GPU Memory Model Overview

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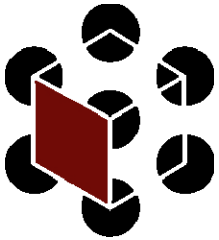
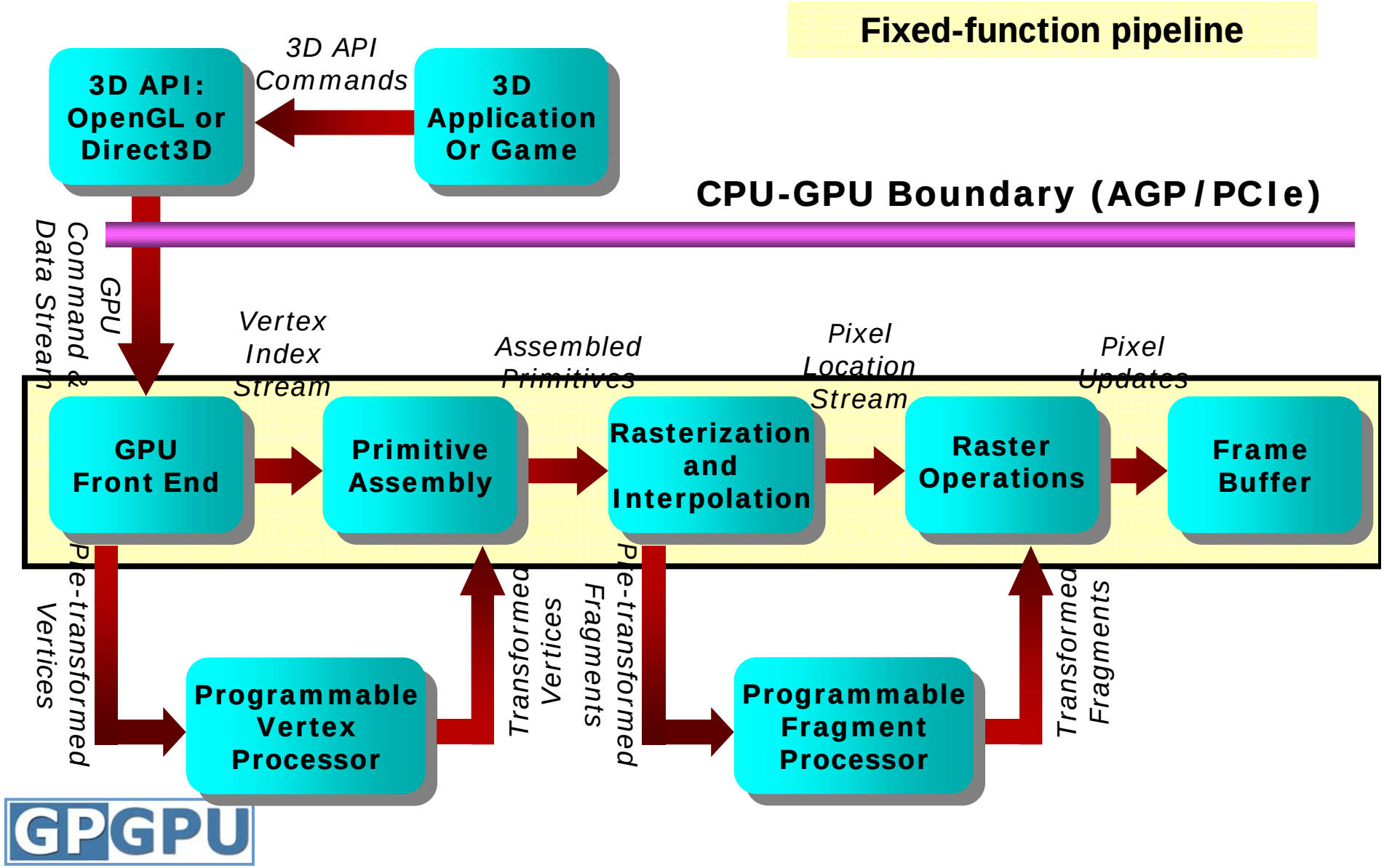


Note: These slides do not include the NVIDIA 8-series memory model

Review



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Review

- Color Buffers
  - Front-left
  - Front-right
  - Back-left
  - Back-right
- Depth Buffer (z-buffer)
- Stencil Buffer
- Accumulation Buffer

Overview

- **GPU Memory Model**
- GPU Data Structure Basics
- Introduction to Framebuffer Objects
- Fragment Pipeline
- Vertex Pipeline

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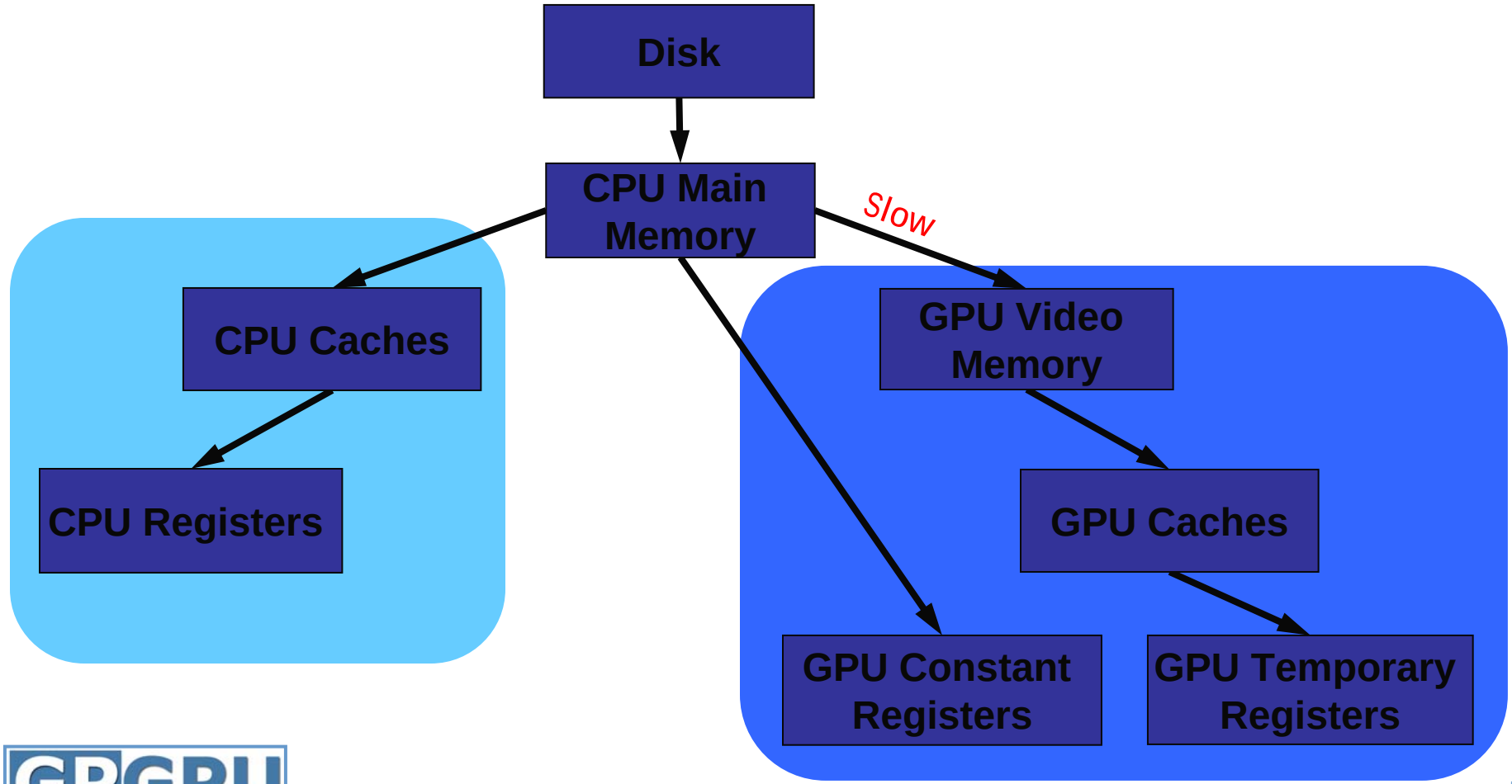
Memory Hierarchy

