The Graphics Pipeline

Ray Tracing: Why Slow?

Basic ray tracing: 1 ray/pixel

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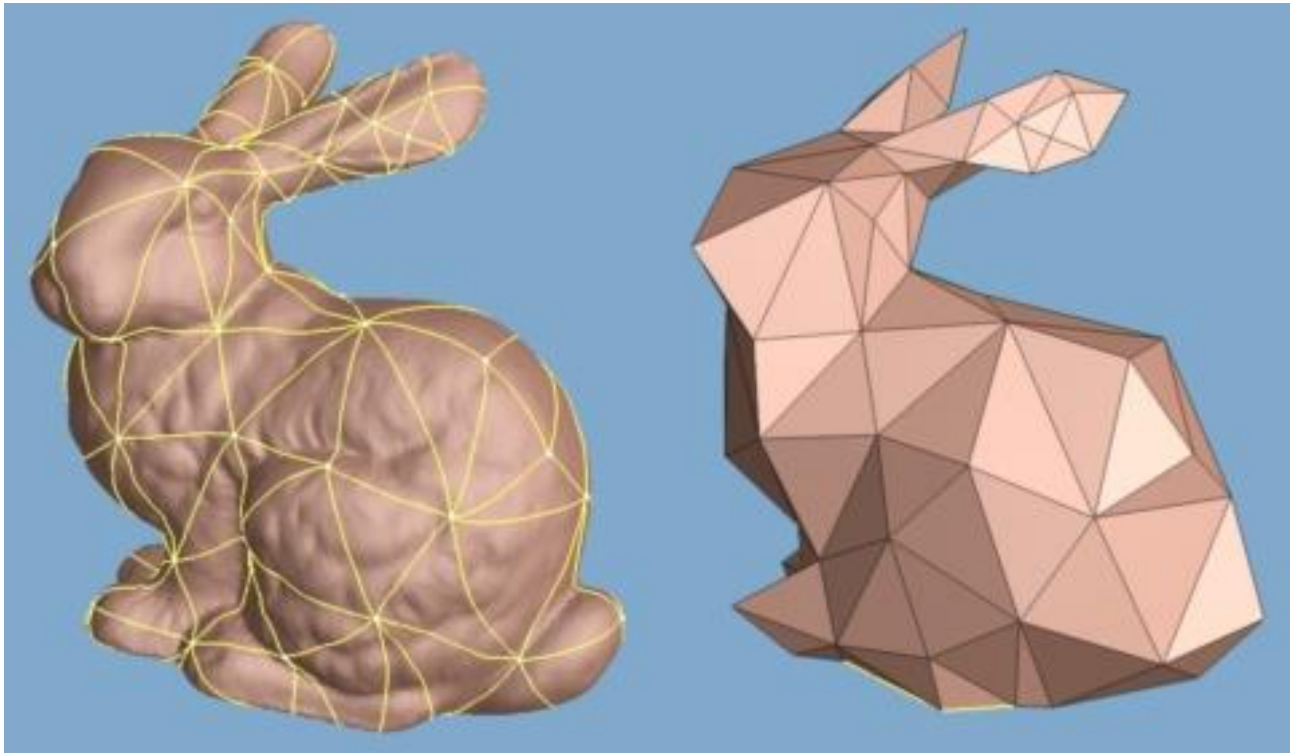
But you **really** want shadows, reflections, global illumination, antialiasing…

- 100-1000 rays/pixel

Rendering: Rasterization

Tessellate objects into primitives

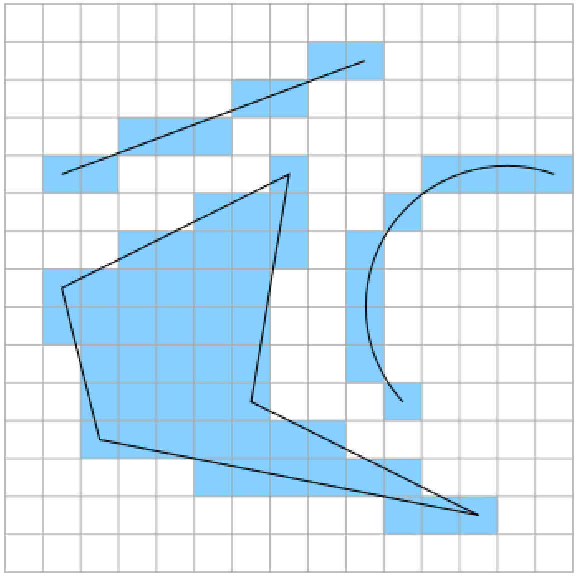


Rendering: Rasterization

Tessellate objects into primitives

Draw each separately:

- determine position and color
- draw pixels to screen



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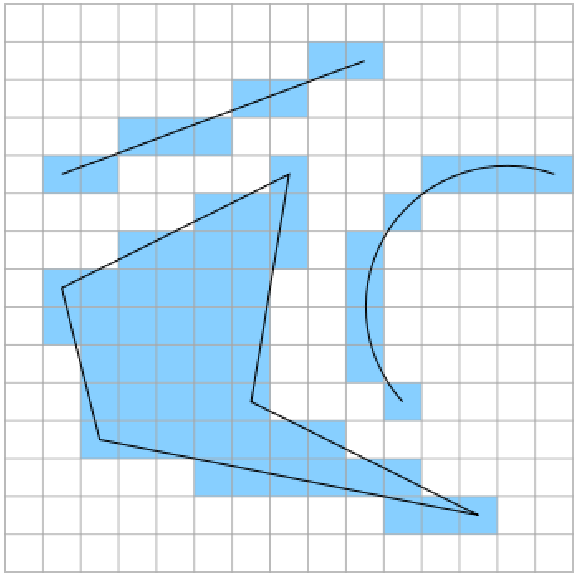
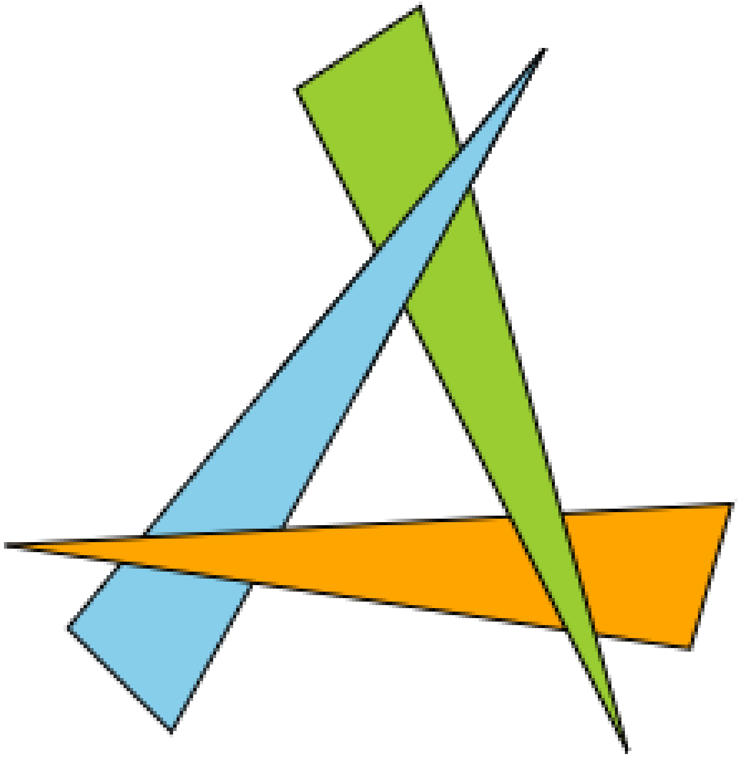


Embarrassingly parallel

Fast

Rendering: Rasterization

How to deal with overlaps?

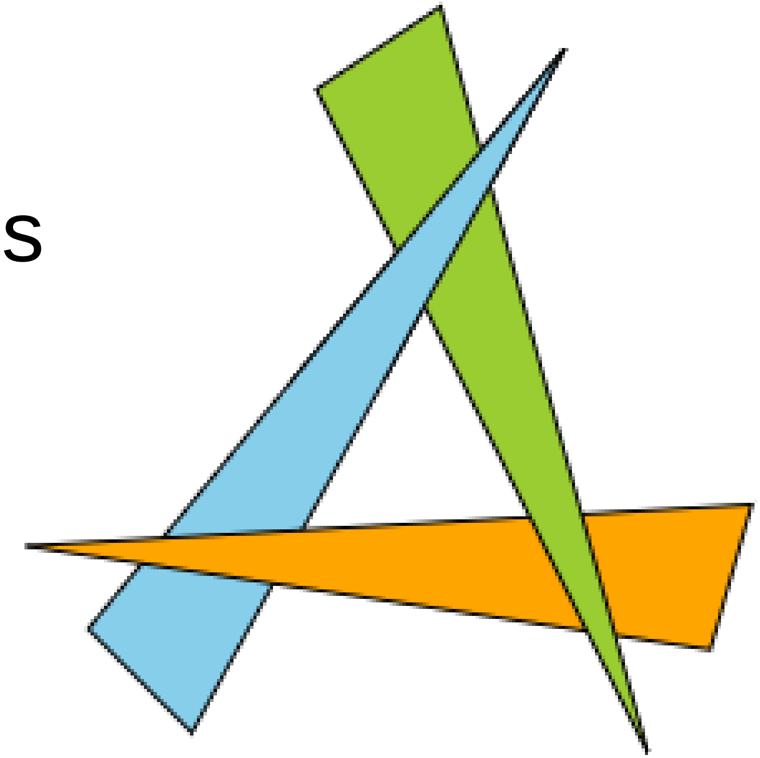


Rendering: Rasterization

How to deal with overlaps?

Keep track of **depth** of previously-drawn pixels

Depth image or depth buffer



Rendering: Rasterization

How to deal with overlaps?

- depth buffer

How to deal with shadows/reflections?

Rendering: Rasterization

How to deal with overlaps?

- depth buffer

How to deal with shadows/reflections?

- hmm…

Ray Tracing vs Rasterization

Ray Tracing	**Rasterization**
Loop over **pixels**	Loop over **triangles**
Light effects “easy” shadows, reflections, caustics, …	Light effects require hacks and tricks
Slow-ish	Blazingly fast
Used in movies	Used in games

