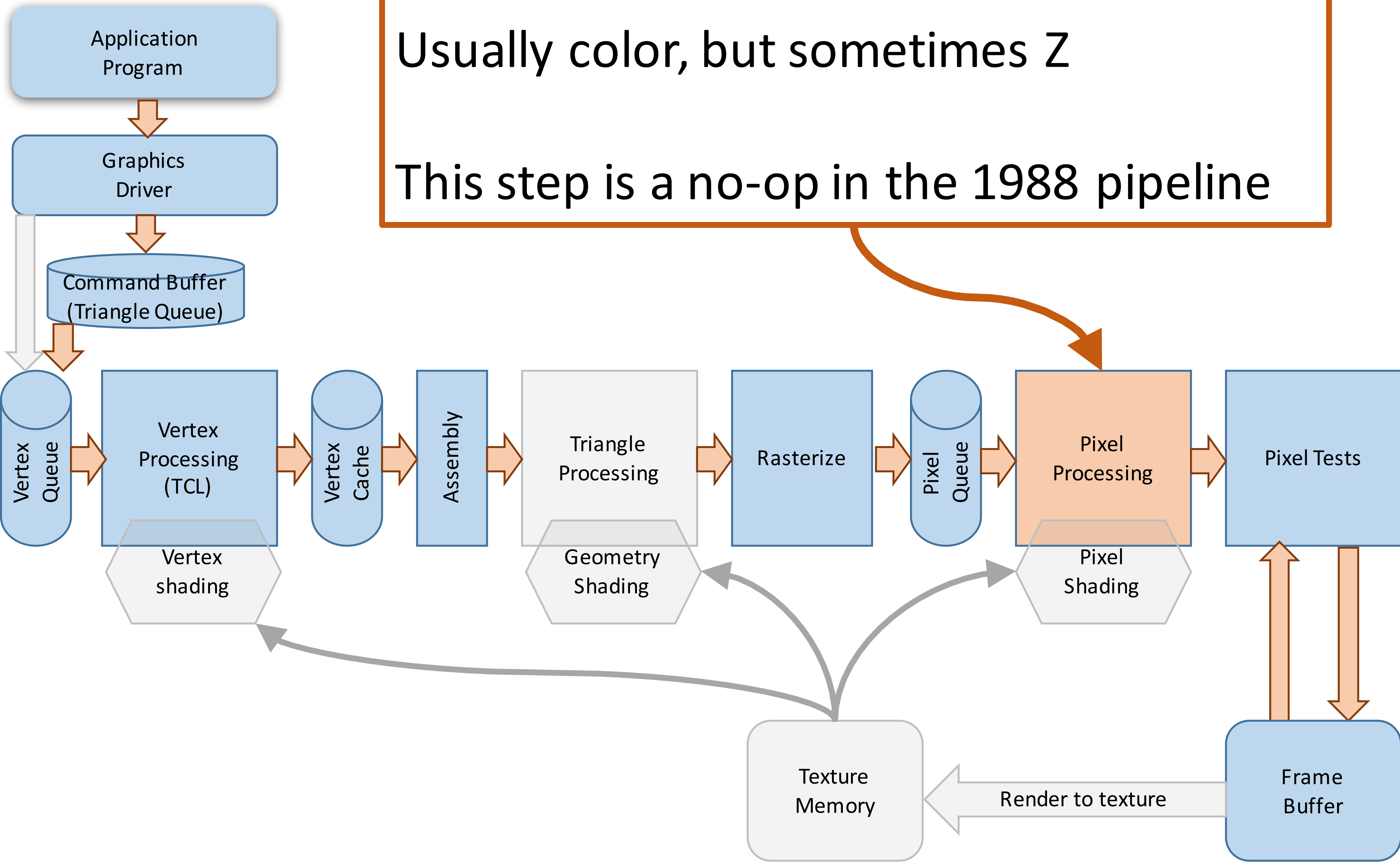
We need to process pixels in parallel
(all of the remaining steps)