- CPU and GPU Memory Hierarchy



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CPU Memory Model

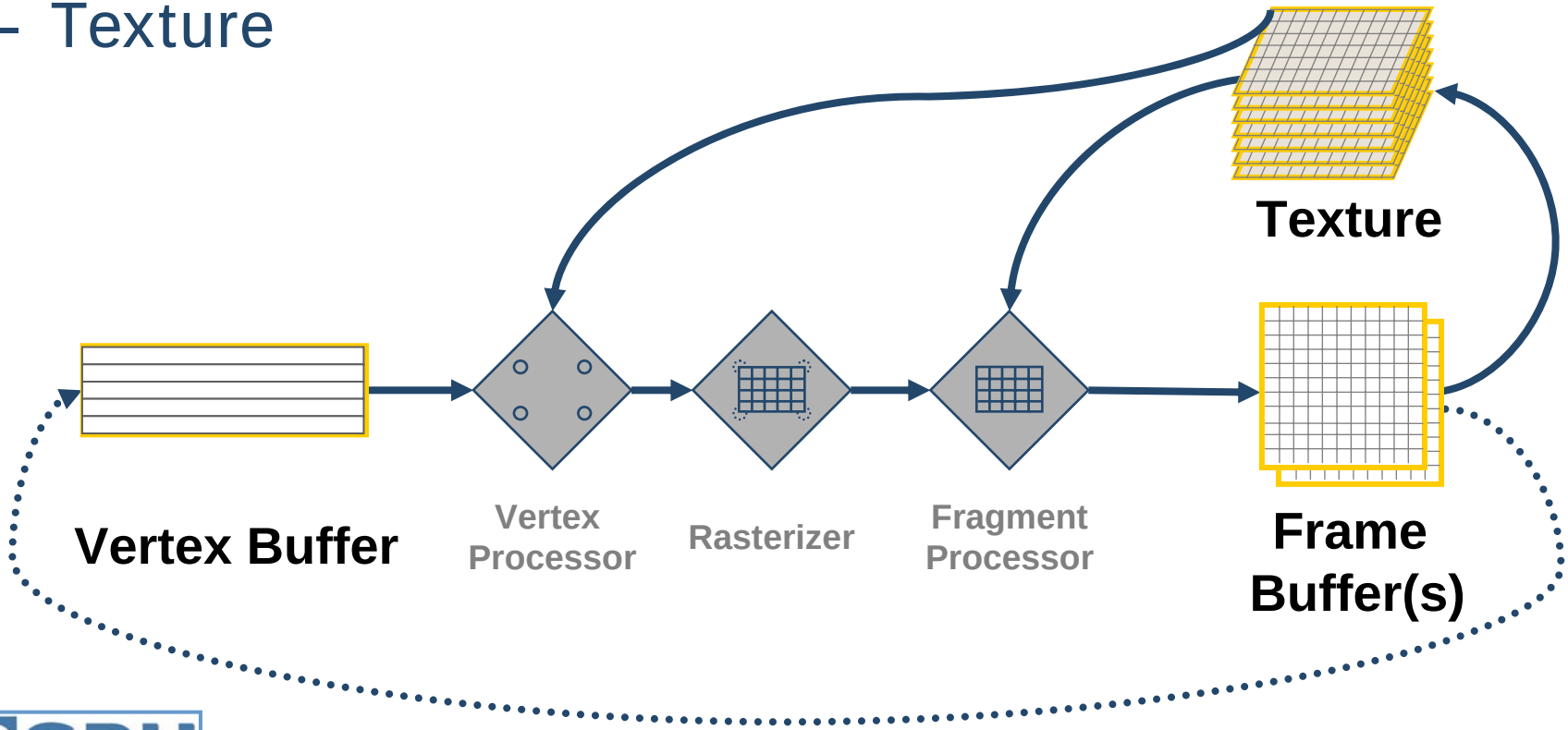
- **At any program point**
  - Allocate/free local or global memory
  - Random memory access
    - Registers
      - Read/write
    - Local memory
      - Read/write to stack
    - Global memory
      - Read/write to heap
    - Disk
      - Read/write to disk

GPU Memory Model

- **Much more restricted memory access**
  - Allocate/free memory only before computation
  - Limited memory access during computation (kernel)
    - Registers
      - Read/write
    - Local memory
      - Read/write
    - Shared Memory
      - Only available in GPGPU not Graphics pipeline
    - Global memory
      - Read-only during computation
      - Write-only at end of computation (pre-computed address)
      - Read/write in GPGPU world only
    - Virtual Memory
      - Does not exist
    - Disk access
      - Does not exist

GPU Memory Model

- **Where is GPU Data Stored?**
  - Vertex buffer
  - Frame buffer
  - Texture



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GPU Memory API

- **Each GPU memory type supports subset of the following operations**
  - CPU interface
  - GPU interface

GPU Memory API

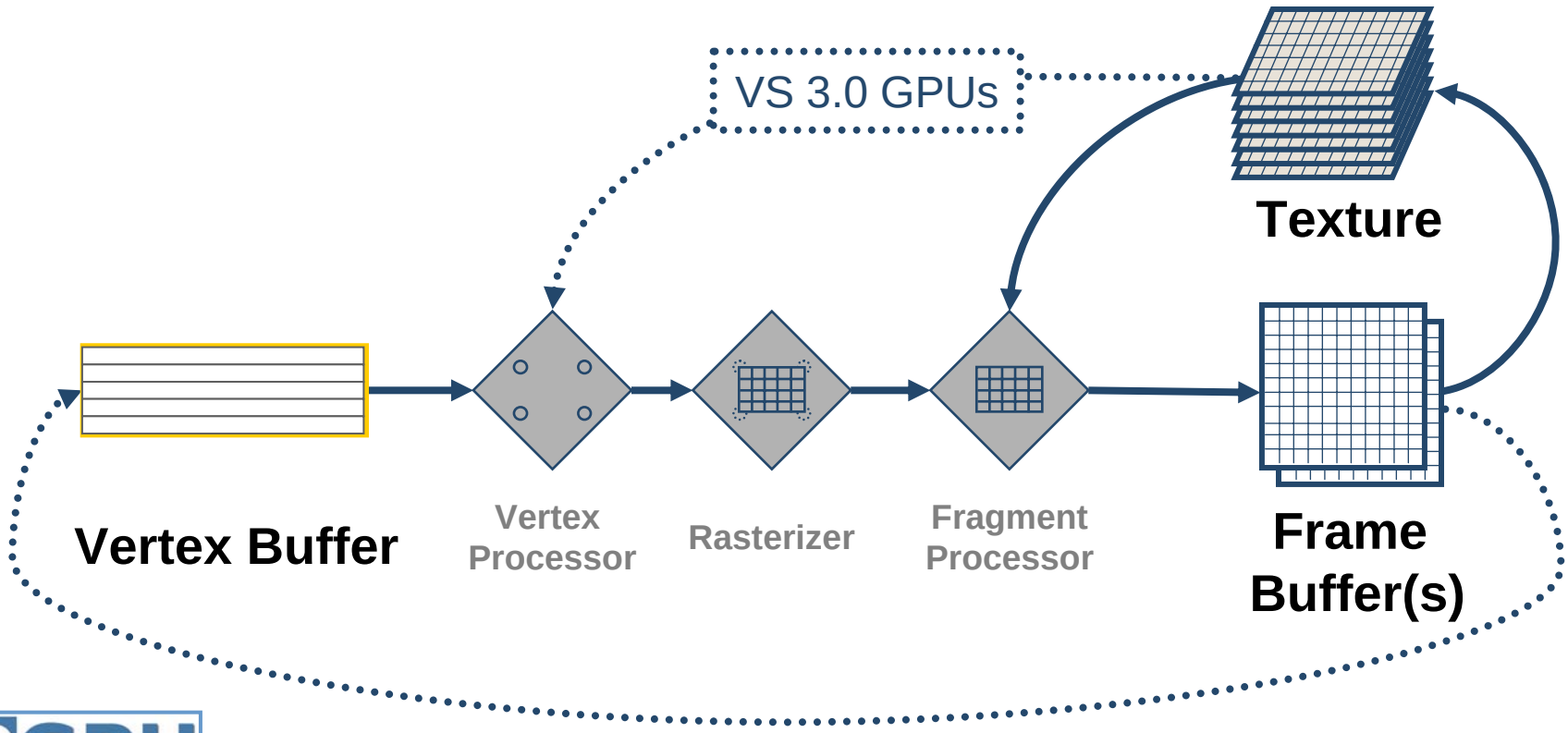
- **CPU interface**
  - Allocate
  - Free
  - Copy CPU → GPU
  - Copy GPU → CPU
  - Copy GPU → GPU
  - Bind for read-only vertex stream access
  - Bind for read-only random access
  - Bind for write-only framebuffer access

