Computer Graphics

– OpenGL –

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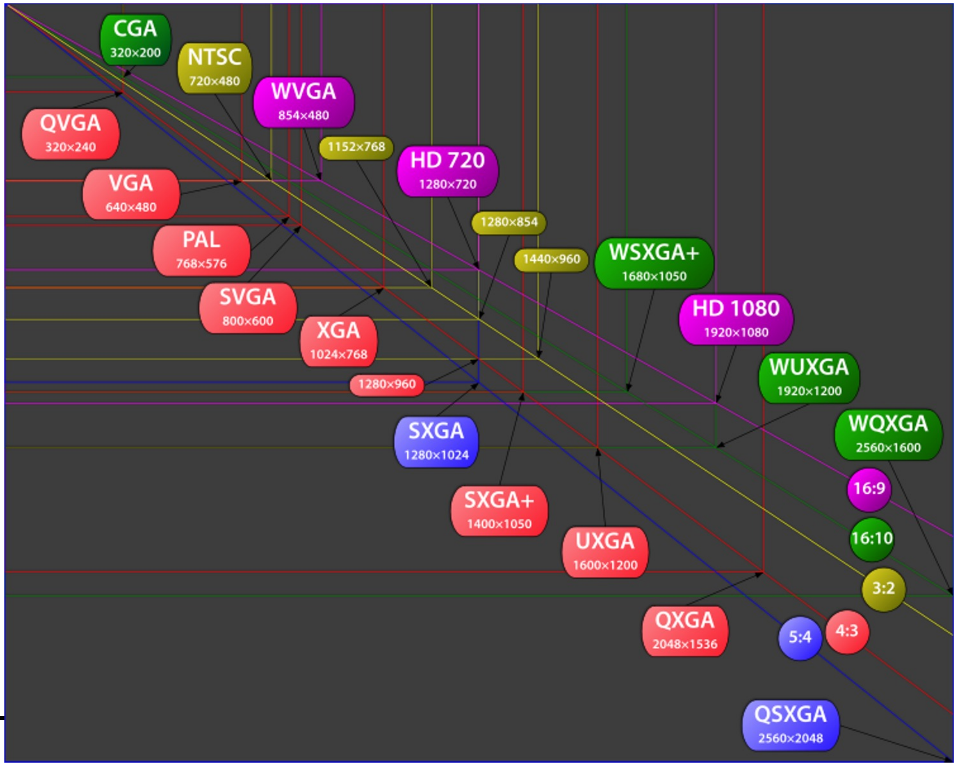
History: Graphics Hardware

- **Graphics in the ‘80ies**
  - Framebuffer was a designated memory area in RAM
  - „HW“: Set individual pixels directly via memory access
    - Peek & poke, getpixel & putpixel, …
    - MDA ('81: text only but 720x350 resolution, monochrome, 4 kB of RAM!)
      - Character code was index into bit pattern in ROM for each character
    - CGA ('81: 160x200: 16 colors w/ tricks; 320x200: 4 col; 640x200: 2 col)
    - EGA ('85: 640x350: 16 from 64 col, CGA mode)
    - VGA ('90: 640x480: 16 col @ table with 2^18 col, 320x200: 256 col), with BIOS extension
  - Everything done on the CPU
    - Except for driving the display output



History: Graphics Hardware (II)

- **Today (Nvidia Ampere Flagship GA 102, RTX 3090)**
  - Discrete graphics card via high-speed link
    - e.g. PCIe-4.0 x16: up to 64 GB/s transfer rate
  - Autonomous, high-performance GPU (more powerful than CPU)
    - 10,496 SIMD processors
    - Up to 24GB of local GDDR6X RAM (A6000: 48 GB, x2 via NVLink)
    - 936 GB/s memory bandwidth
    - 35.6 TFLOPS 16bit floats
    - 35.6 TFLOPS single precision (SP) + ? TFLOPS doubles (DP)
    - 35.6/142/284/568 TFLOPS in FP32/16/Int8/4 via 328 Tensor Cores (RTX)
    - ~20 GigaRays/s, 84 RT Cores
    - Dedicated ray tracing HW unit (BVH traversal & tri. interpol & intersect)
    - Total of 28.3 Billion transistors at 350 Watt
  - Performs all low-level tasks & a lot of high-level tasks
    - Clipping, rasterization, hidden surface removal, … + Ray Tracing
    - Procedural geometry, shading, texturing, animation, simulation, …
    - Video rendering, de- and encoding, deinterlacing, …
    - Full programmability at several pipeline stages
    - Deep Learning & Matrix-Multiply (sparse x2): Training and Inference