Process each pixel to get its final values

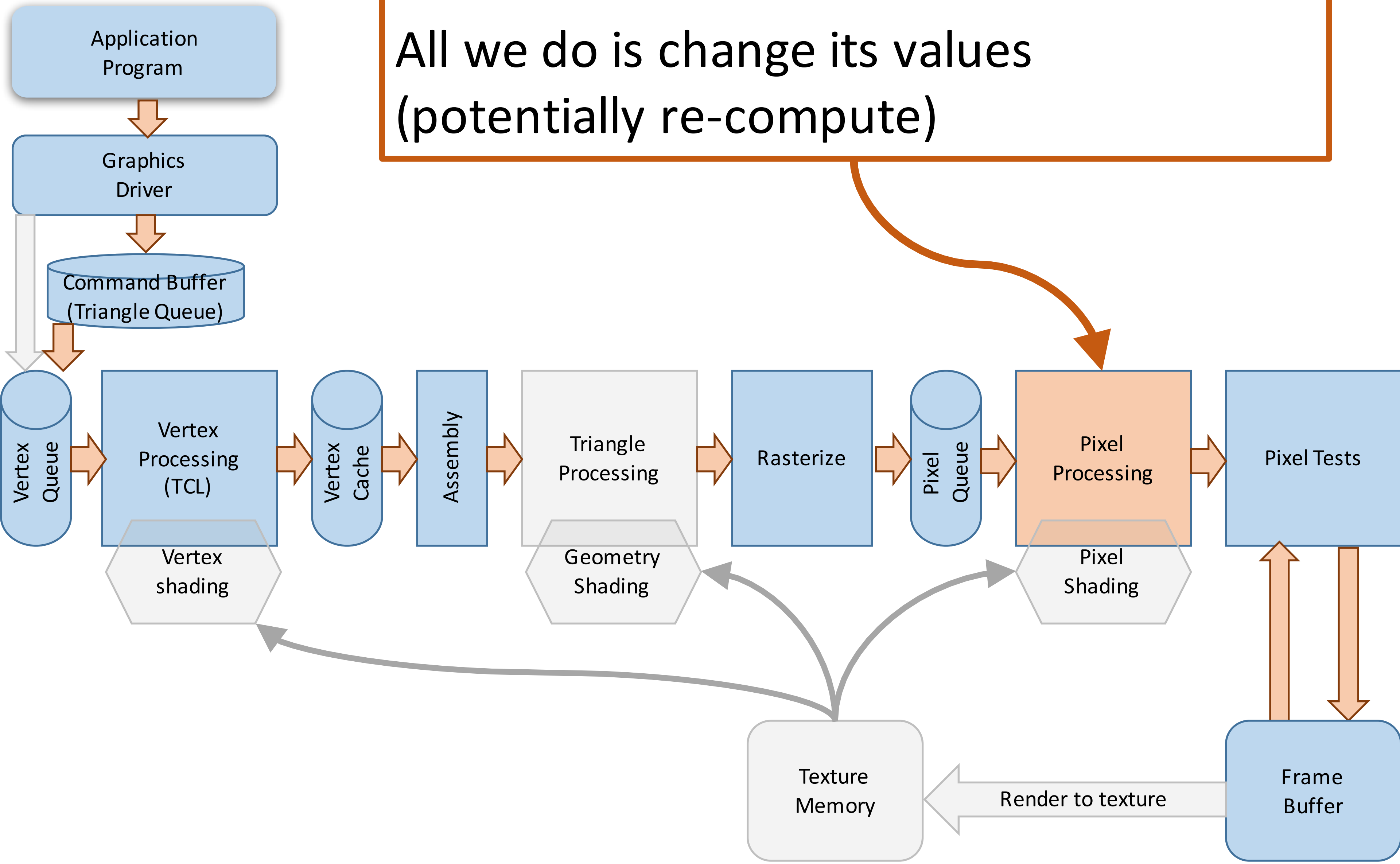
Usually color, but sometimes Z

This step is a no-op in the 1988 pipeline