GPU Memory API

- **GPU (shader/kernel) interface**
  - Random-access read
  - Stream read

Vertex Buffers

- GPU memory for vertex data
- Vertex data required to initiate render pass



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Vertex Buffers

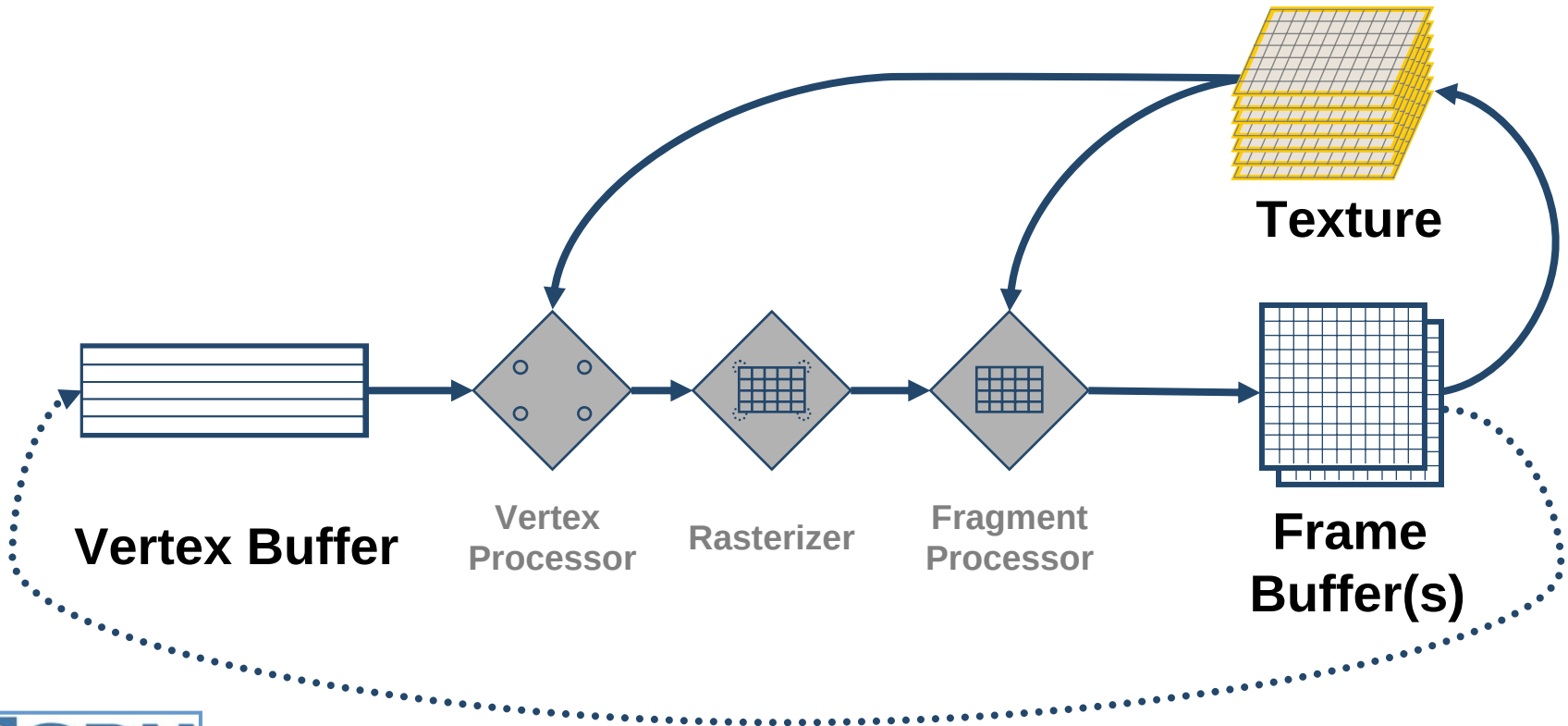
- **Supported Operations**
  - CPU interface
    - Allocate
    - Free
    - Copy CPU → GPU
    - Copy GPU → GPU (Render-to-vertex-array)
    - Bind for read-only vertex stream access
  - GPU interface
    - Stream read (vertex program only)

Vertex Buffers

- **Limitations**
  - CPU
    - No copy GPU → CPU
    - No bind for read-only random access
    - No bind for write-only framebuffer access
  - GPU
    - No random-access reads
    - No access from fragment programs

Textures

- Random-access GPU memory



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Textures

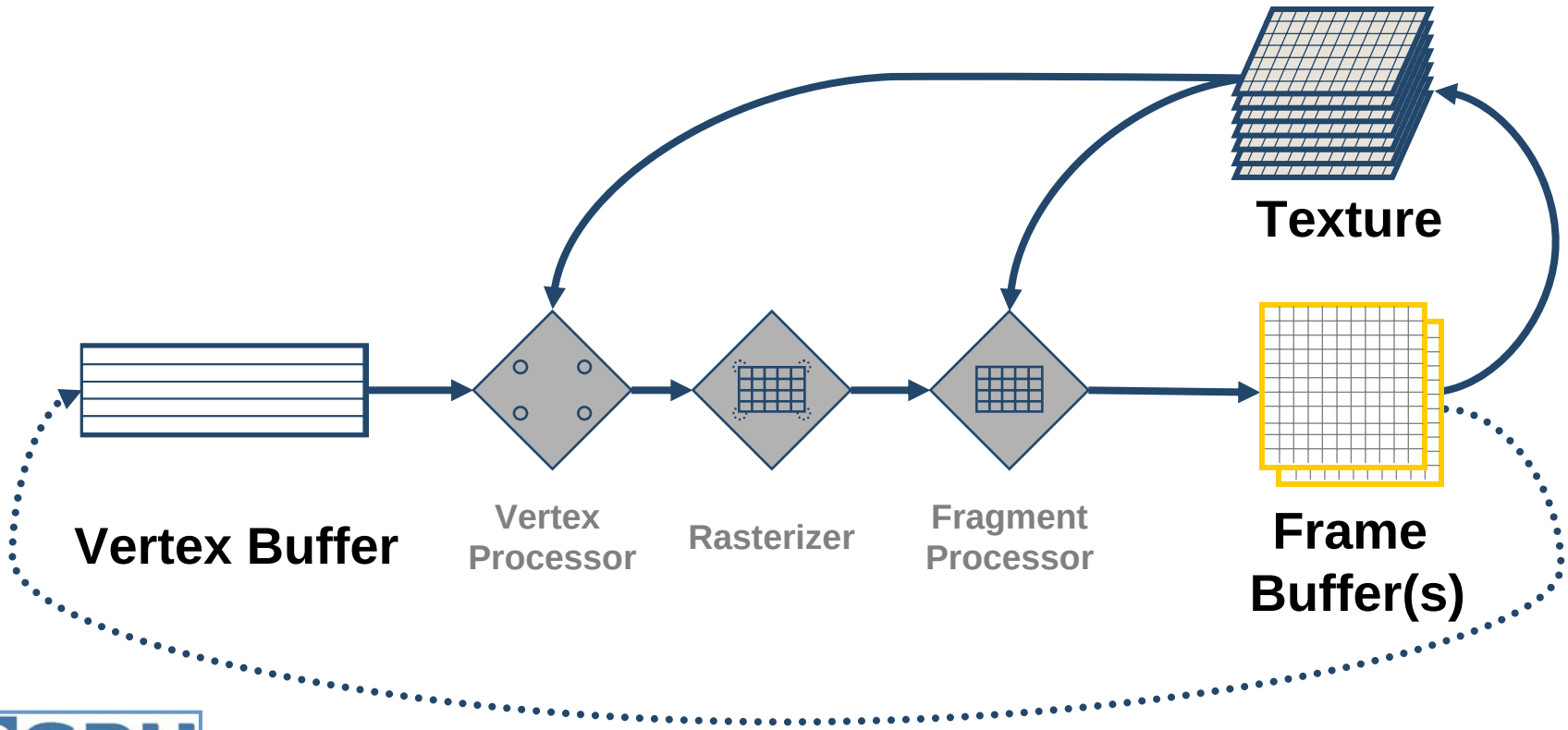
- **Supported Operations**
  - CPU interface
    - Allocate
    - Free
    - Copy CPU → GPU
    - Copy GPU → CPU
    - Copy GPU → GPU (Render-to-texture)
    - Bind for read-only random access (vertex or fragment)
    - Bind for write-only framebuffer access
  - GPU interface
    - Random read