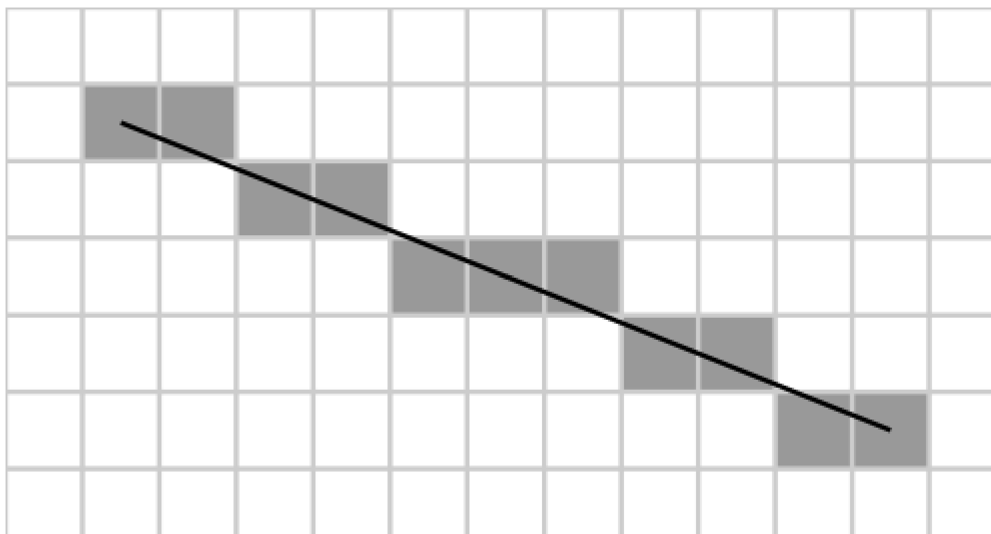
Ray Tracing vs Rasterization

Rasterized 3D graphics imagery

Ray traced 3D graphics imagery ©Siliconarts

Rasterization Algorithms

Actually rasterizing objects not so easy…



Rasterization Algorithms

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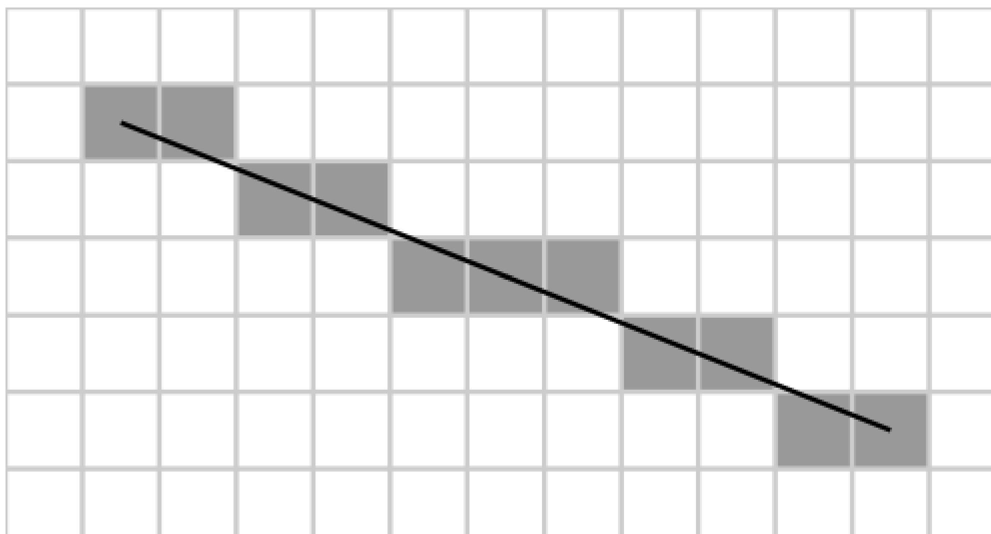
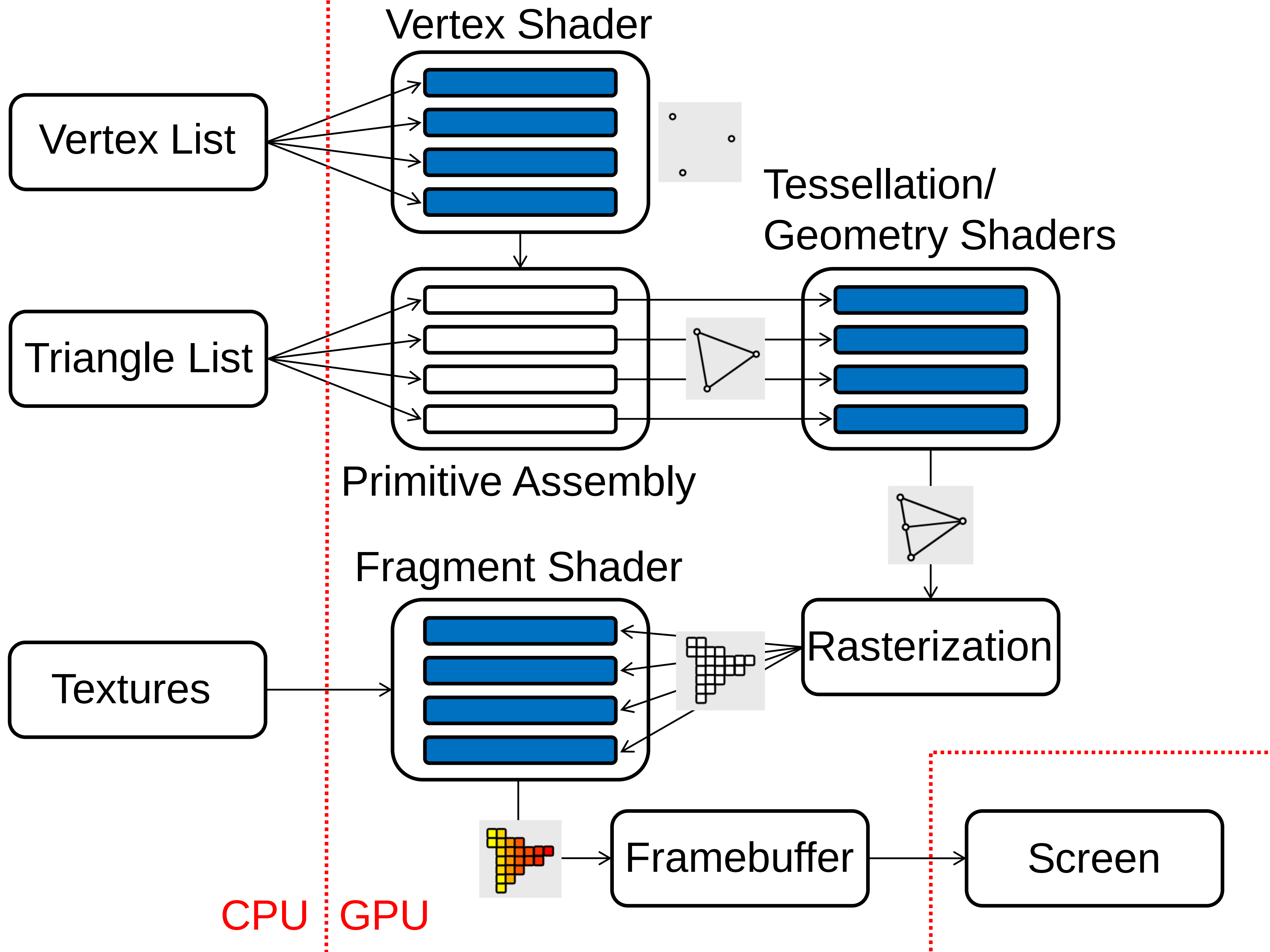
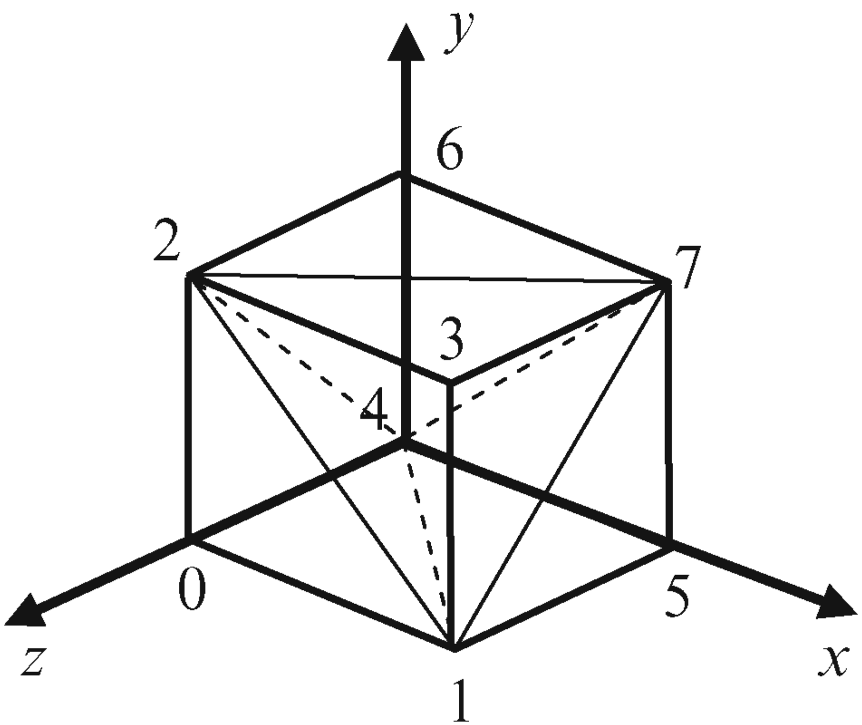


…so use specialized hardware to do it


Vertex Shader
Vertex List
Tessellation/
Geometry Shaders
Triangle List
Primitive Assembly
Fragment Shader
Rasterization
Textures
Framebuffer
Screen
CPU
GPU

Vertices and Triangles



Vertex List		
x	y	z
0.0	0.0	1.0
1.0	0.0	1.0
0.0	1.0	1.0
1.0	1.0	1.0
0.0	0.0	0.0
1.0	0.0	0.0
0.0	1.0	0.0
1.0	1.0	0.0

Triangle List		
i	j	k
0	1	2
1	3	2
2	3	7
2	7	6
1	7	3
1	5	7
6	7	4
7	5	4
0	4	1
1	4	5
2	6	4
0	2	4

Sending Data to the GPU

One vertex/triangle at a time: very slow

Vertex Buffer Objects: big arrays of data

- vertex positions
- vertex colors
- texture info
- etc

Shaders

Small arbitrary programs that run on GPU

Massively parallel

Shaders

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Massively parallel

Four kinds: vertex, tessellation, geometry, fragment

Shaders

Small arbitrary programs that run on GPU

Massively parallel

Four kinds: vertex, tessellation, geometry, fragment

These days: used for many non-rendering applications (GPGPU)

Vertex Shader

Runs in parallel on every vertex

- no access to triangles or other verts

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Main job: transform vertex positions

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Runs in parallel on every vertex

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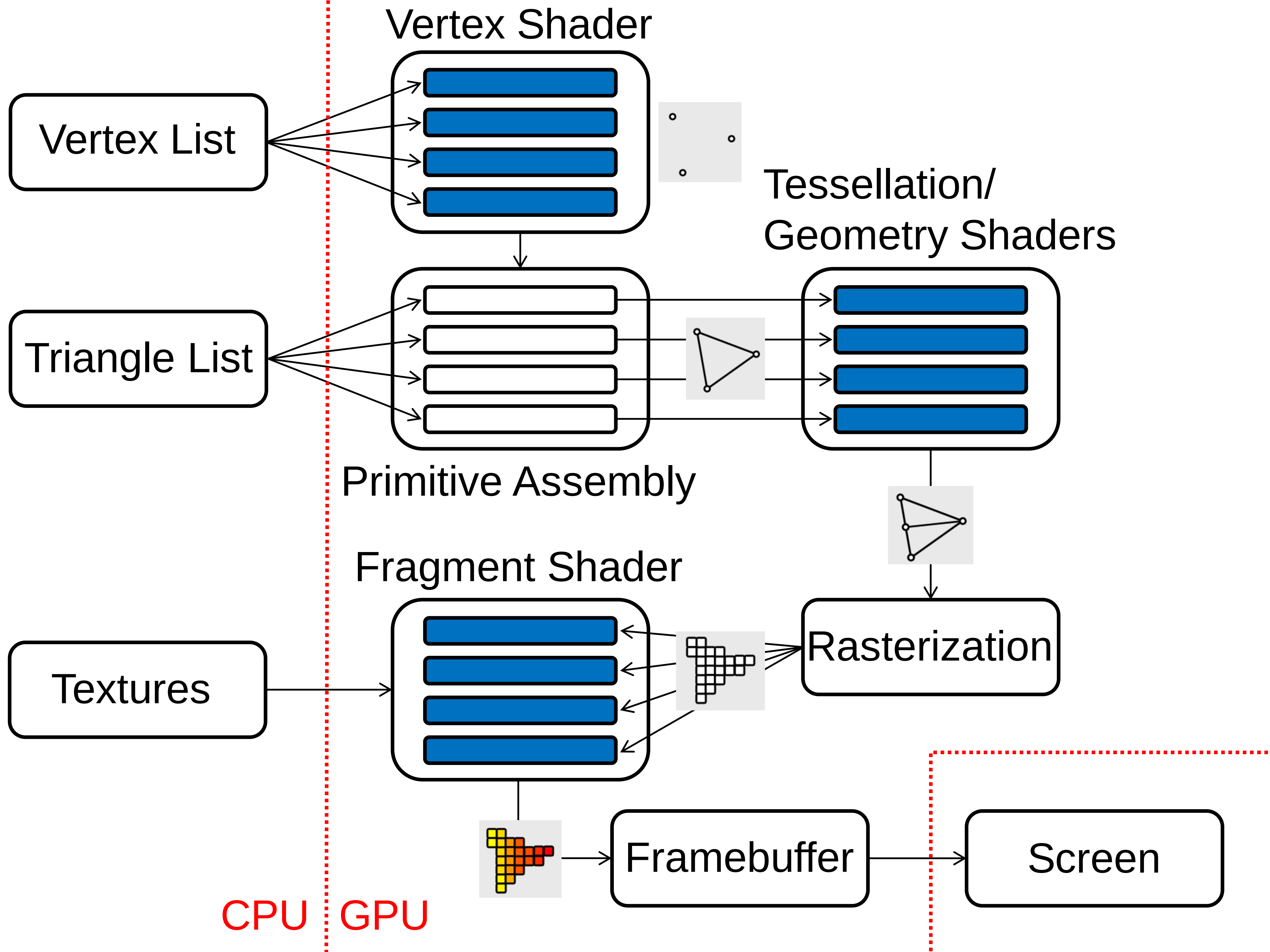
Main job: transform vertex positions

Also used for shading



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Processing Primitives

Assembly: group verts into polygons

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Tessellation shader: runs on each triangle

- can split triangles into subtriangles
  - increase level of detail near camera, etc