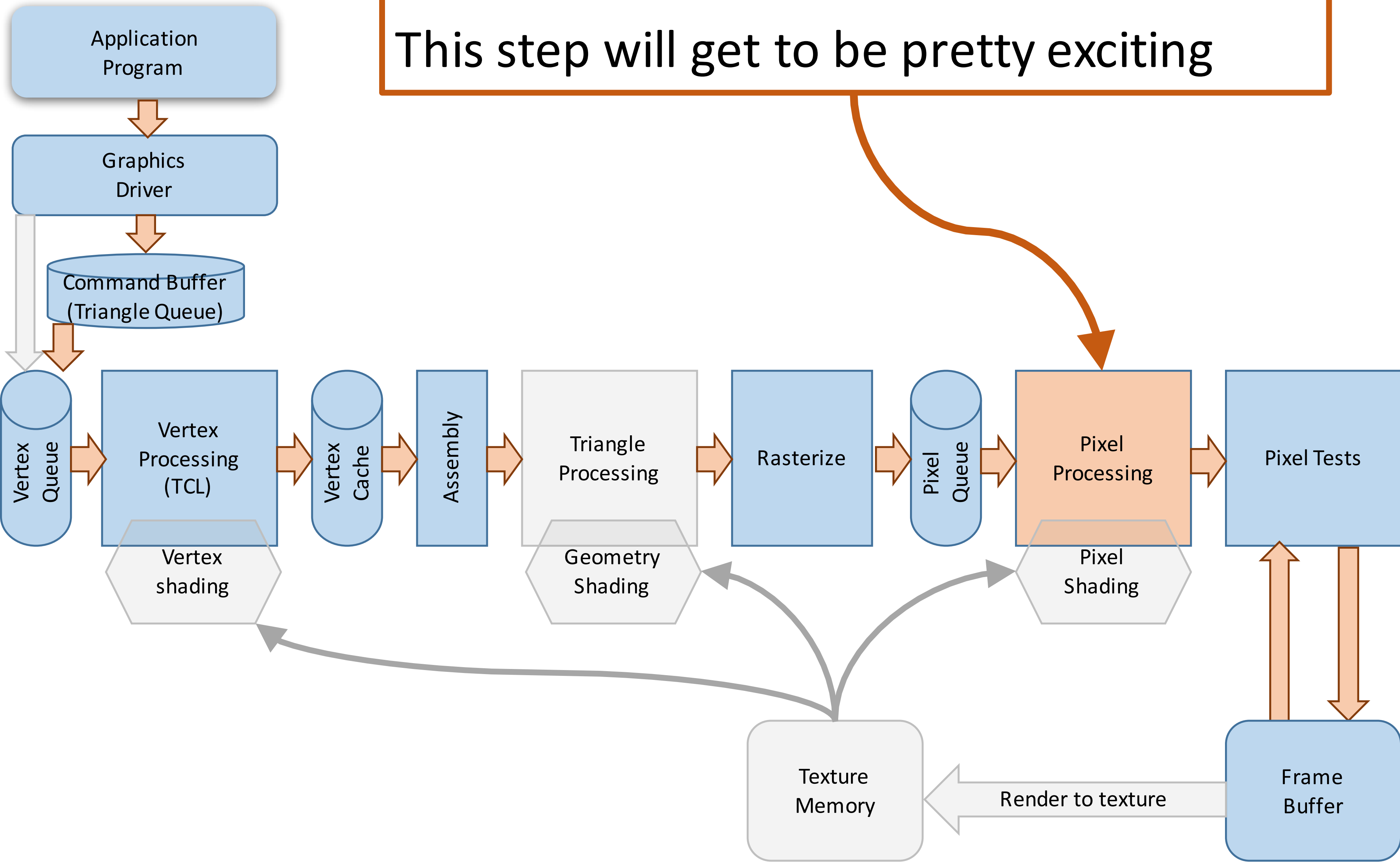
Pixel in → Pixel out, each independent

All we do is change its values (potentially re-compute)