Textures

- **Limitations**
  - No bind for vertex stream access

Framebuffer

- Memory written by fragment processor
- Write-only GPU memory



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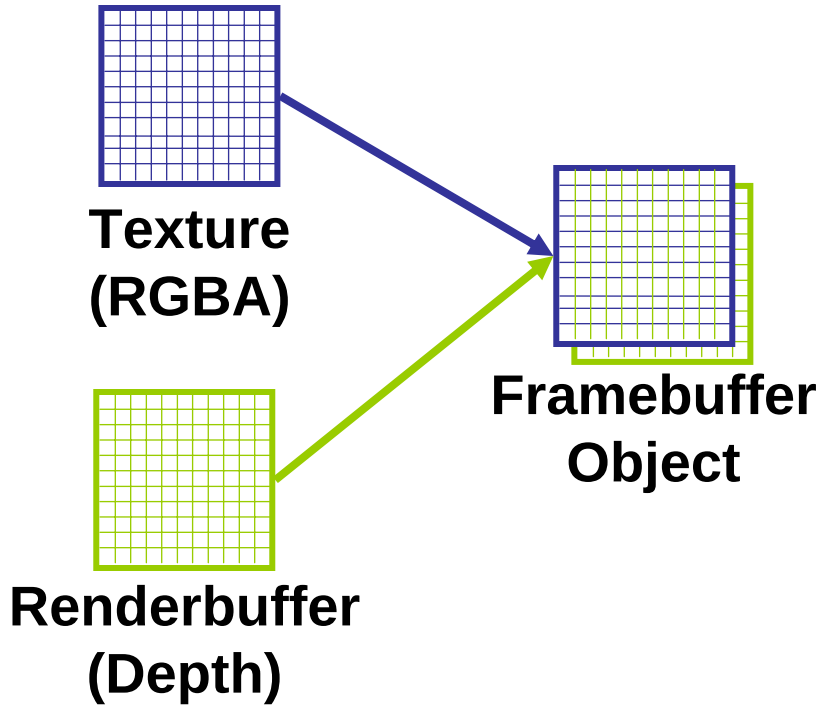
OpenGL Framebuffer Objects

- **General idea**
  - Framebuffer object is lightweight struct of pointers
  - Bind GPU memory to framebuffer as write-only
  - Memory cannot be read while bound to framebuffer
- **Which memory?**
  - Texture
  - Renderbuffer
  - Vertex buffer??



What is a Renderbuffer?

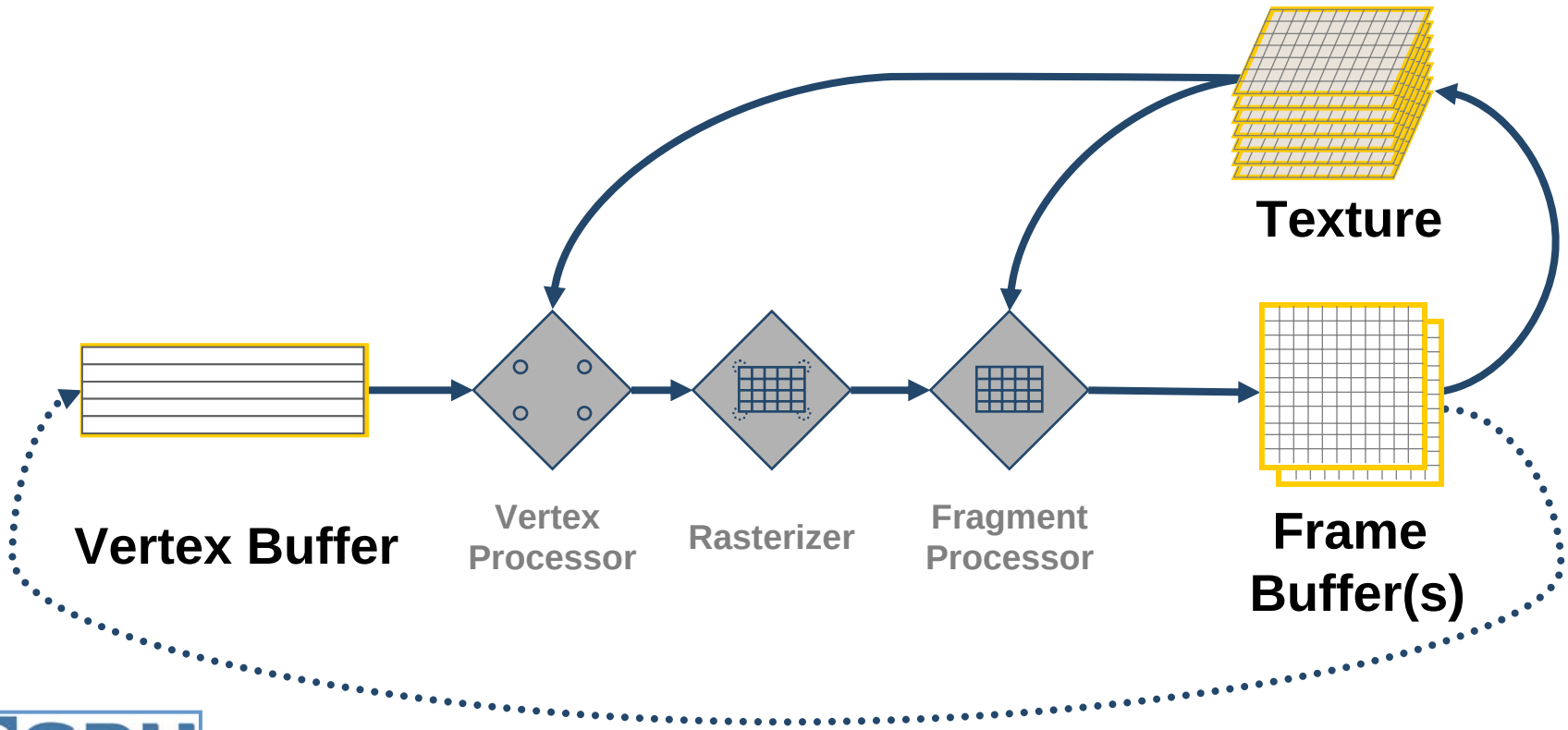
- **“Traditional” framebuffer memory**
  - Write-only GPU memory
    - Color buffer
    - Depth buffer
    - Stencil buffer
- **New OpenGL memory object**
  - Part of Framebuffer Object extension

Renderbuffer

- **Supported Operations**
  - CPU interface
    - Allocate
    - Free
    - Copy GPU → CPU
    - Bind for write-only framebuffer access