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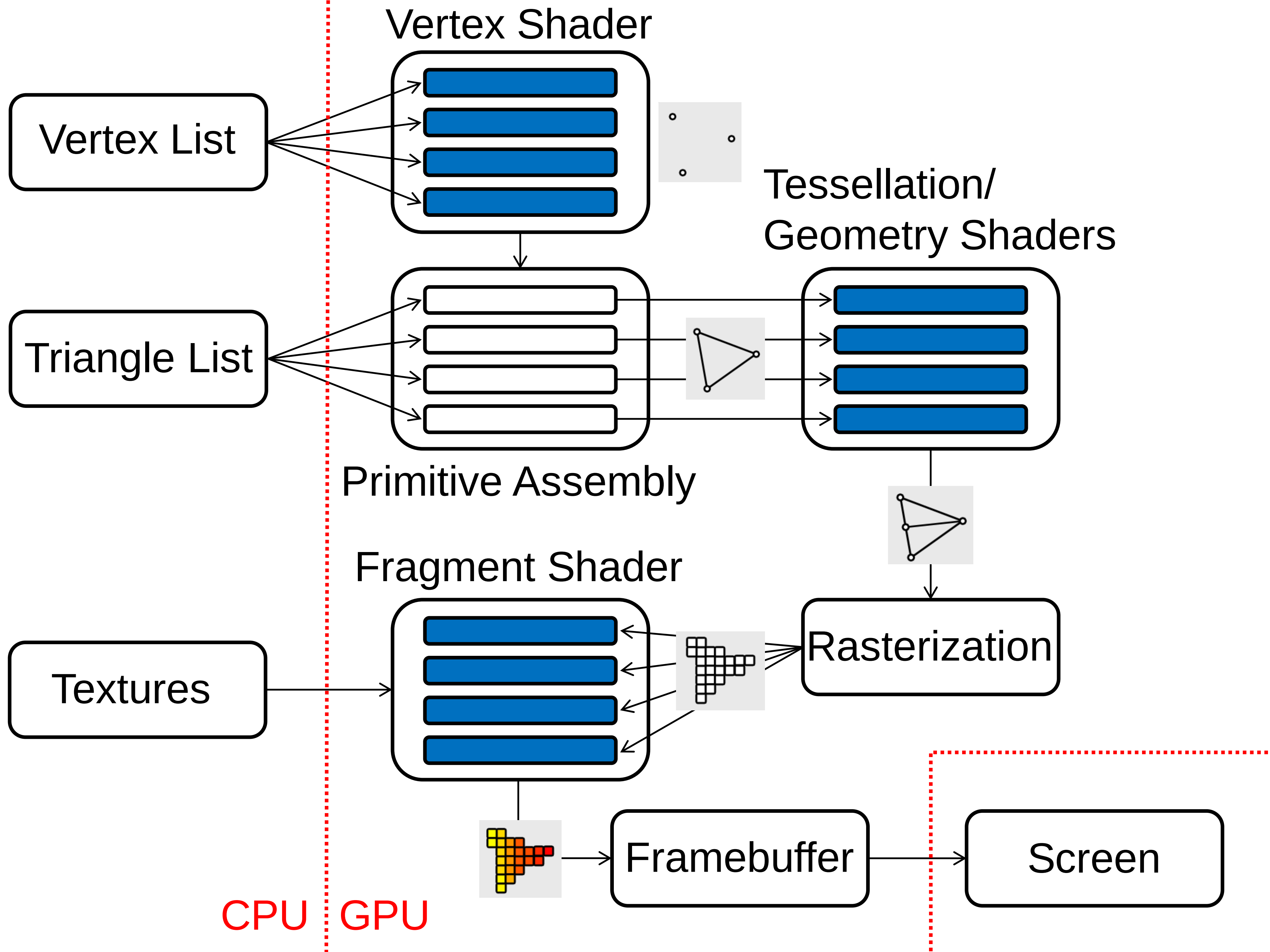
Assembly: group verts into polygons

Tessellation shader: runs on each triangle

- can split triangles into subtriangles
  - increase level of detail near camera, etc

Geometry shader: runs on each triangle

- can access verts and neighbors
- more general than tessellation, slower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Fragment Shader

Runs in parallel on each fragment (pixel)

- rasterization: one tri -> many fragments

Writes color and depth for one pixel (only)

Final texturing/coloring of the pixels

Fragment Shader

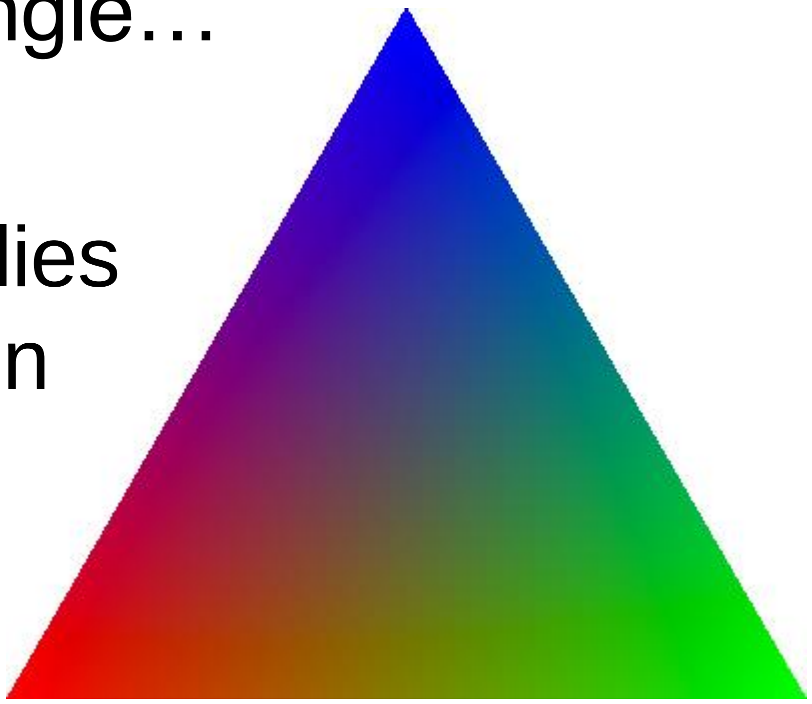
Many fragments per triangle…

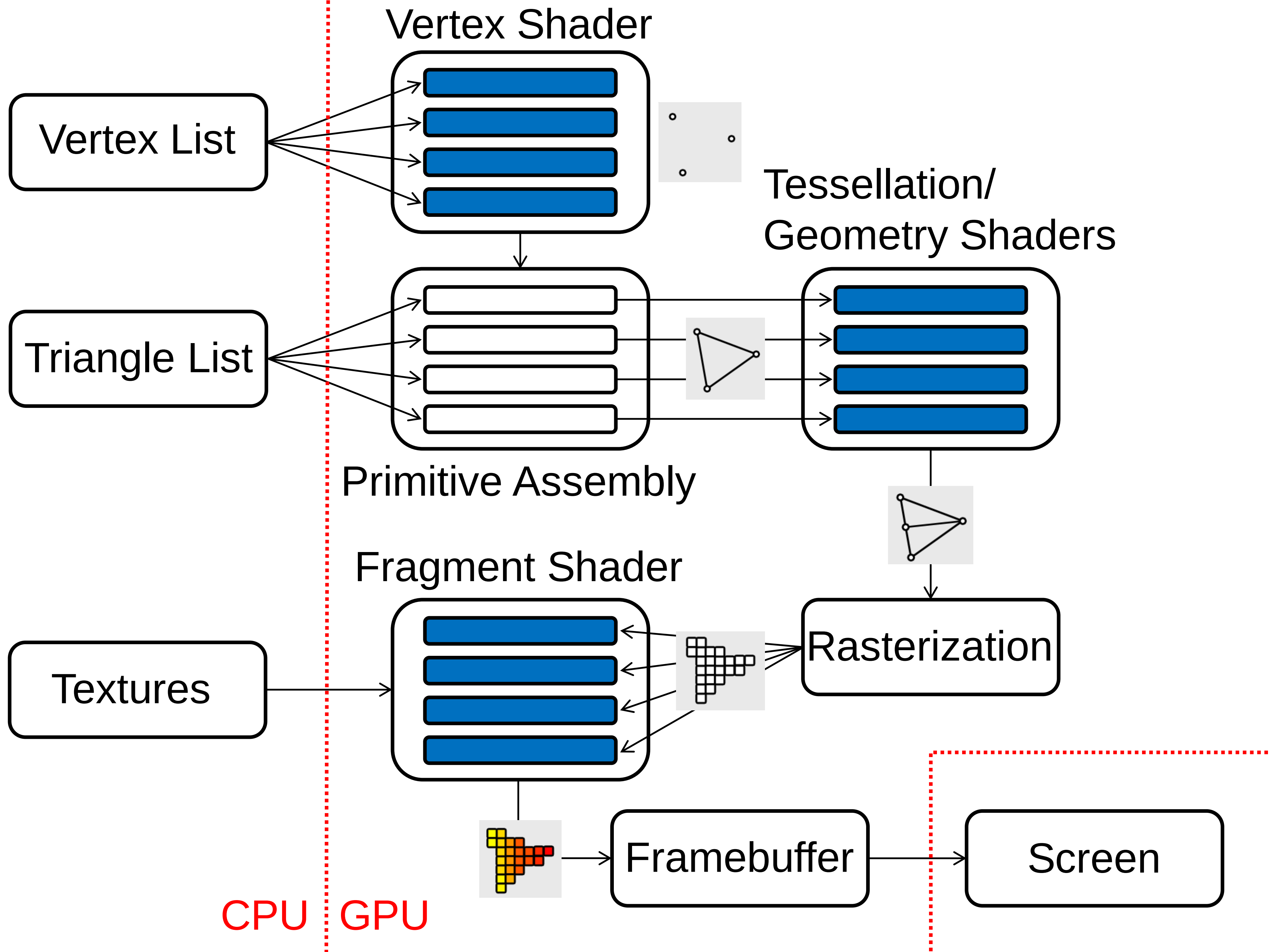
Fragment Shader

Many fragments per triangle…

GPU **automatically** applies barycentric interpolation

UV coords, normals, colors, …





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Normalized Device Coordinates

Before rasterization, must decide what geometry to show and where

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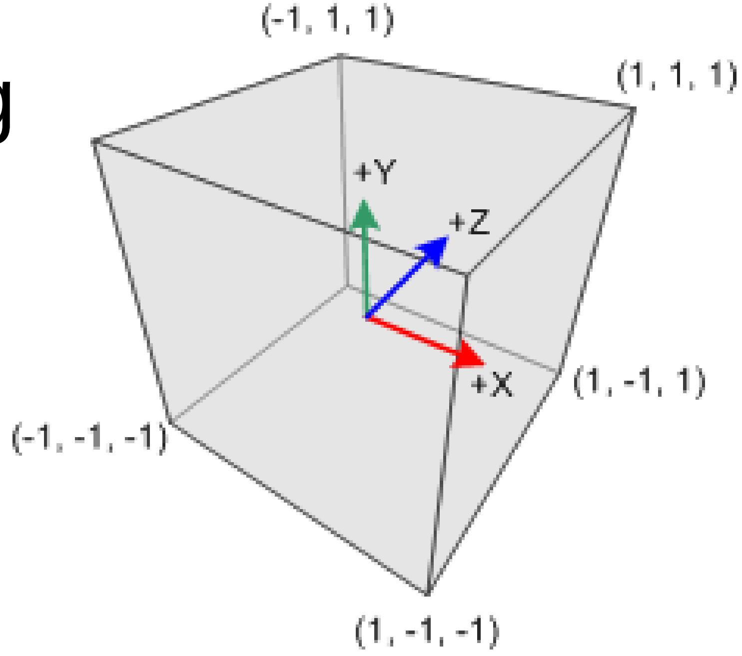
GPU draws everything in unit cube