Coming attractions…

This step will get to be pretty exciting



# Pixel Processing Ground Rules

Pixels are independent

Pixel in → Pixel out

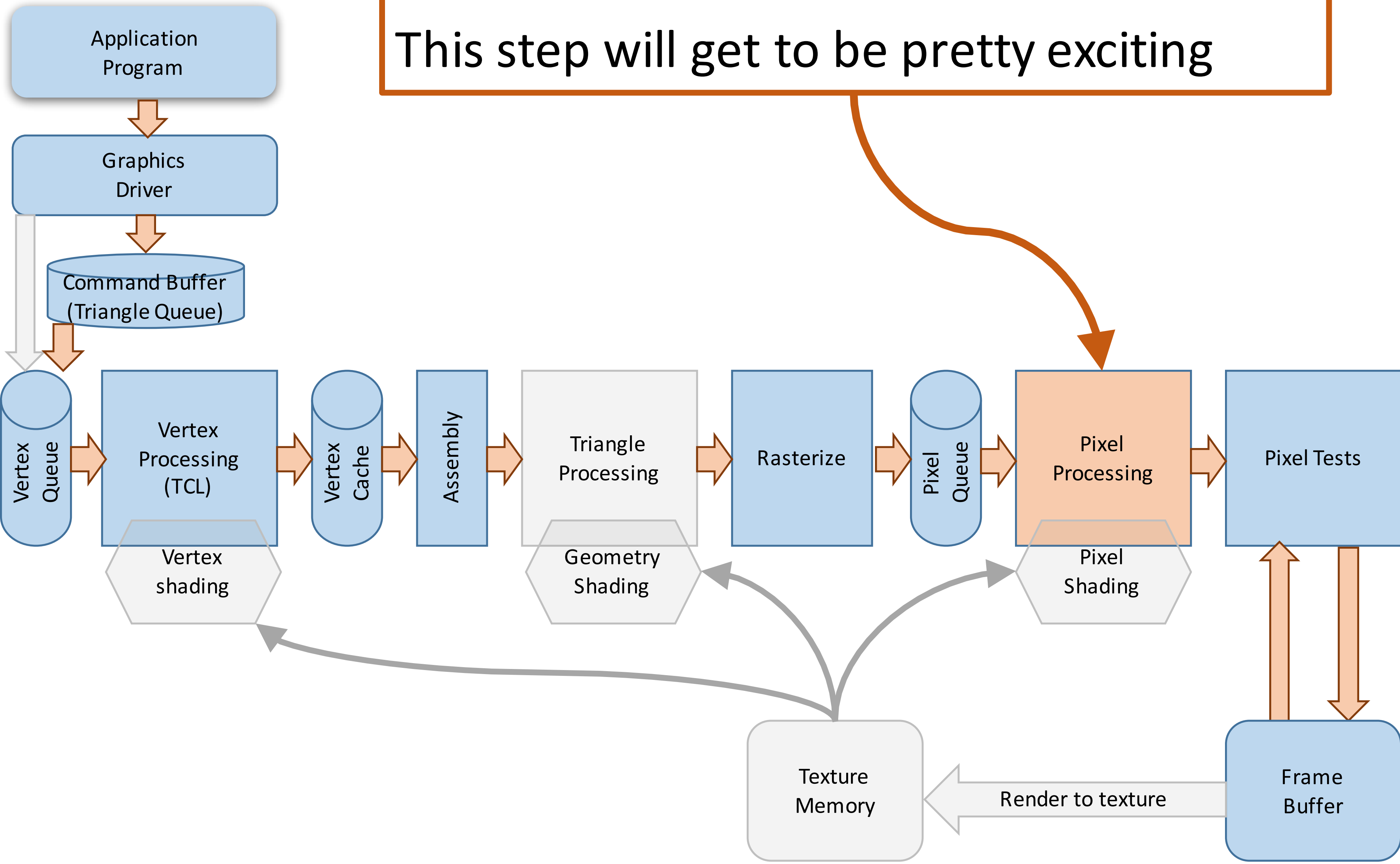
Changing its position (x,y) makes it a different pixel (so you can't)