Pixel Buffer Objects

- **Mechanism to efficiently transfer pixel data**
  - API nearly identical to vertex buffer objects



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Pixel Buffer Objects

- **Uses**
  - Render-to-vertex-array
    - glReadPixels into GPU-based pixel buffer
    - Use pixel buffer as vertex buffer
  - Fast streaming textures
    - Map PBO into CPU memory space
    - Write directly to PBO
    - Reduces one or more copies

Pixel Buffer Objects

- **Uses (continued)**
  - Asynchronous readback
    - Non-blocking GPU → CPU data copy
    - glReadPixels into PBO does *not* block
    - Blocks when PBO is mapped into CPU memory

Summary : Render-to-Texture

- **Basic operation in GPGPU apps**

- **OpenGL Support**
  - Save up to 16, 32-bit floating values per pixel
    - Multiple Render Targets (MRTs) on ATI and NVIDIA

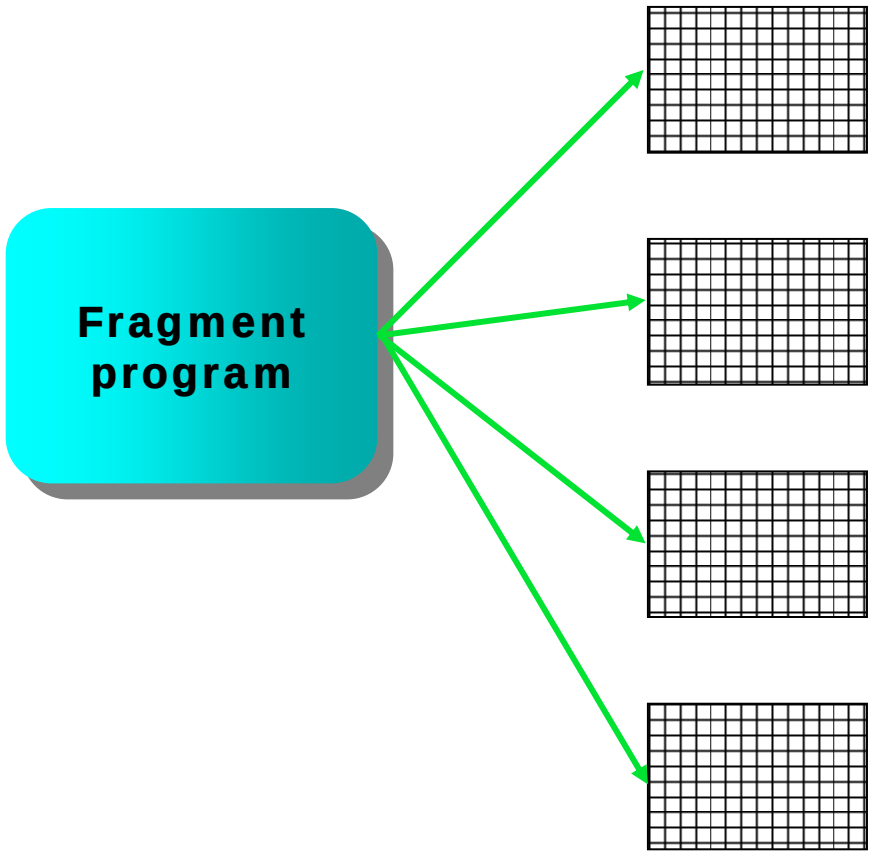
  1. Copy-to-texture
     - glCopyTexSubImage

     Render-to-texture
     - GL_EXT_framebuffer_object

Summary : Render-To-Vertex-Array

- **Enable top-of-pipe feedback loop**
- **OpenGL Support**
  - Copy-to-vertex-array
    - GL_ARB_pixel_buffer_object
    - NVIDIA and ATI
  - Render-to-vertex-array
    - Maybe future extension to framebuffer objects

Multiple Render to Texture (MRT) [nv40]



MRT allows us to compress multiple passes into a single one.

This does not fundamentally change the model though, since read/write access is still not allowed.

Overview

- GPU Memory Model
- **GPU Data Structure Basics**
- Introduction to Framebuffer Objects
- Fragment Pipeline
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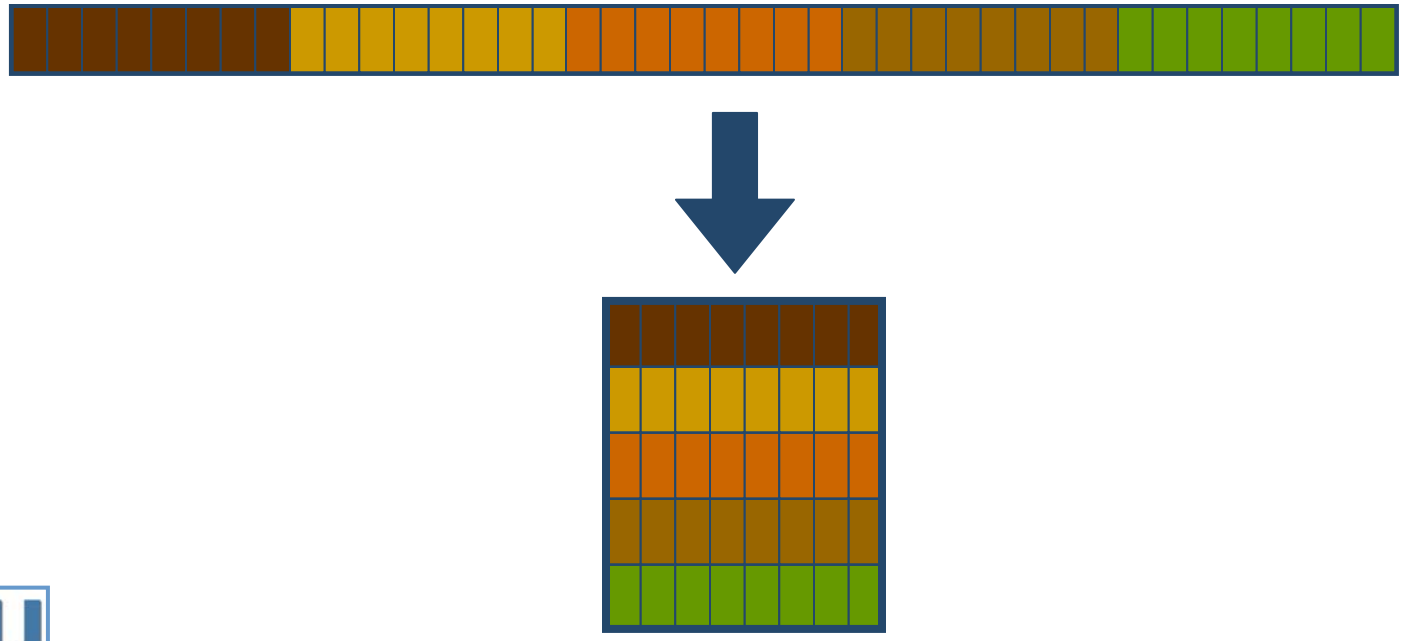
GPU Arrays

- **Large 1D Arrays**
  - Current GPUs limit 1D array sizes to 2048 or 4096
  - Pack into 2D memory
  - 1D-to-2D address translation



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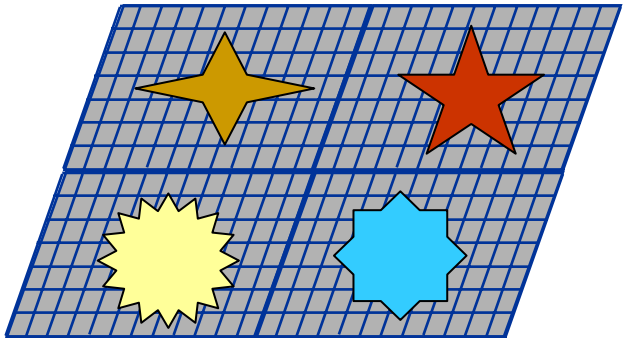
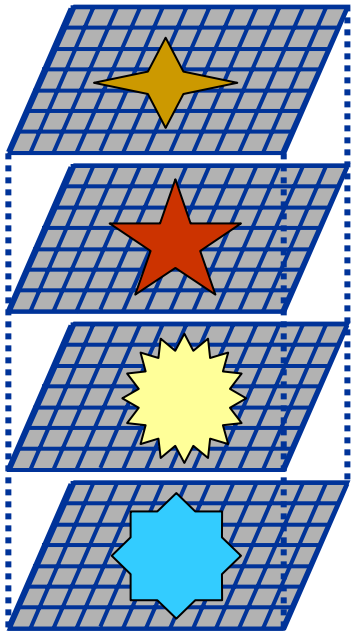
GPU Arrays