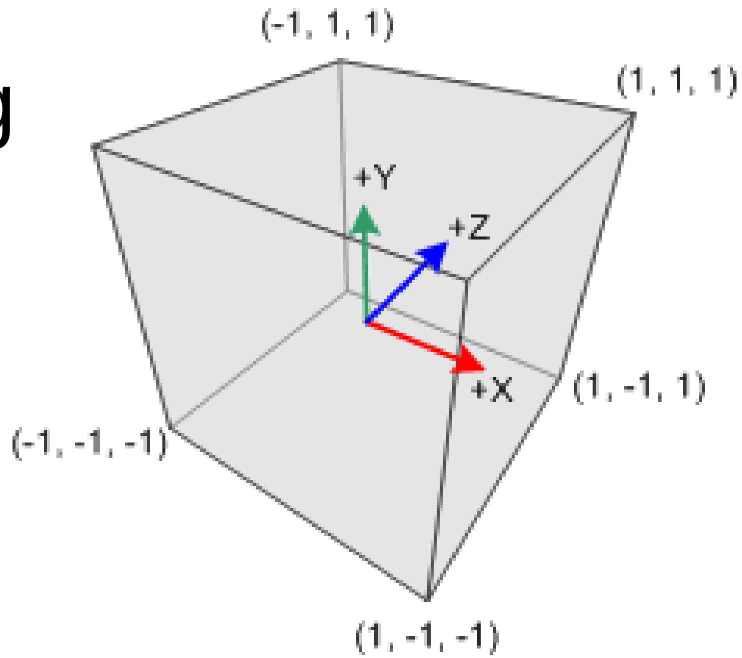


Normalized Device Coordinates

Before rasterization, must decide what geometry to show and where

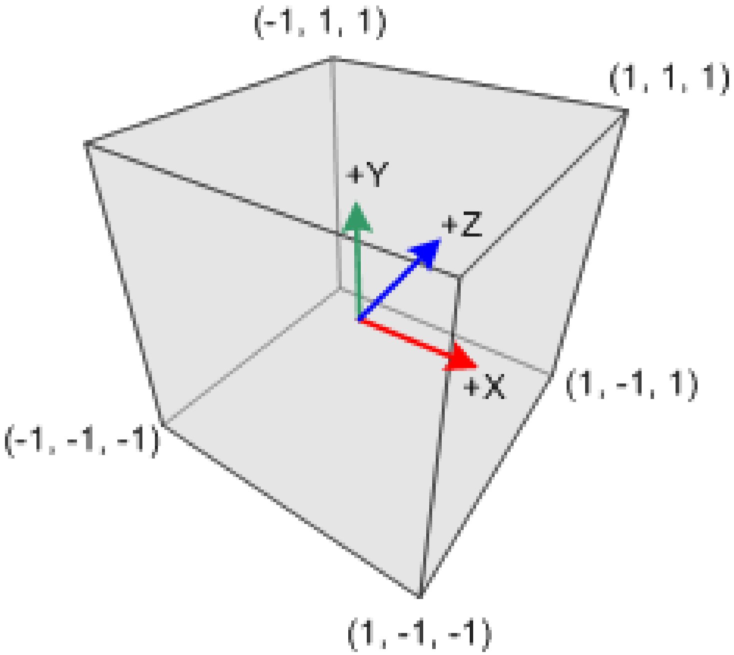
GPU draws everything in unit cube

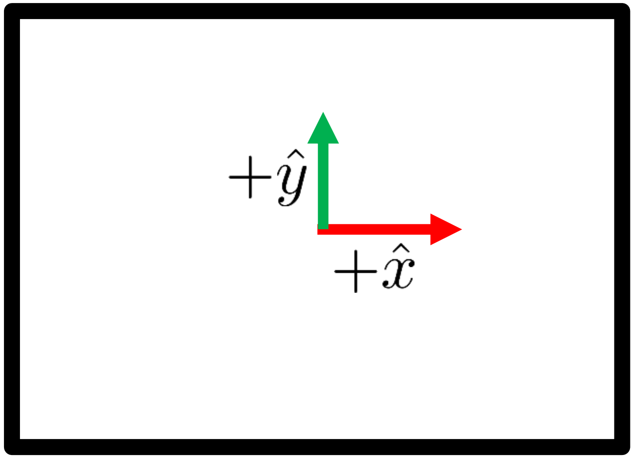
Everything **clipped**



Normalized Device Coordinates

X & Y axes map to screen width & height

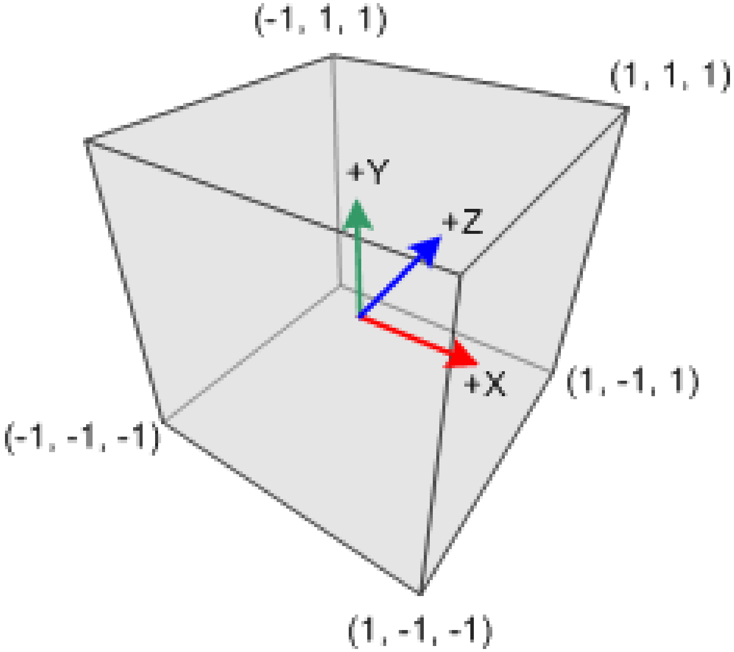


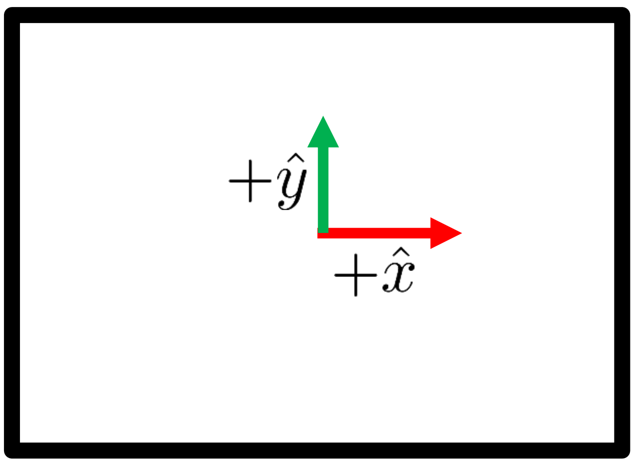


Normalized Device Coordinates

X & Y axes map to screen width & height

Z used for **depth**

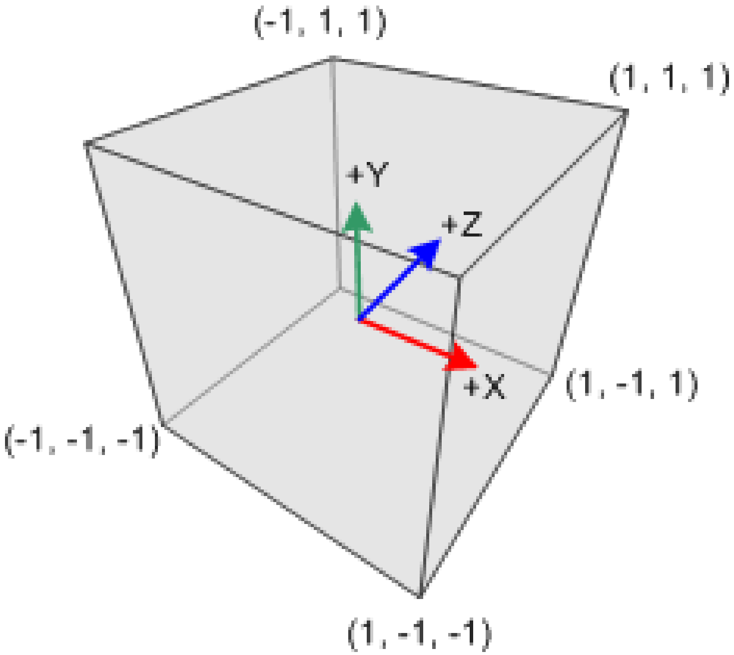




Normalized Device Coordinates

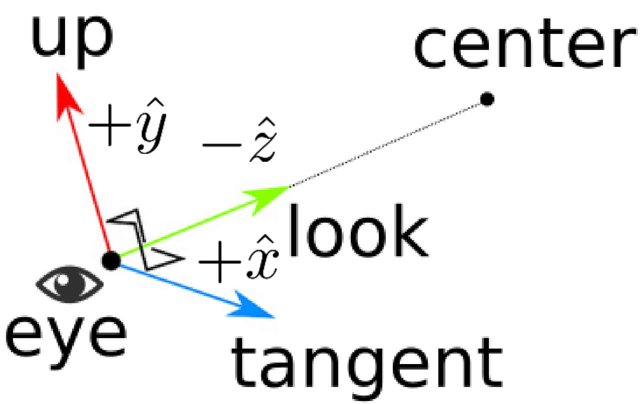
Notice: deeper points have **higher** z

(not right-handed)



Camera Coordinates

Notice: look down **negative** z direction

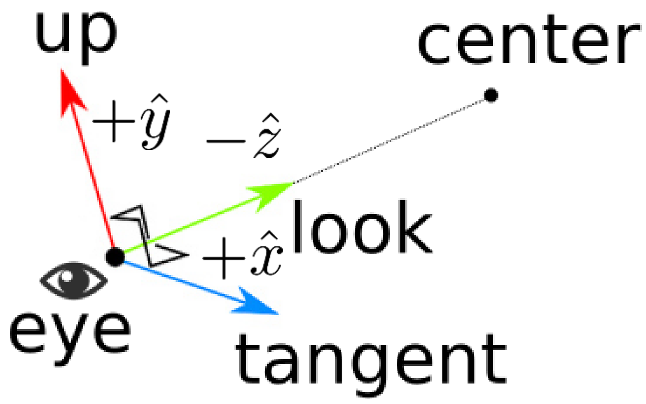


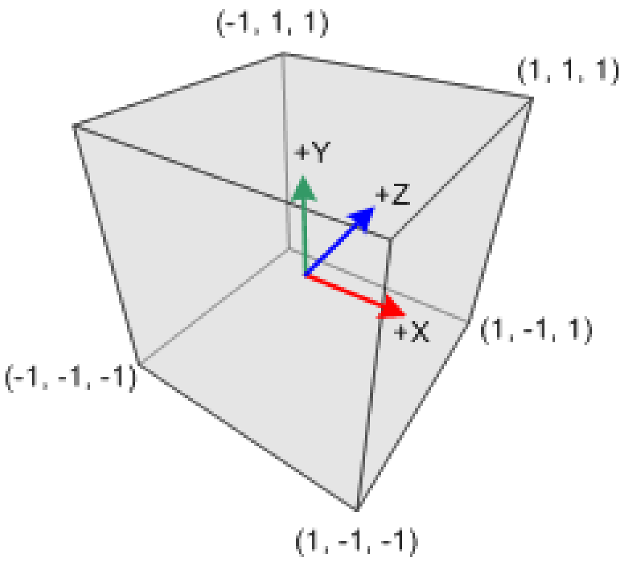
Camera Coordinates

Notice: look down **negative** z direction

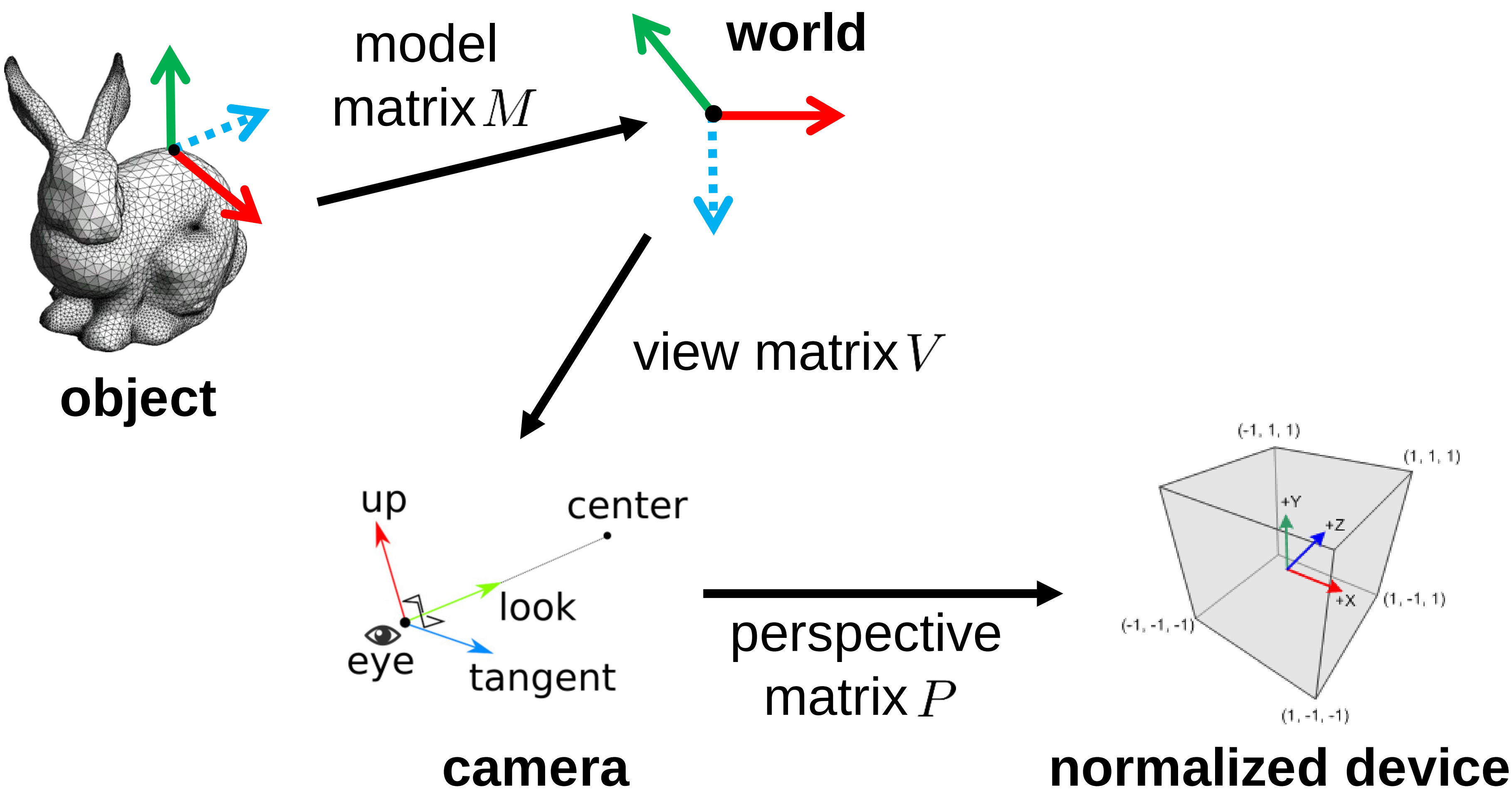
Projection: transform from camera to NDC