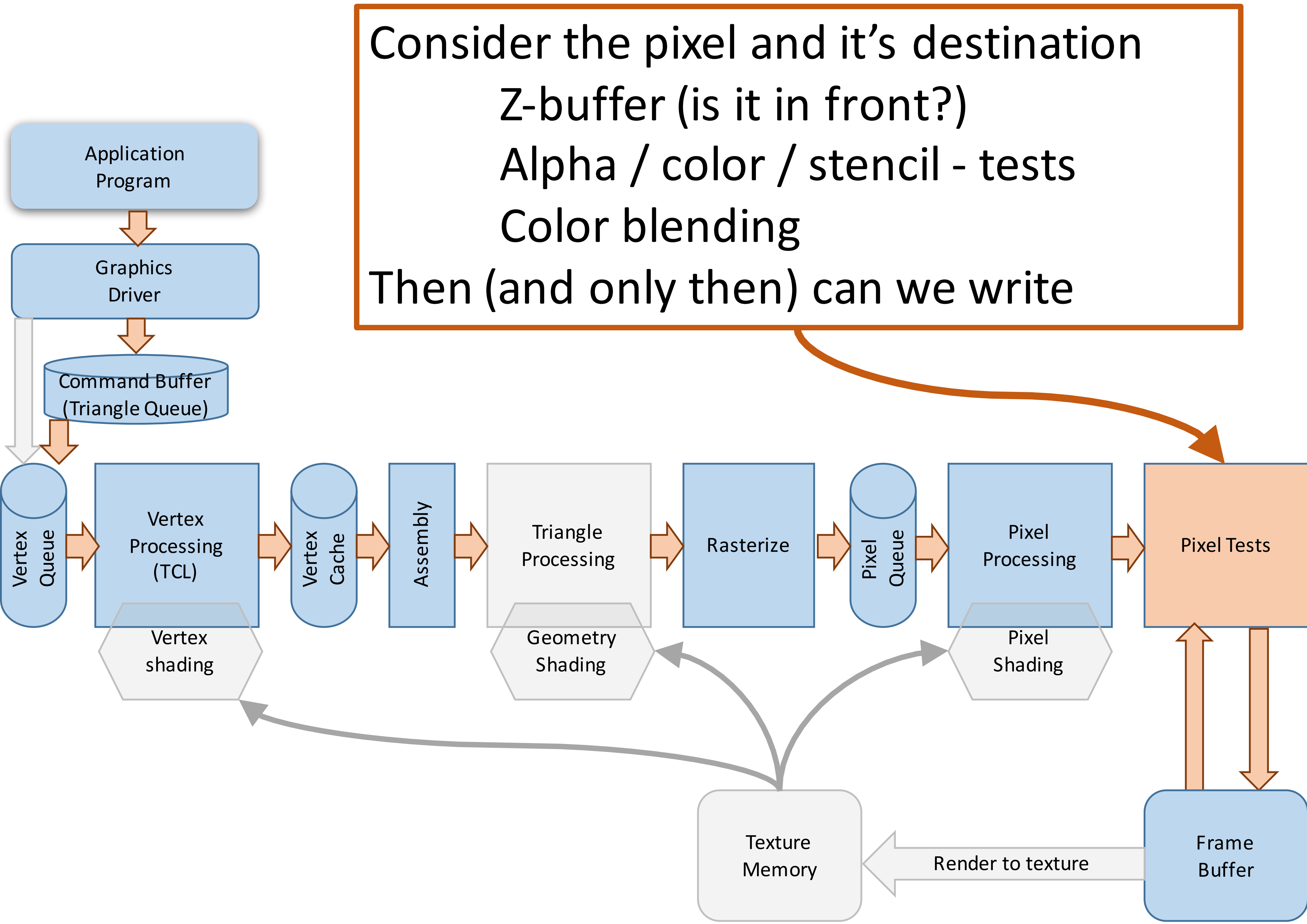
Can change other values

Or "reject"