- **3D Arrays**
  - Problem
    - GPUs do not have 3D frame buffers
    - No render-to-slice-of-3D-texture yet (coming soon?)
  - Solutions
    1. Stack of 2D slices
    2. Multiple slices per 2D buffer





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GPU Arrays

- **Problems With 3D Arrays for GPGPU**
  - Cannot read stack of 2D slices as 3D texture
  - Must know which slices are needed in advance
  - Visualization of 3D data difficult

- **Solutions**
  - Flat 3D textures
  - Need render-to-slice-of-3D-texture
    - Maybe with GL_EXT_framebuffer_object
  - Volume rendering of flattened 3D data
    - "Deferred Filtering: Rendering from Difficult Data Formats," GPU Gems 2, Ch. 41, p. 667

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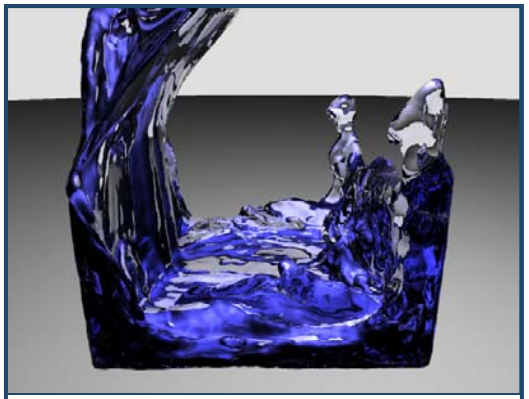
GPU Arrays

- **Higher Dimensional Arrays**
  - Pack into 2D buffers
  - N-D to 2D address translation
  - Same problems as 3D arrays if data does not fit in a single 2D texture

Sparse/Adaptive Data Structures

- **Why?**
  - Reduce memory pressure
  - Reduce computational workload

- **Examples**
  - Sparse matrices
    - Krueger et al., Siggraph 2003
    - Bolz et al., Siggraph 2003



Premoze et al. Eurographics 2003

  - Deformable implicit surfaces (sparse volumes/PDEs)
    - Lefohn et al., IEEE Visualization 2003 / TVCG 2004

  - Adaptive radiosity solution (Coombe et al.)

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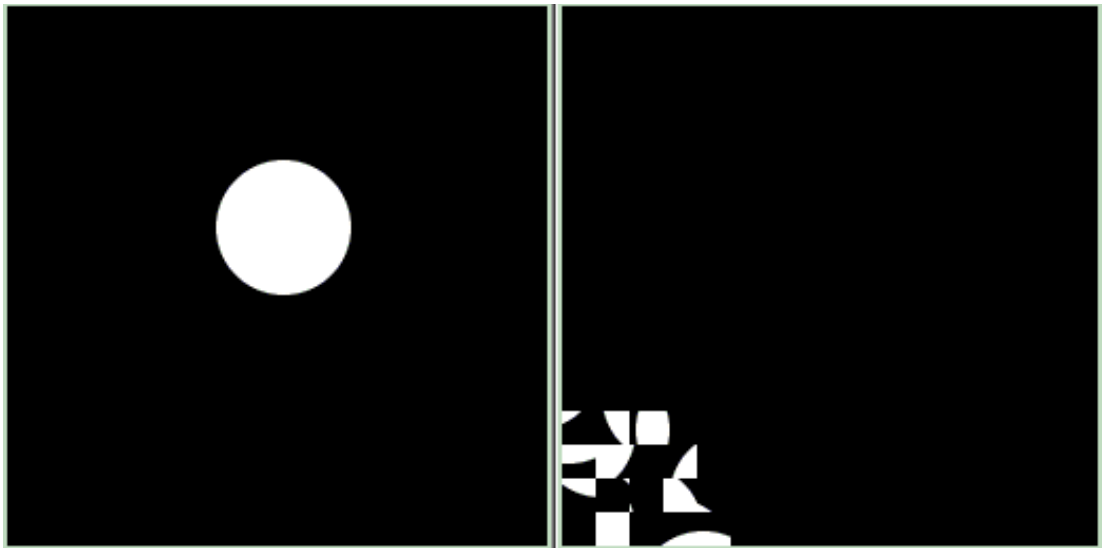
Sparse/Adaptive Data Structures

- **Basic Idea**
  - Pack “active” data elements into GPU memory

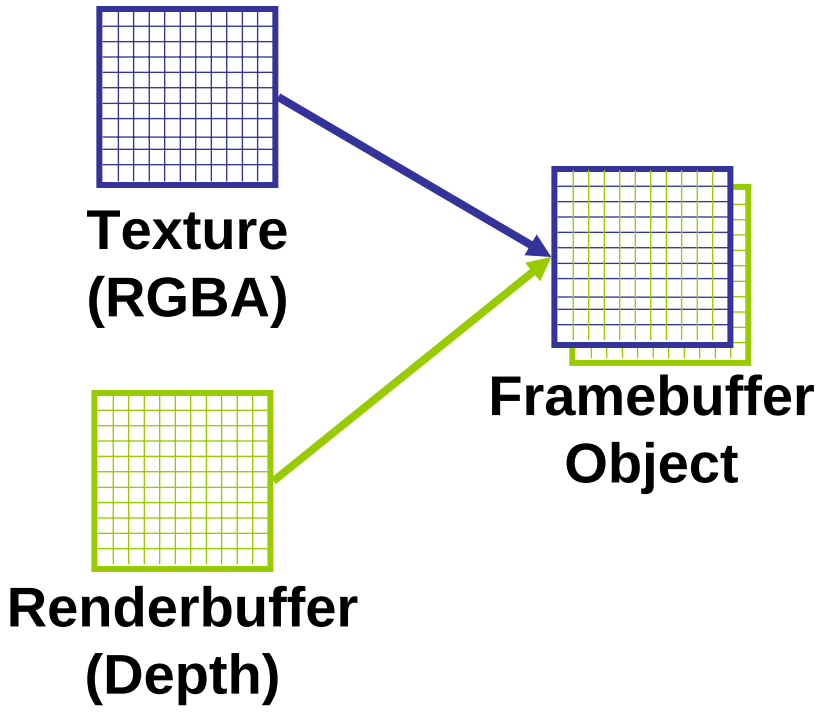


Overview

- GPU Memory Model
- GPU-Based Data Structures
- **Introduction to Framebuffer Objects**
- Fragment Pipeline
- Vertex Pipeline

Framebuffer Objects

- **What is an FBO?**
  - A struct that holds pointers to memory objects
  - Each bound memory object can be a framebuffer rendering surface
  - Platform-independent



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Framebuffer Objects

- **Which memory can be bound to an FBO?**
  - Textures
  - Renderbuffers
    - Depth, stencil, color
    - Traditional write-only framebuffer surfaces

Framebuffer Objects

- **Usage models**
  - Keep N textures bound to one FBO (up to 16)
    - Change render targets with glDrawBuffers
  - Keep one FBO for each size/format
    - Change render targets with attach/unattach textures
  - Keep several FBOs with textures attached
    - Change render targets by binding FBO

Framebuffer Objects

- **Performance**
  - Render-to-texture
    - glDrawBuffers is fastest on NVIDIA/ATI
      - As-fast or faster than pbuffers
    - Attach/unattach textures same as changing FBOs
      - Slightly slower than glDrawBuffers but faster than wglMakeCurrent
    - Keep format/size identical for all attached memory
      - Current driver limitation, not part of spec
  - Readback
    - Same as pbuffers for NVIDIA and ATI