(typically in vertex shader)



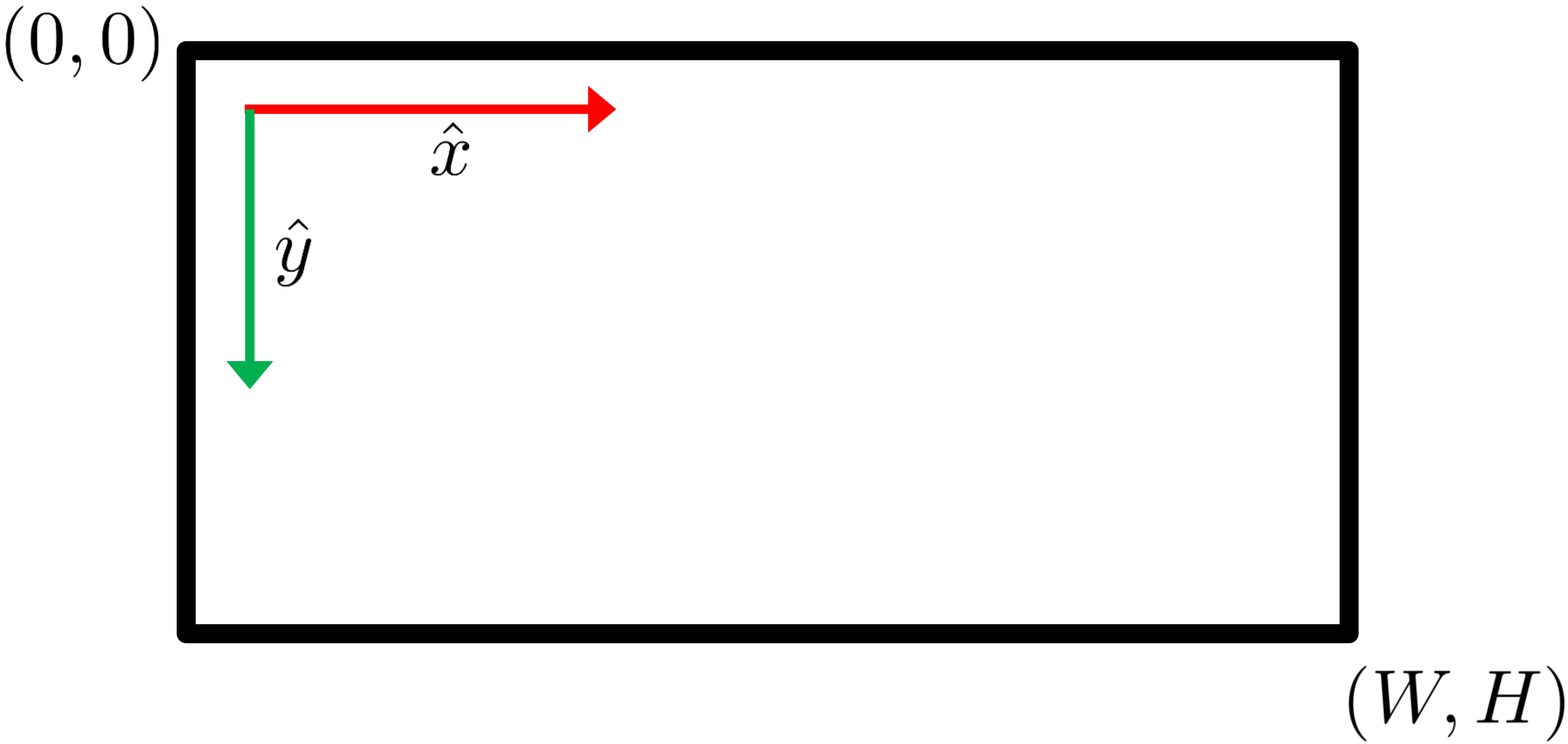


Coordinate Systems in Graphics



For Extra Confusion

Screen coordinates



Framebuffer

Memory region containing pixel data

The old days: mapped to RAM with DMA

- CPU could write to it directly

Framebuffer

Memory region containing pixel data

The old days: mapped to RAM with DMA

- CPU could write to it directly

Now: GPU controls it

Framebuffer

Several layers:

- Color buffer: RGB of each pixel

Framebuffer

Several layers:

- Color buffer: RGB of each pixel
- Depth buffer

Framebuffer

Several layers:

- Color buffer: RGB of each pixel
- Depth buffer
- Stencil buffer, etc

Framebuffer

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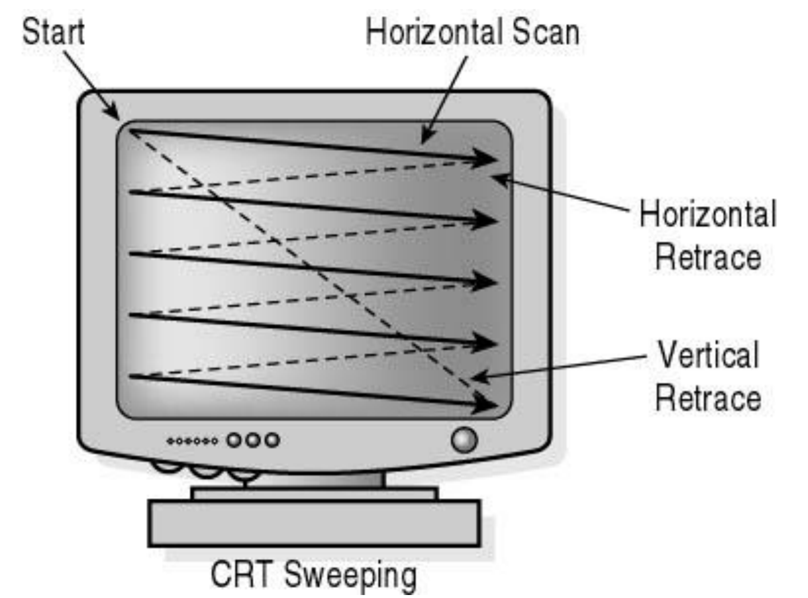
Can be saved to file, to texture, to screen

Displaying the Framebuffer

CRTs: beam sweeps across screen drawing pixels

- one pass: 1/60 secs

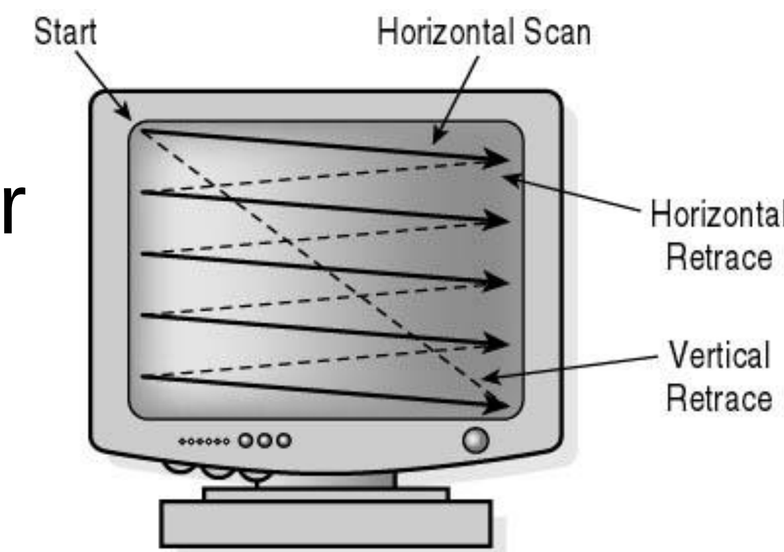


Displaying the Framebuffer

CRTs: beam sweeps across screen drawing pixels

- one pass: 1/60 secs

LCDs: grabs framebuffer every 1/60 secs



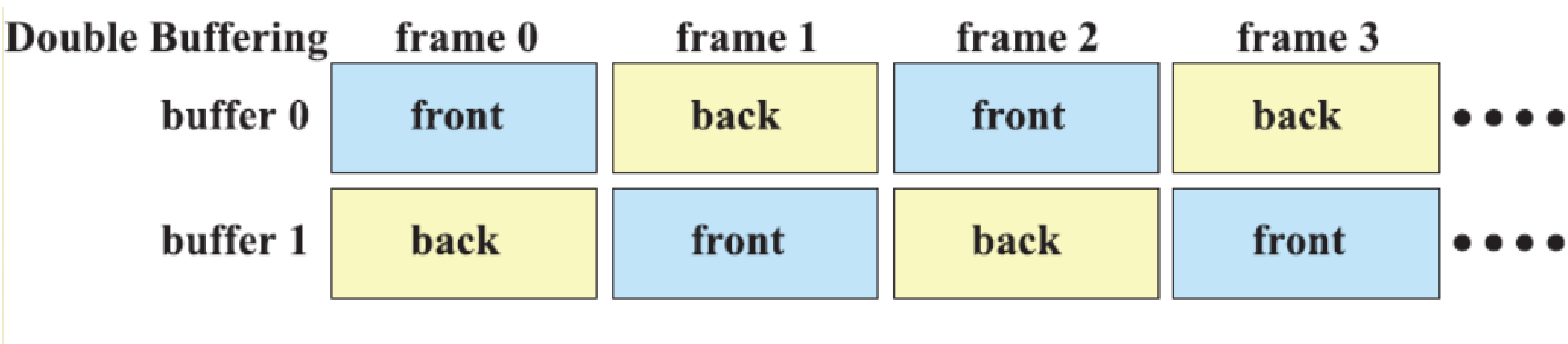
CRT Sweeping

Flickering and Tearing

Framebuffer changes while monitor draws

Double-Buffering to Stop Tearing

Use two framebuffers

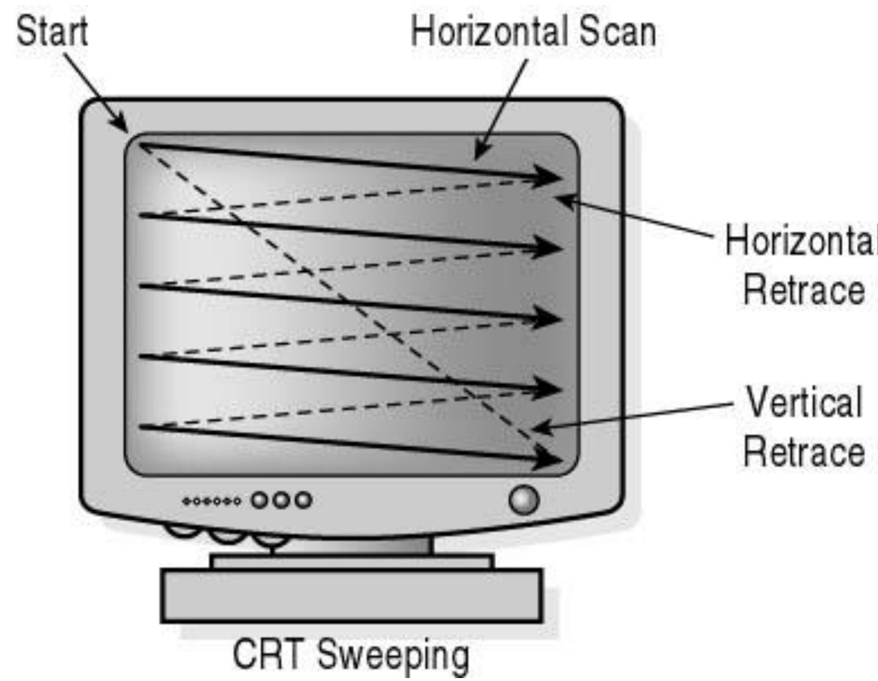


Render to **back buffer** while showing **front buffer**

Then swap

Double-Buffering to Stop Tearing

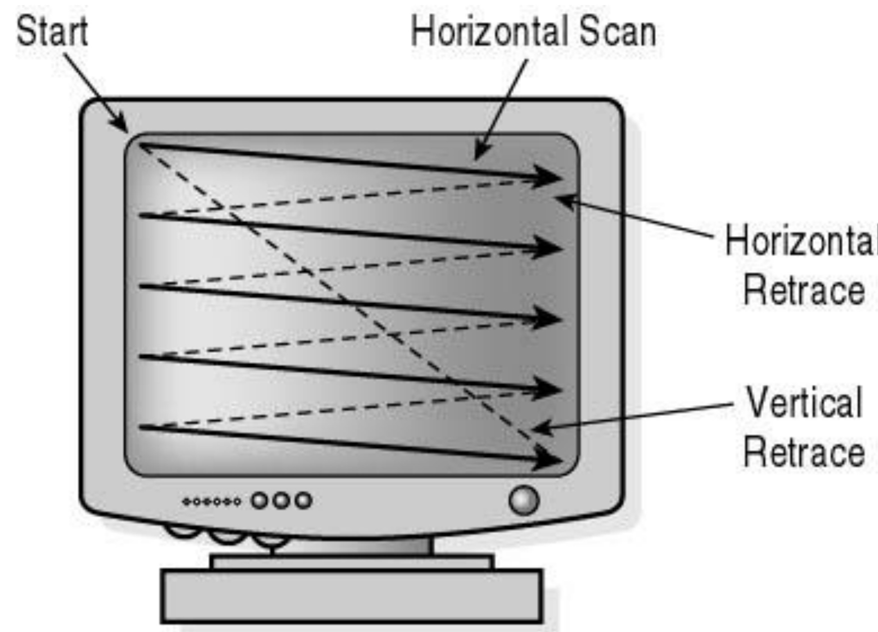
On CRTs: must wait for **vertical retrace** to swap