Coming attractions…

This step will get to be pretty exciting

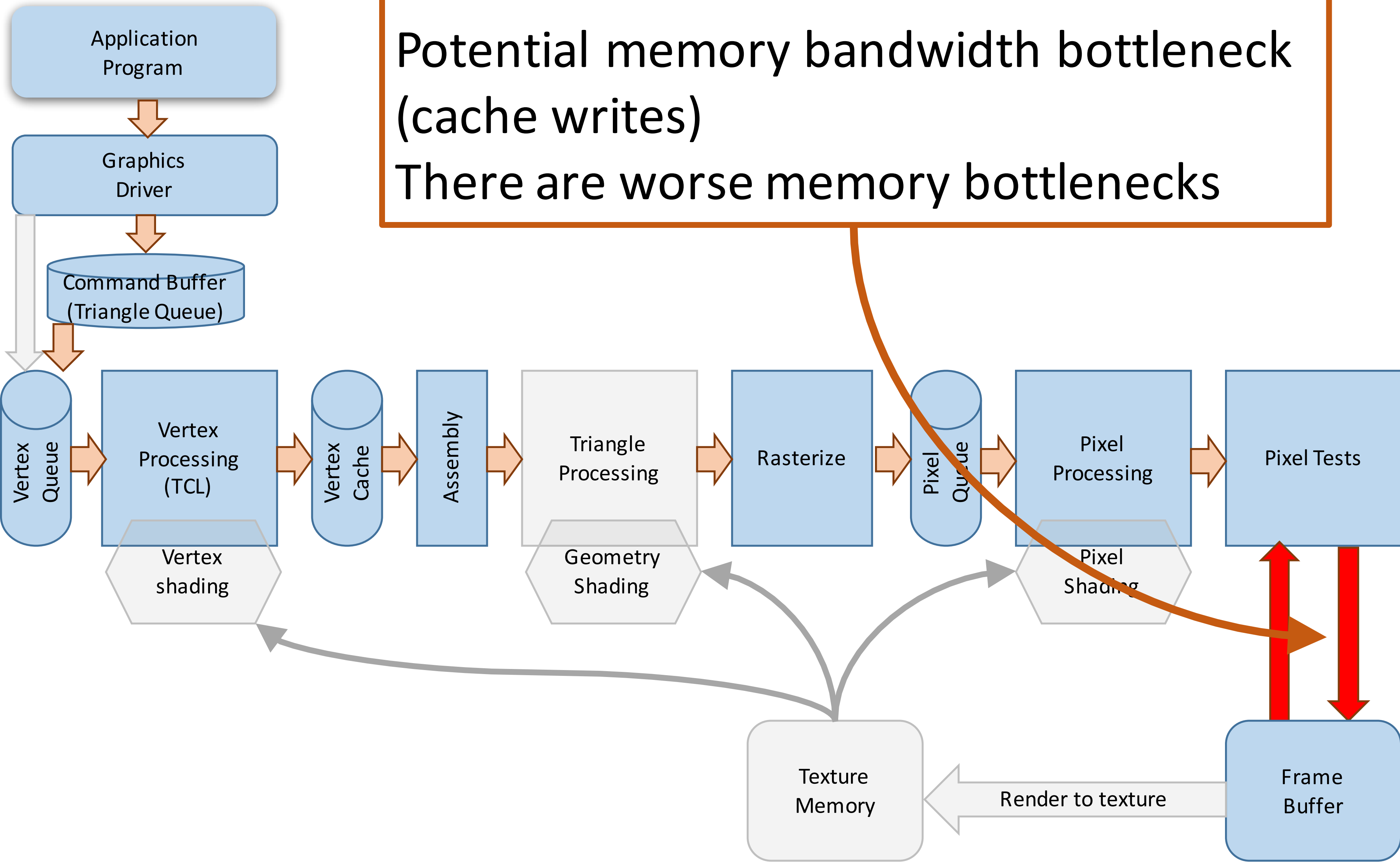



Consider the pixel and it's destination
Z-buffer (is it in front?)
Alpha / color / stencil - tests
Color blending
Then (and only then) can we write
Application Program
Graphics Driver
Command Buffer (Triangle Queue)
Vertex Queue
Vertex Processing (TCL)
Vertex shading
Vertex Cache
Assembly
Triangle Processing
Geometry Shading
Rasterize
Pixel Queue
Pixel Processing
Pixel Shading
Pixel Tests
Texture Memory
Render to texture
Frame Buffer