Framebuffer Objects

- **Driver support still evolving**
  - GPUBench FBO tests coming soon…
    - "fbocheck" evalulates completeness
    - Other tests…

Framebuffer Object

- **Code examples**
  - Simple C++ FBO and Renderbuffer classes
    - HelloWorld example
    - http://gpgpu.sourceforge.net/
  - OpenGL Spec

    http://oss.sgi.com/projects/ogl-sample/registry/EXT/framebuffer_object.txt

Overview

- GPU Memory Model
- GPU Data Structure Basics
- Introduction to Framebuffer Objects
- **Fragment Pipeline**
- Vertex Pipeline

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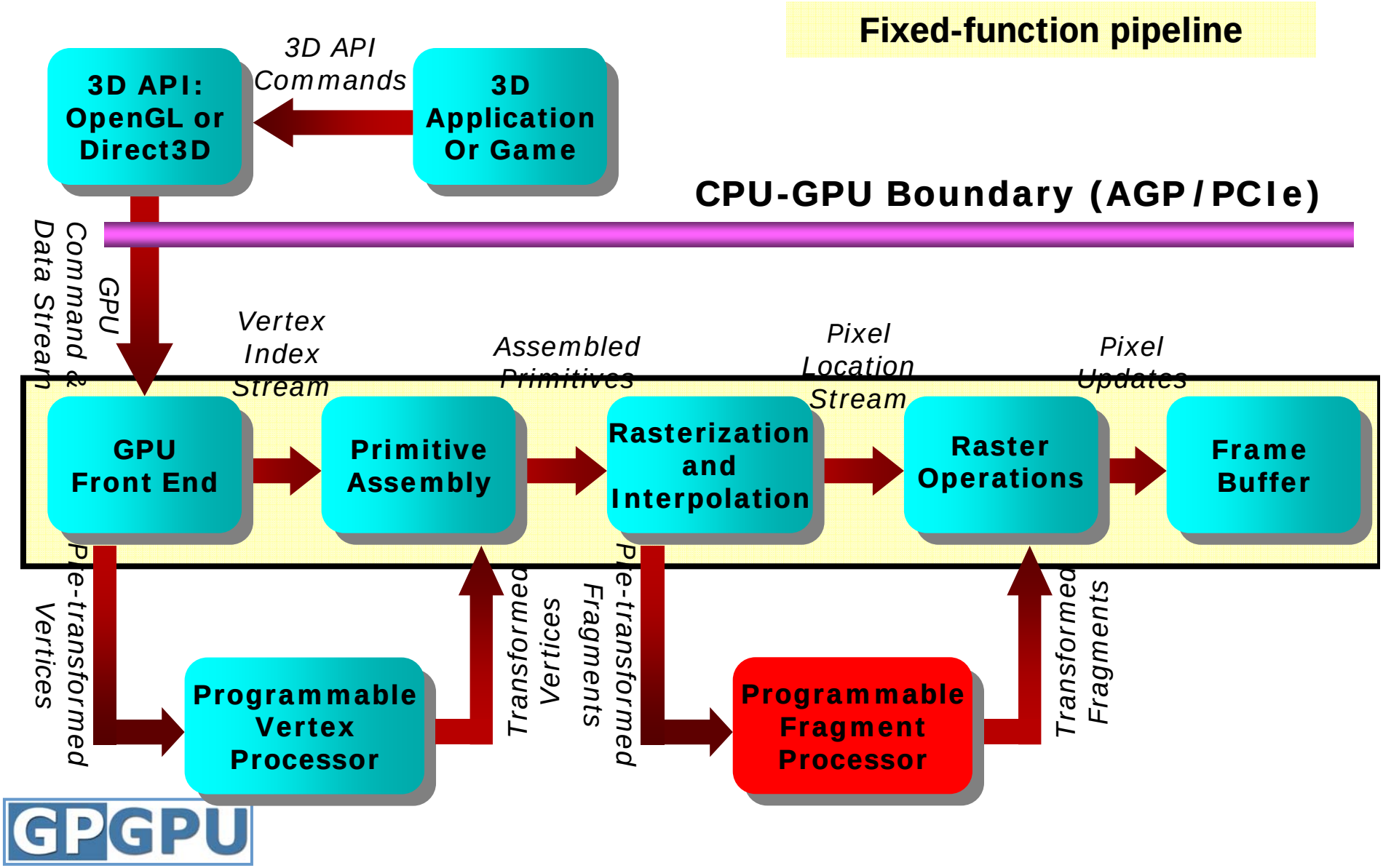
Review



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The fragment pipeline

Input: Fragment

Attributes

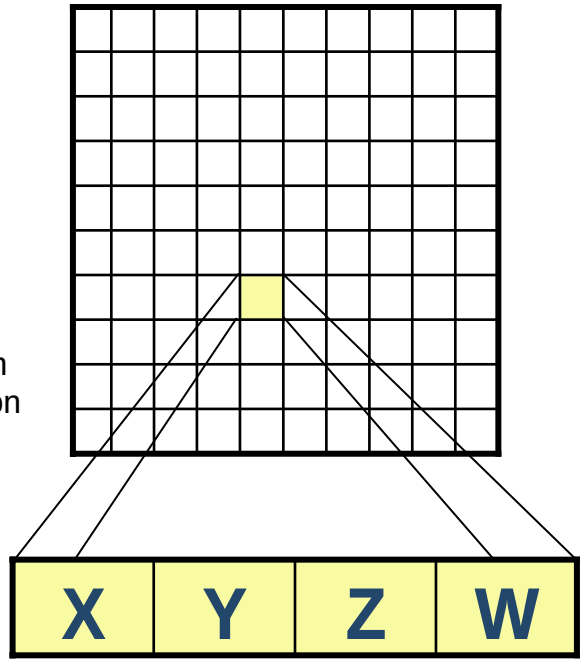
Color	R	G	B	A
Position	X	Y	Z	W
Texture coordinates	X	Y	[Z]	-
Texture coordinates	X	Y	[Z]	-
...				

Interpolated from vertex information

32 bits = float

16 bits = half

Input: Texture Image



- Each element of texture is 4D vector
- Textures can be “square” or rectangular (power-of-two or not)

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The fragment pipeline

Input: Uniform parameters

- **Can be passed to a fragment program like normal parameters**
- **set in advance before the fragment program executes**

Example:

A counter that tracks which pass the algorithm is in.

Input: Constant parameters

- **Fixed inside program**
- **E.g. float4 v = (1.0, 1.0, 1.0, 1.0)**

Examples:

3.14159..

Size of compute window

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The fragment pipeline

Math ops: USE THEM !

- cos(x)/log2(x)/pow(x,y)
- dot(a,b)
- mul(v, M)
- sqrt(x)
- cross(u, v)

Using built-in ops is more efficient than writing your own

Swizzling/masking: an easy way to move data around.

```
v1 = (4,-2,5,3); // Initialize
v2 = v1.yx;      // v2 = (-2,4)
s = v1.w;        // s = 3
v3 = s.rrr;      // v3 = (3,3,3)
```