Double-Buffering to Stop Tearing

On CRTs: must wait for **vertical retrace** to swap

- “vsync”
- occurs 1/60 sec



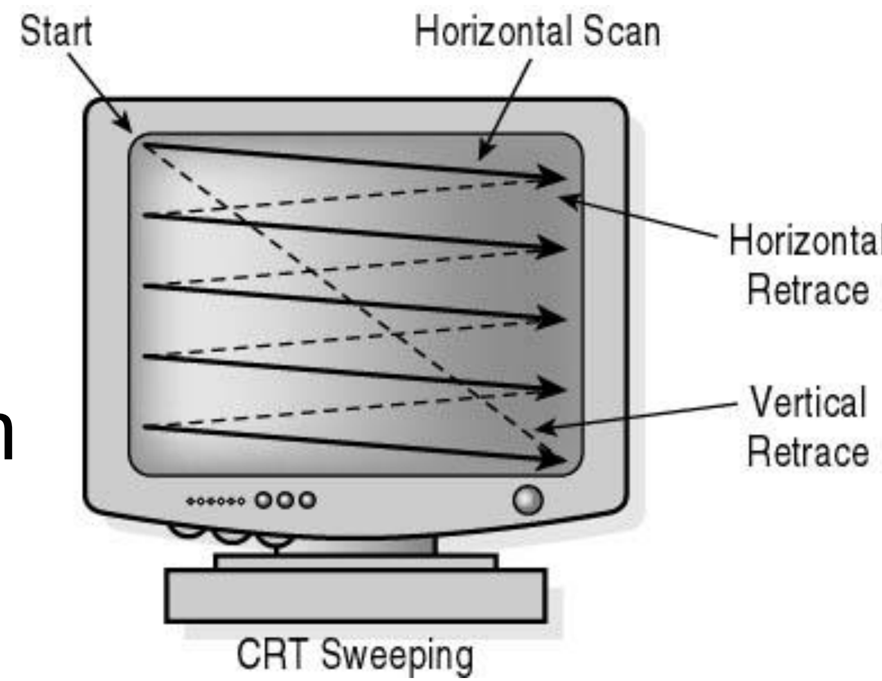
CRT Sweeping

Double-Buffering to Stop Tearing

On CRTs: must wait for **vertical retrace** to swap

- "vsync"
- occurs 1/60 sec

On LCDs: swap when not reading



Communicating with GPU

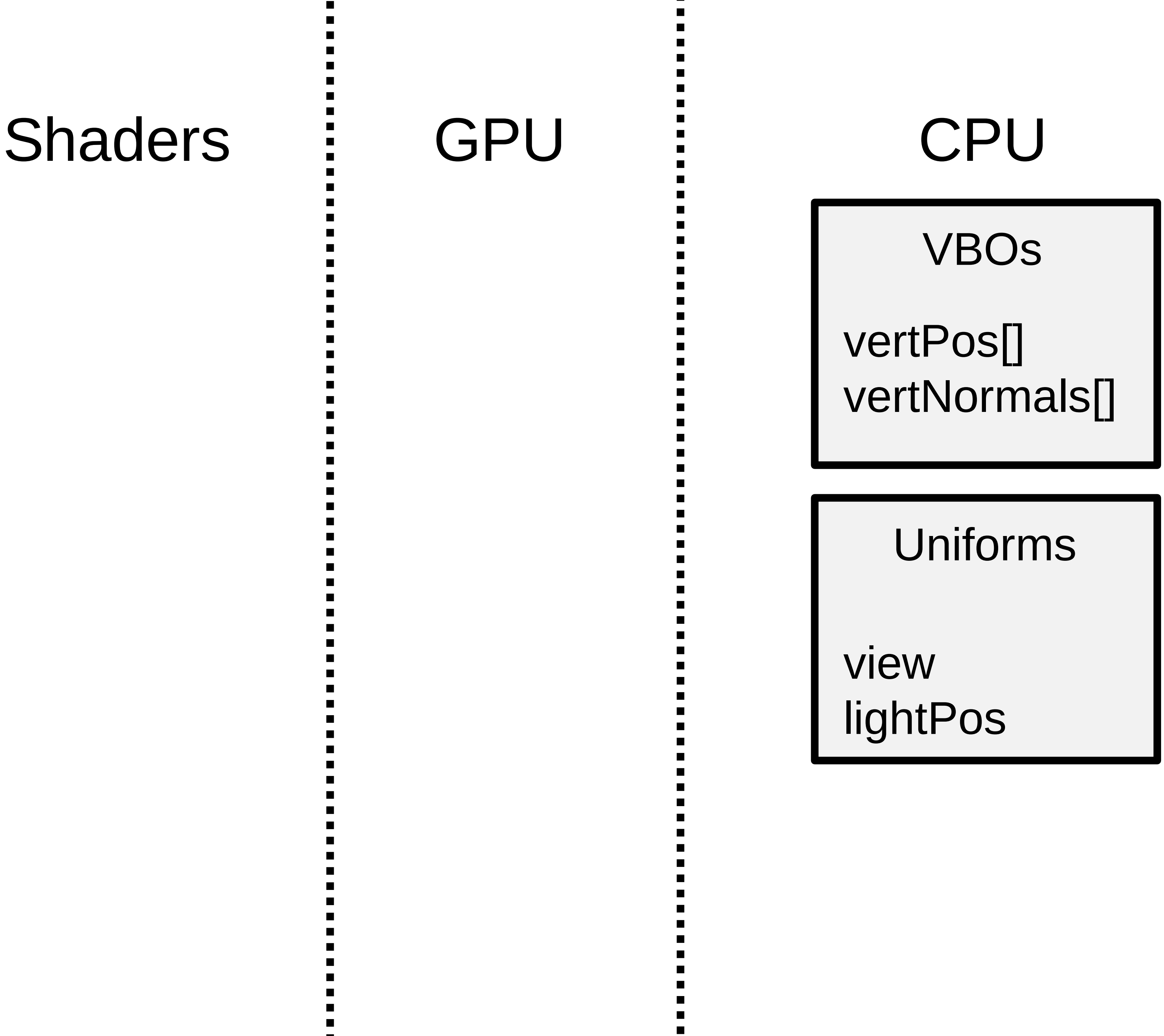
Very low level / awkward

Communicating with GPU

Very low level / awkward

Two types of data:

- vertex attributes in VBOs
- global variables (“uniforms”)


Shaders
GPU
CPU
VBOs
vertPos[]
vertNormals[]
Uniforms
view
lightPos

Communicating with GPU

Very low level / awkward

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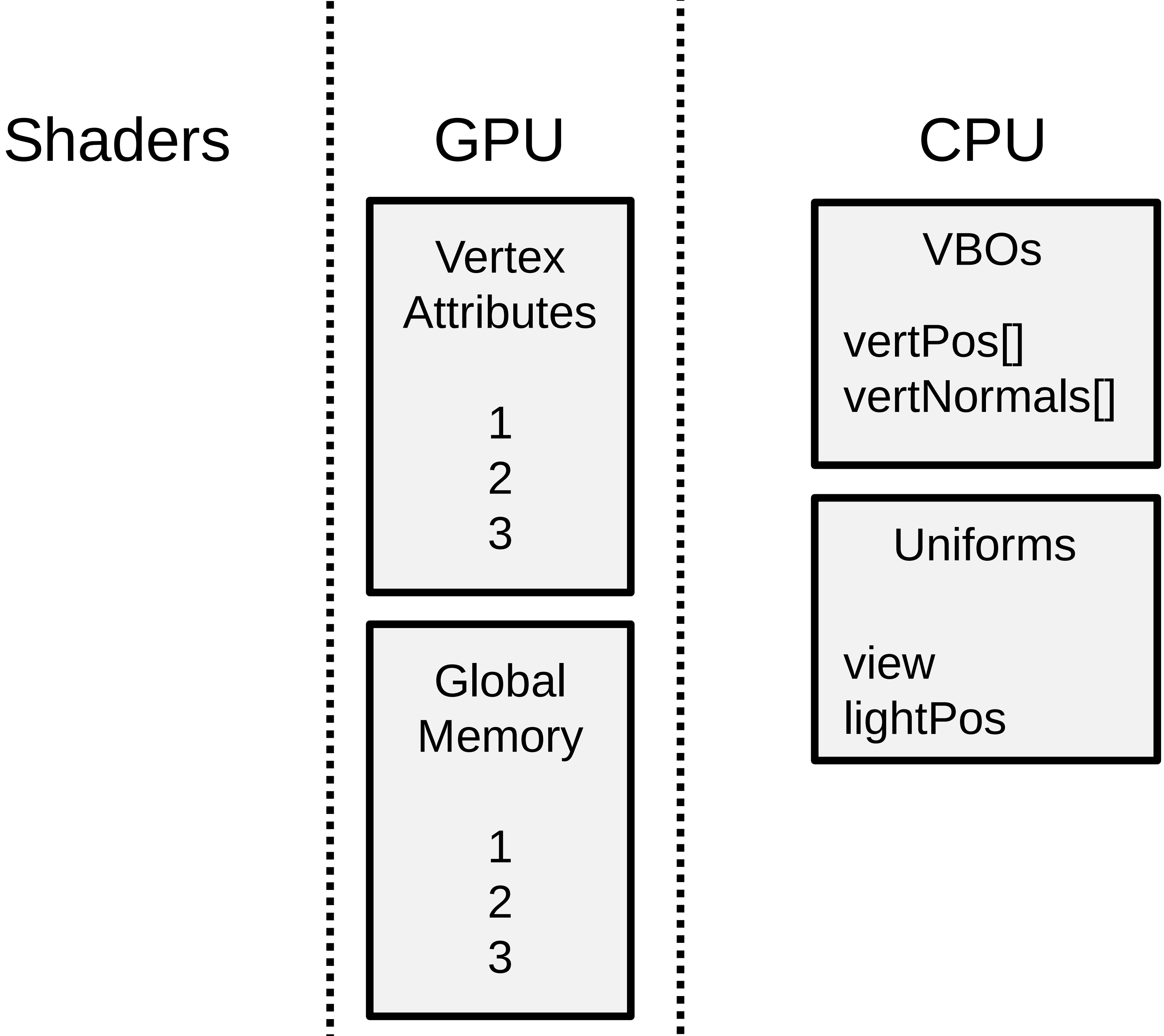
GPU stores no variable names – just location numbers


Shaders
GPU
CPU
Vertex Attributes
1
2
3
Global Memory
1
2
3
VBOs
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Communicating with GPU