Each pixel requires a read/write cycle

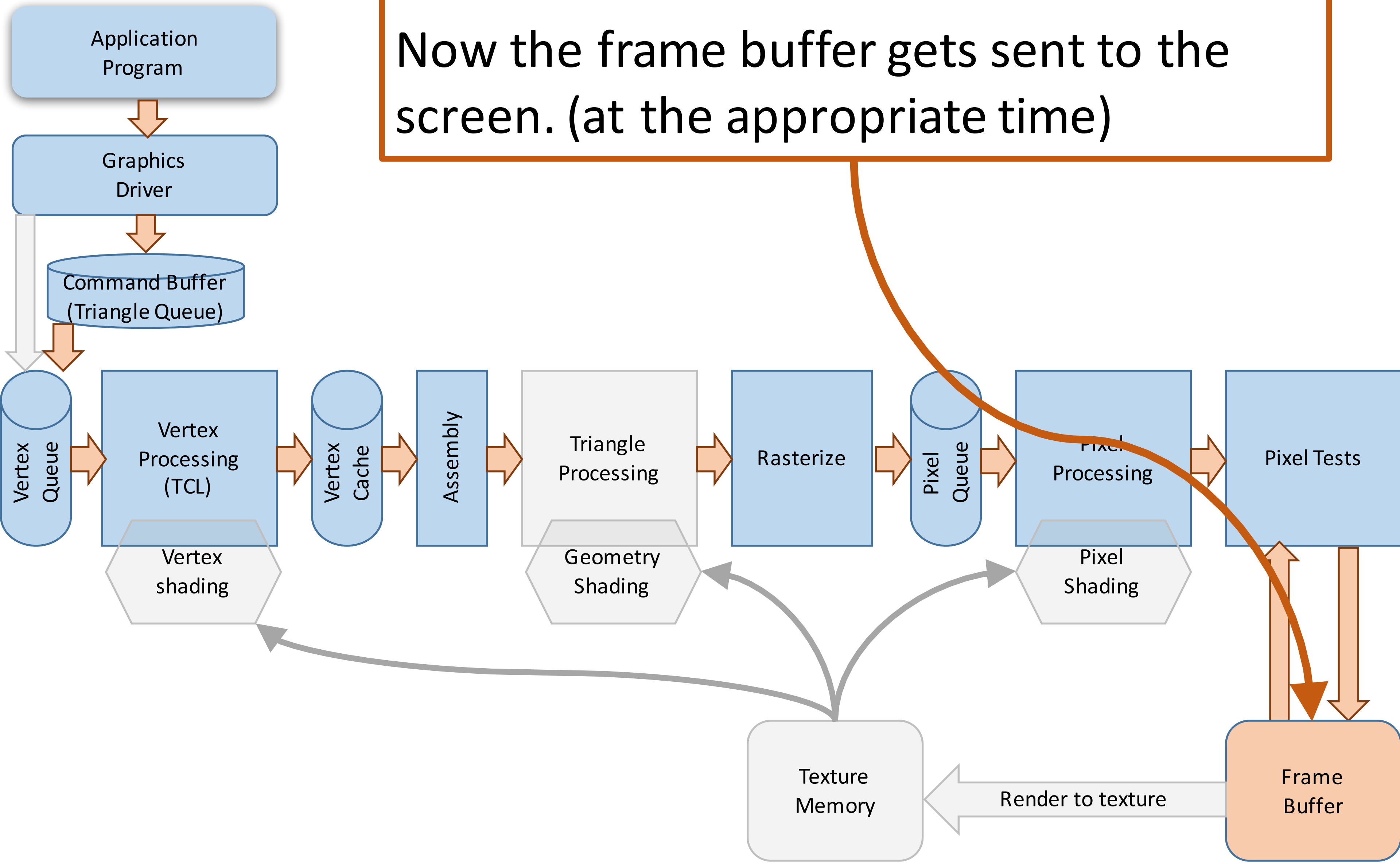
Potential memory bandwidth bottleneck (cache writes)

There are worse memory bottlenecks



We've made it!

Now the frame buffer gets sent to the screen. (at the appropriate time)



# What if we didn't make it…

Suppose the triangle's pixels are occluded

Removed by the z-buffer

Normal Z-Test

Happens at the end

We wasted all that work!