Write masking:

```
v4 = (1,5,3,2);
v4.ar = v2;      // v4=(4,5,4,-2)
```

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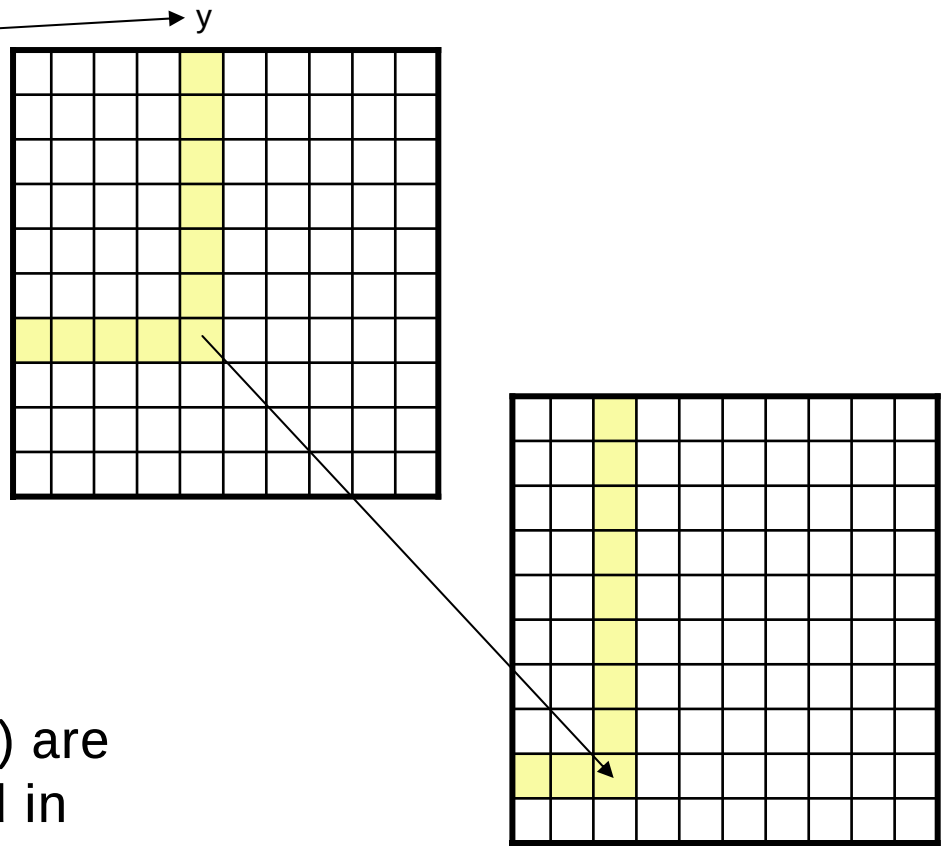
The fragment pipeline

```
float4 v = tex2D(IMG, float2(x,y))
```



Texture access is like an array lookup.

The value in v can be used

to perform another lookup!

This is called a dependent read

Texture reads (and dependent reads) are expensive resources, and are limited in different GPUs. Use them wisely !

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The fragment pipeline

Control flow:

- **(<test>)?a:b operator.**
- **if-then-else conditional**
  - **[nv3x]** Both branches are executed, and the condition code is used to decide which value is used to write the output register.
  - **[nv40]** True conditionals
- **for-loops and do-while**
  - **[nv3x]** limited to what can be unrolled (i.e no variable loop limits)
  - **[nv40]** True looping.

WARNING: Even though nv40 has true flow control, performance will suffer if there is no coherence (more on this later)

The fragment pipeline

Fragment programs use call-by-result

```
out float4 result : COLOR
// Do computation
result = <final answer>
```

Notes:

- **Only output color can be modified**
- **Textures cannot be written**
- **Setting different values in different channels of result can be useful for debugging**

Overview

- GPU Memory Model
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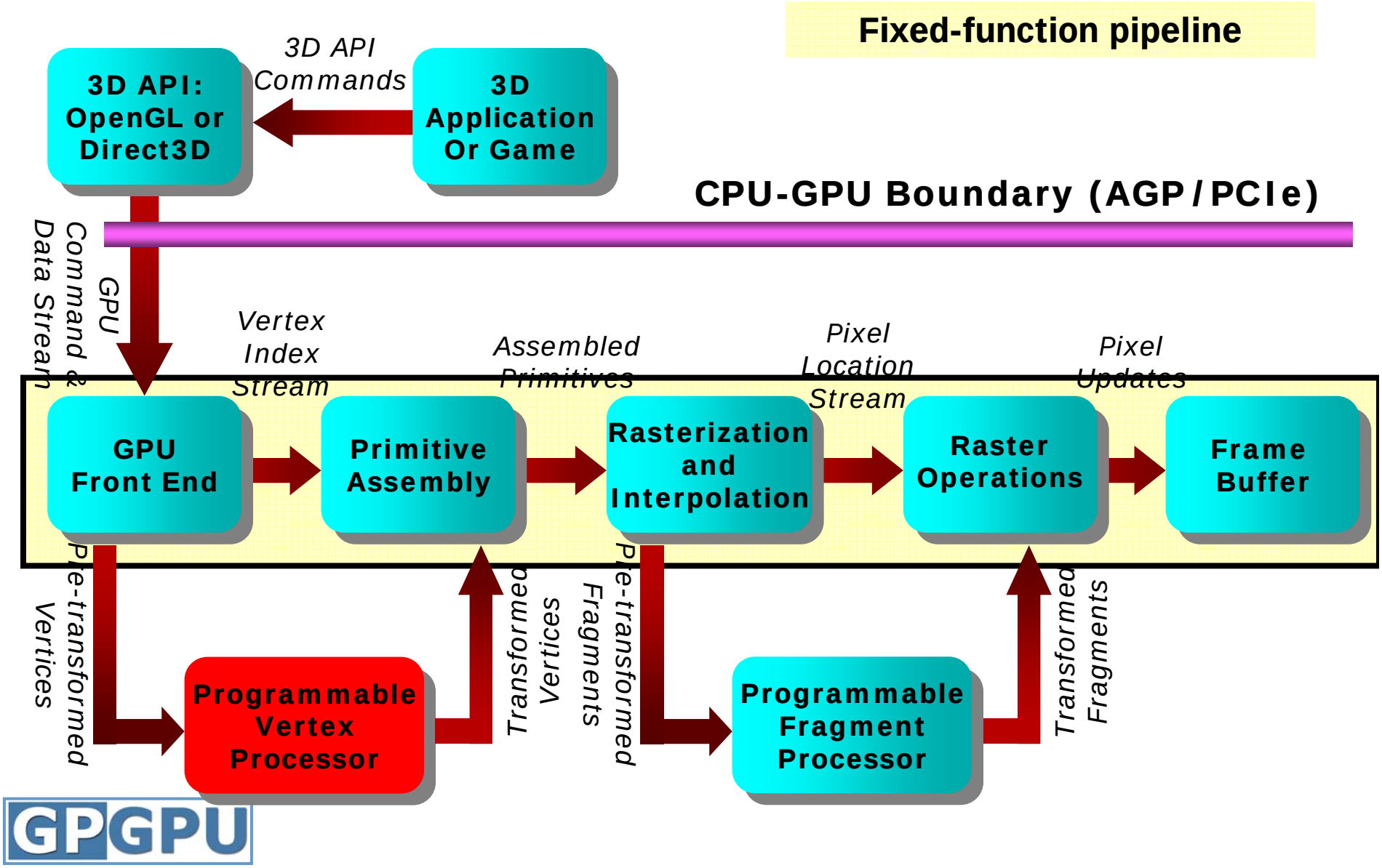
- Fragment Pipeline
- **Vertex Pipeline**

GPGPU

Review



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The Vertex Pipeline

Input: vertices

- position, color, texture coords.

Input: uniform and constant parameters.

- Matrices can be passed to a vertex program.
- Lighting/material parameters can also be passed.

The Vertex Pipeline

Operations:

- **Math/swizzle ops**
- **Matrix operators**
- **Flow control (as before)**

[nv3x] **No access to textures.**

Output:

- **Modified vertices (position, color)**
- **Vertex data transmitted to primitive assembly.**

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Vertex programs are useful

- We can replace the entire geometry transformation portion of the fixed-function pipeline.
- Vertex programs used to change vertex coordinates (move objects around)
- There are many fewer vertices than fragments: shifting operations to vertex programs improves overall pipeline performance.
- Much of shader processing happens at vertex level.
- We have access to original scene geometry.

Vertex programs are not useful for GPGPU

- **Fragment programs allow us to exploit full parallelism of GPU pipeline ("a processor at every pixel").**
- **Vertex programs can't read input !** [nv3x]
- **NV4X Cards can read vertex textures but can not read FBOs**

Rule of thumb:
If computation requires intensive calculation,
it should probably be in the fragment processor.

If it requires more geometric/graphic computing,
it should be in the vertex processor.

GPGPU

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