Very low level / awkward

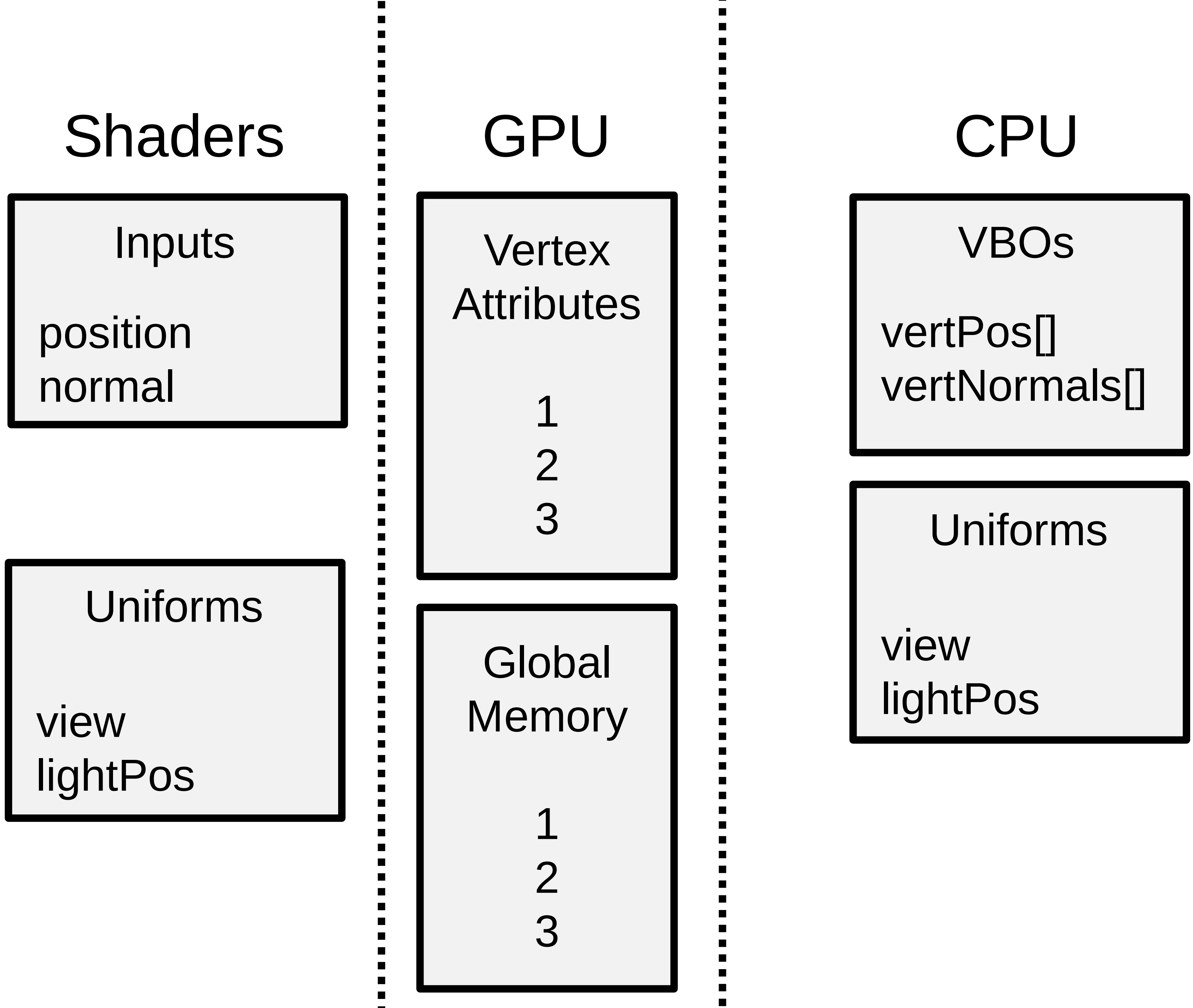
Two types of data:

- vertex attributes in VBOs
- global variables (“uniforms”)

GPU stores no variable names – just location numbers

GPU programming is lots of “plumbing”

- binding inputs and outputs correctly


Shaders
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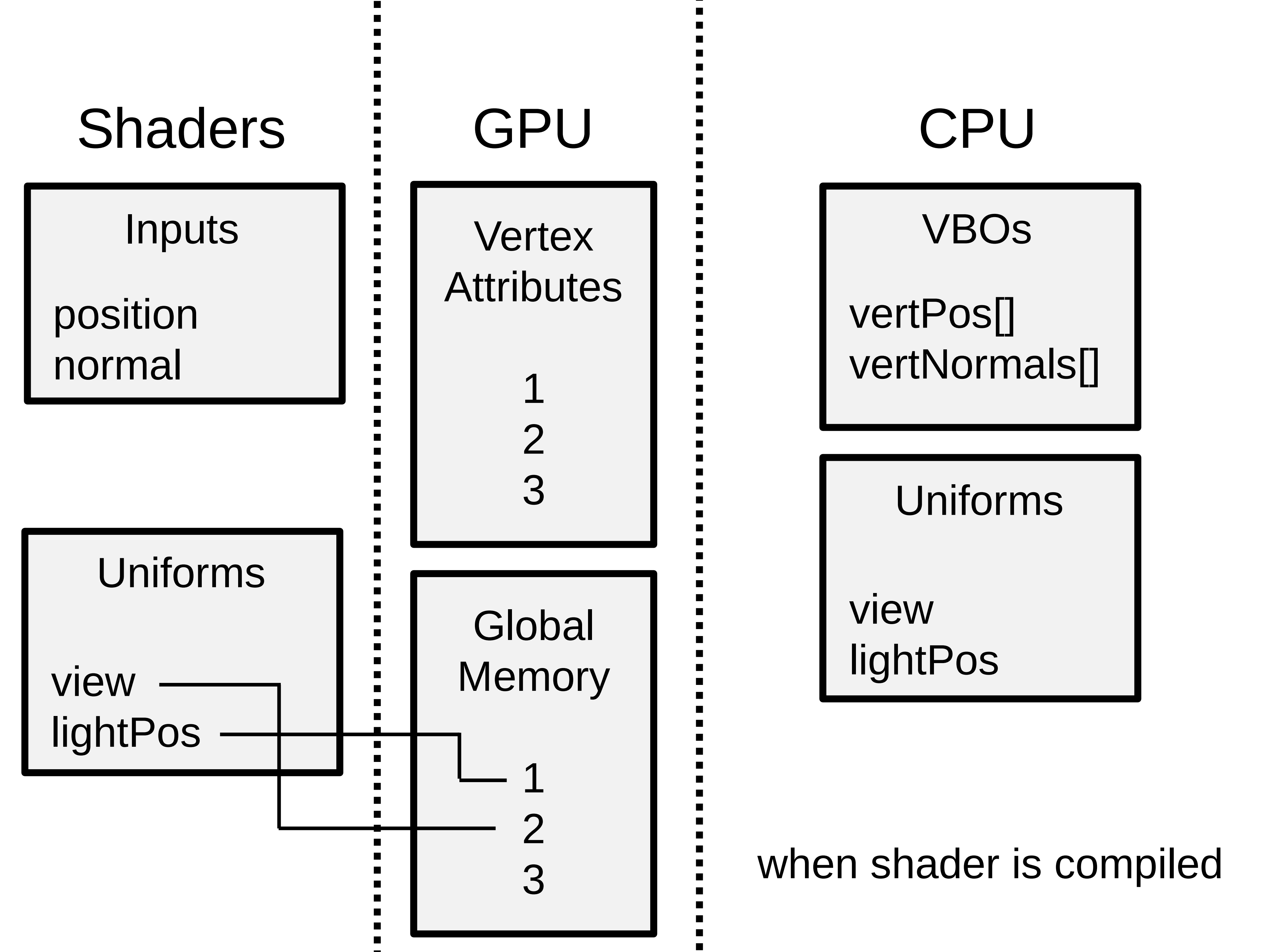
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1
2
3
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view
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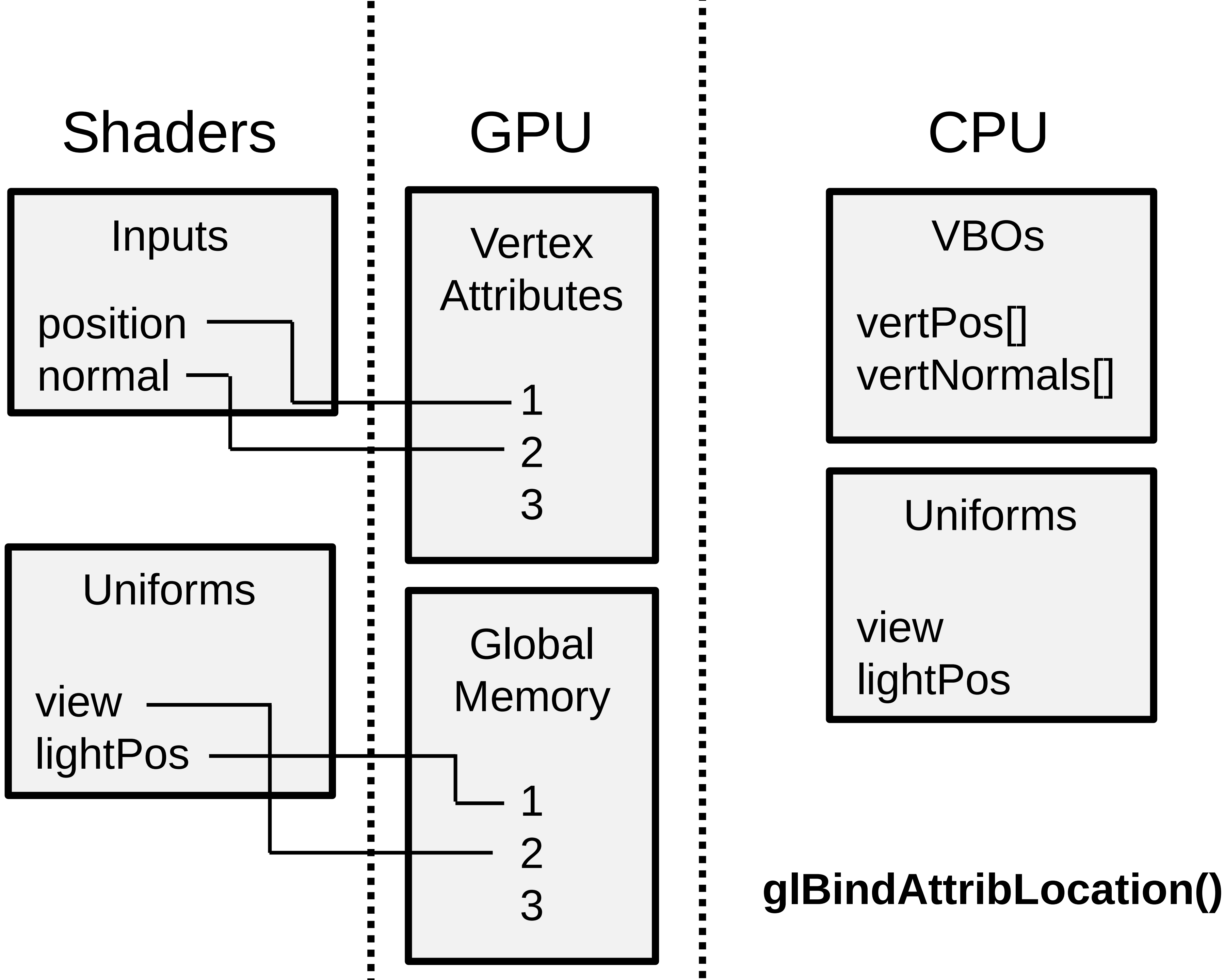
when shader is compiled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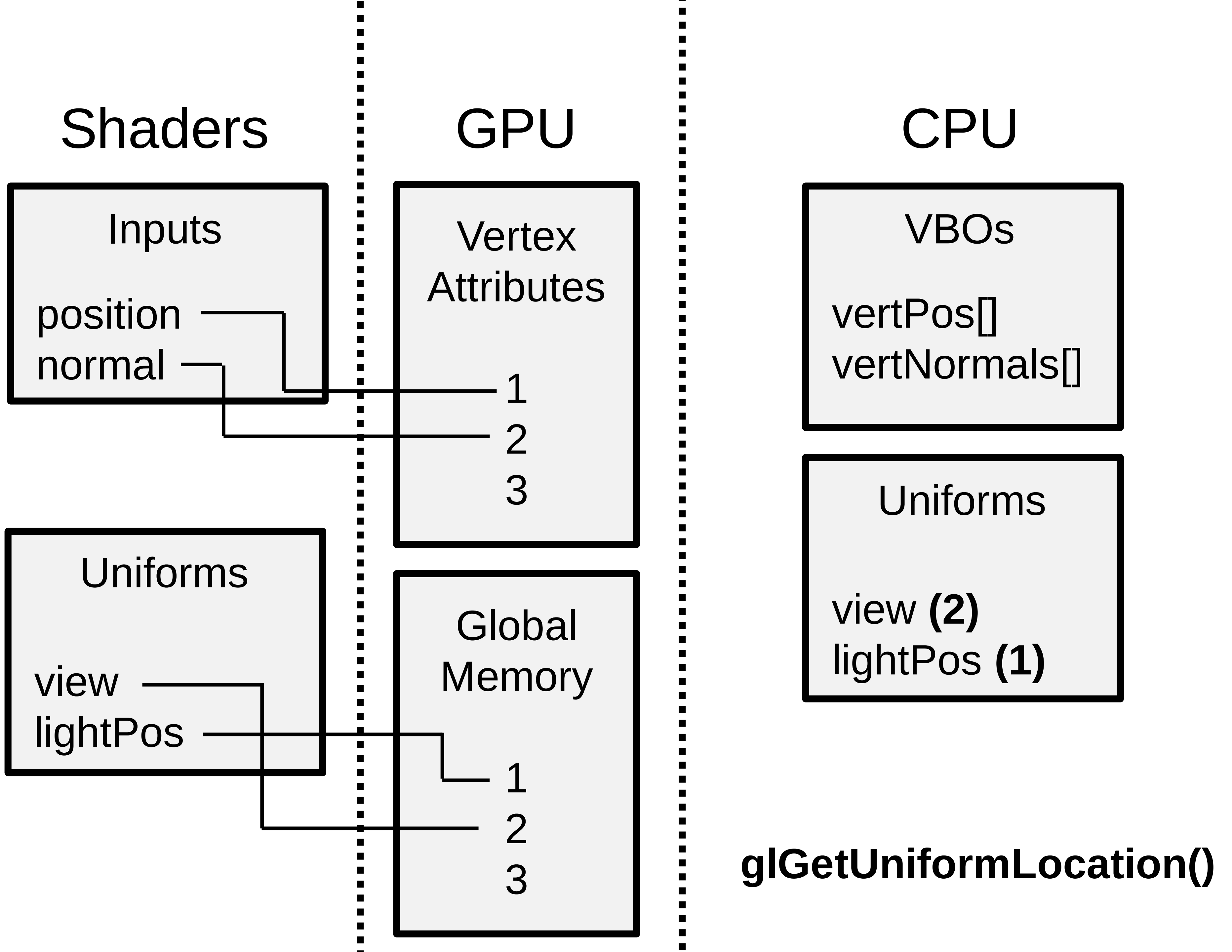
Global
Memory
1
2
3
Uniforms
view
lightPos
glBindAttribLocation()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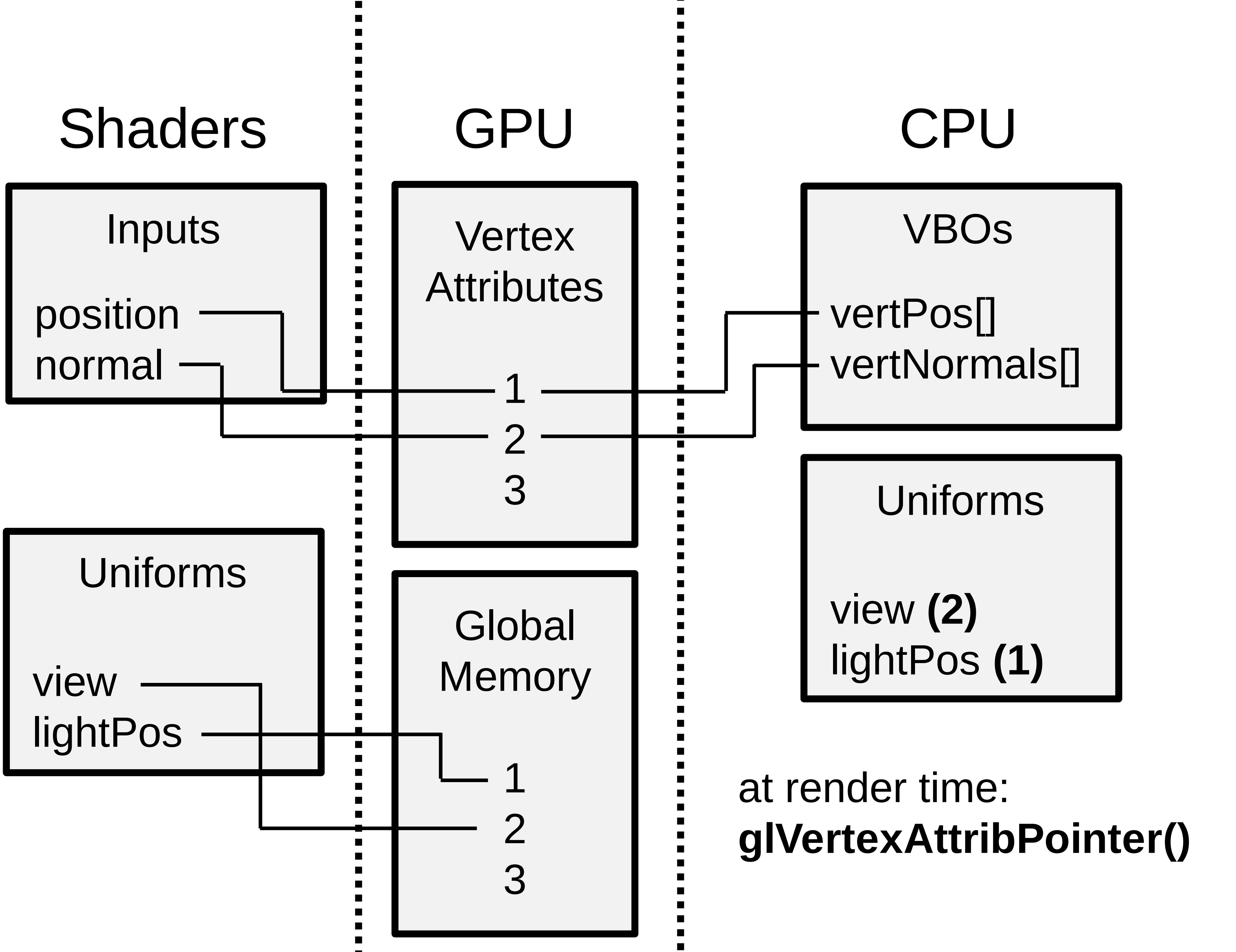
Uniforms
view
lightPos
Global
Memory
1
2
3
Uniforms
view (2)
lightPos (1)
glGetUniformLocation()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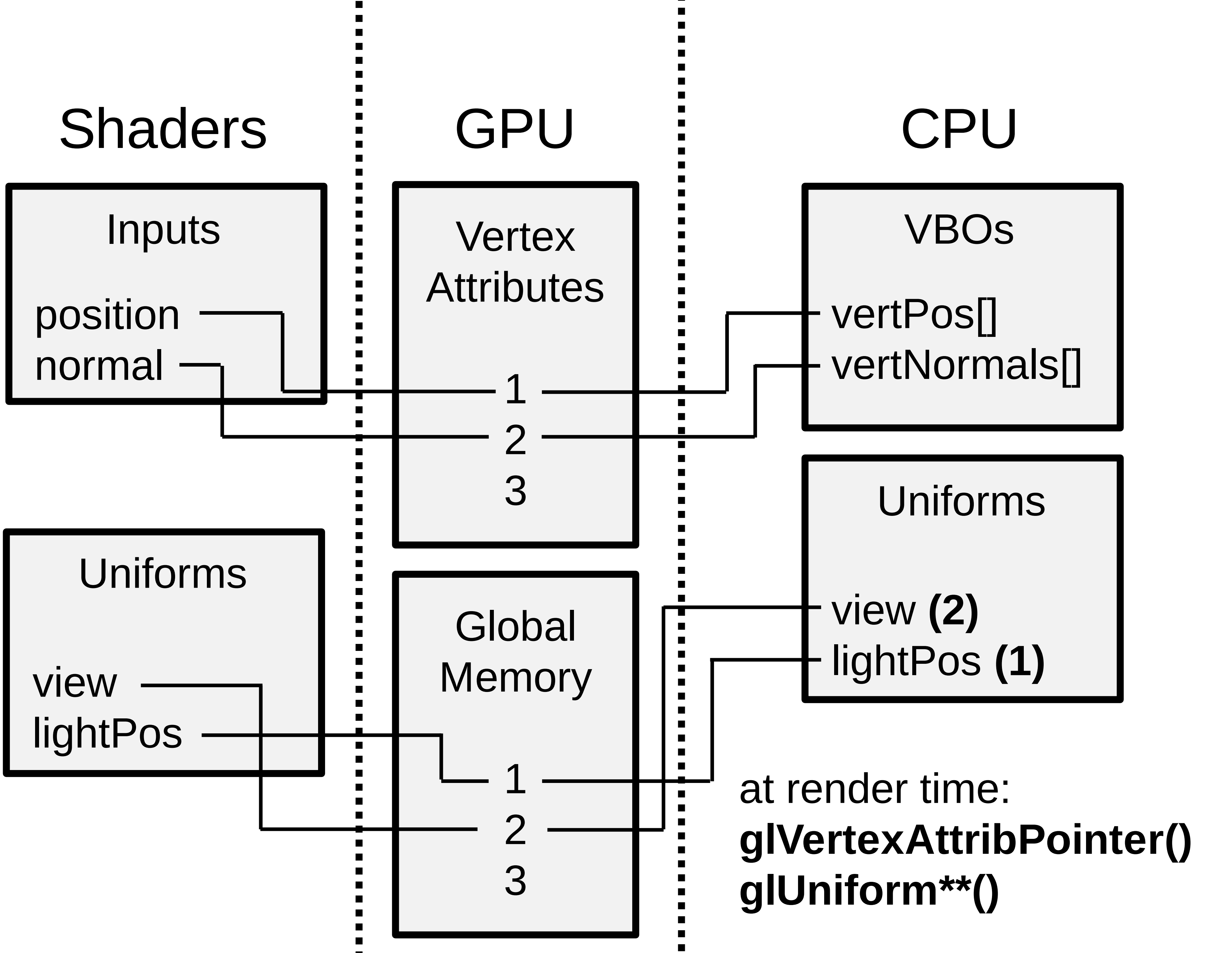
Uniforms
view
lightPos
Global
Memory
1
2
3
Uniforms
view **(2)**
lightPos **(1)**
at render time:
glVertexAttribPointer()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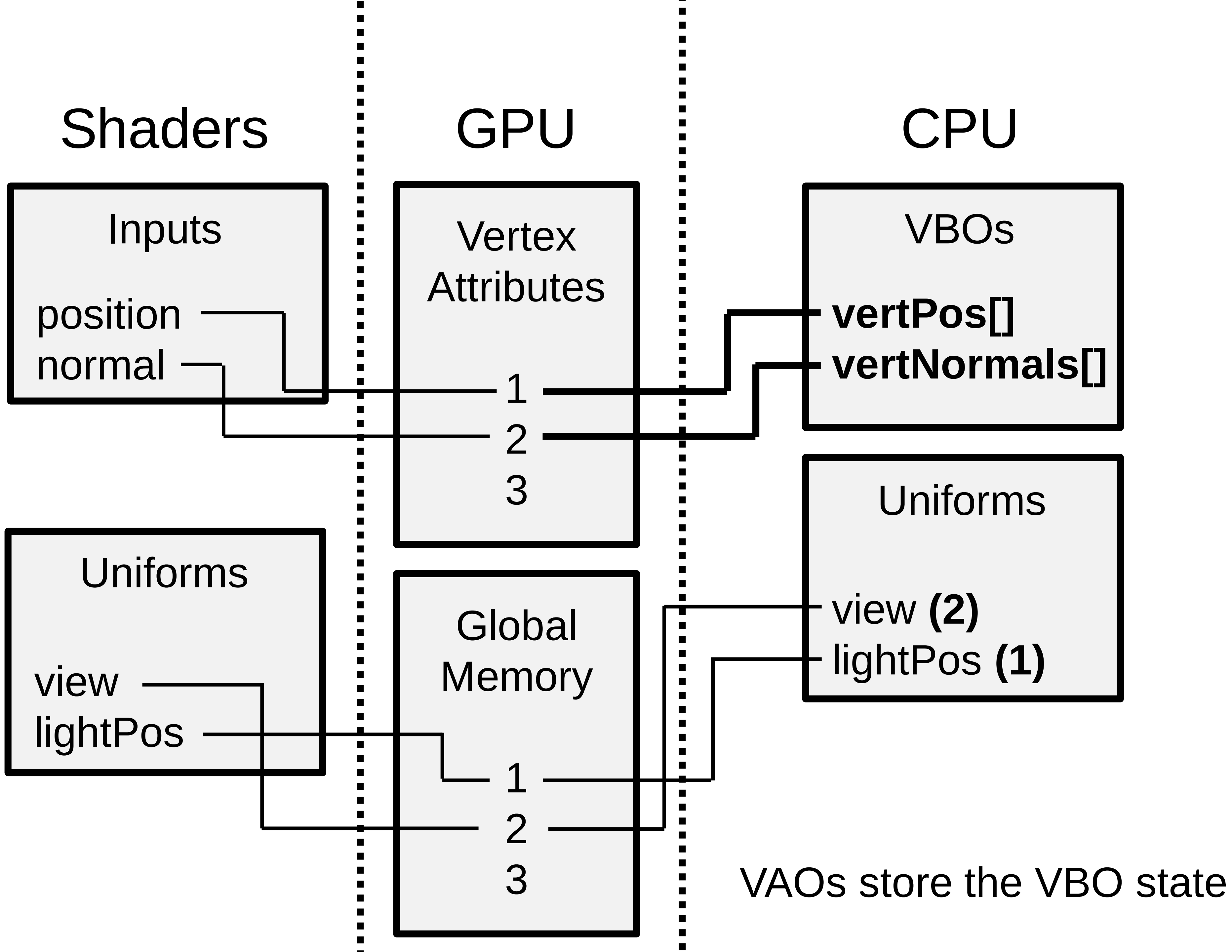
glVertexAttribPointer()
glUniform()**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Uniforms
view (2)
lightPos (1)
VAOs store the VBO state

Ray Tracing: Why Slow? Reprise

Basic ray tracing: 1 ray/pixel

But you **really** want shadows, reflections, global illumination, antialiasing…

- 100-1000 rays/pixel

Much less hardware support

- inhomogeneous / unpredictable work