Nvidia GA102 GPU

History: Graphics APIs

- **Brief history of graphics APIs**
  - Initially every company had its own 3D-graphics API
  - Many early standardization efforts
    - CORE, GKS/GKS-3D, PHIGS/PHIGS-PLUS, ...
  - 1984: SGI´s proprietary Graphics Library (GL / IrisGL)
    - 3D rendering, menus, input, events, text, ... → „Naturally grown“ :-)
- **OpenGL (1992)**
  - By Mark Segal & Kurt Akeley
    - Explicit design of a general & vendor independent standard
  - Close to hardware but hardware-independent → highly efficient
  - Orthogonal design and extensible
    - Common interface from mobile phone to supercomputer
  - OpenGL 3.0/3.2 (2008/2009), 4.0/4.1 (2010), … , 4.6 (2019)
    - Major redesign & cleanup, deprecated and removed functionality
    - Since Version 3.2: Profiles (core, compatibility, forward compatibility)
    - OpenCL for compute, tesselation shaders, 64 bit variables, multi-viewpoint
    - 4.3: Compute shaders, adv. texture compression, …
    - 4.5: Direct state access, compatibility to OGL ES3.1, …

History: Graphics APIs (II)

- **Direct3D (Microsoft, Part of DirectX multimedia APIs)**
  - Started as *Reality Labs* by RenderMorphics, bought by MS (SW focus)
  - First version in 1996, Retained & Immediate Mode API
  - Played catch-up to OpenGL until Direct3D 6.0 (1998)
  - Advanced fast & significantly by close collaboration with HW vendors
  - Largely feature parity since about 2008
- **Race to "Zero Driver Overhead"**
  - Started with initiative by game developers to have better control and avoid driver getting in their way, working with AMD since 2012
  - Goals: Move API closer to HW, give better control, eliminate SW overhead, more direct state handling, better multithreading, …
  - OpenGL showed performance advantages in 4.3 and 4.4 (2012/13)
  - AMD Mantle (2013) showing strong performance advantages
  - Similar approach be Apple with Metal (2014 (iOS) & 2015 (OS X))
  - DirectX 12 (Dec 2015) moved this idea into mainline gaming
- **Cross-platform API with Vulkan (Khronos, since 2016)**
  - Much lower level, requires expert programmer, …
  - Vulkan is the way to go for most applications and products

Meta Discussion

- **Why teach an API, like OpenGL?**
  - We are not typically doing this at a university (focus on principles)?
    - Yes, but Rasterization on GPUs is a key application topic in graphics, and we should not ignore it
    - Talking about the principles would mostly address the same topics, but only in a more abstract form
    - So, chose a concrete API to show the same principles behind it
  - But APIs change quite often?
    - Yes, but the principles behind it change only slowly, focus on those
  - Multiple APIs available, so which one should we teach?
    - OpenGL is cross-platform and most widely available
  - Why not use OpenGL's successor, Vulkan?
    - It is much lower level and not well-suited for teaching
    - Requires good understanding of low-level features, e.g. on HW-level

Introduction to OpenGL

- **What is OpenGL?**
  - Cross-platform, low-level software API for graphics HW (GPUs)
  - Controlled by Khronos (https://www.khronos.org/)
  - Only covers 2D/3D rendering (points, lines, triangles, …)
  - Related APIs: Vulkan, MS Direct3D, Apple Metal
    - Related GUI APIs: X11, MS Windows GDI, QT, GTK, Apple, ...
  - Was focused on ***immediate mode*** operation
    - As opposed to **retained mode** operation (storage of scene data)
    - Thin hardware abstraction layer – almost direct access to HW
    - Points, lines, triangles as base primitives
  - Today more efficient **batch processing** (immediate mode is gone)
    - Vertex arrays and buffer objects (controlled by app, but stored on GPU)
    - Vulkan: More of this: prevalidated buffers created by CPU threads
  - Network-transparent protocol
    - GLX-Protocol – X11extension, allowed 3D rendering on remote display
      - Only in X11 environment!, now deprecated

Related APIs and Languages

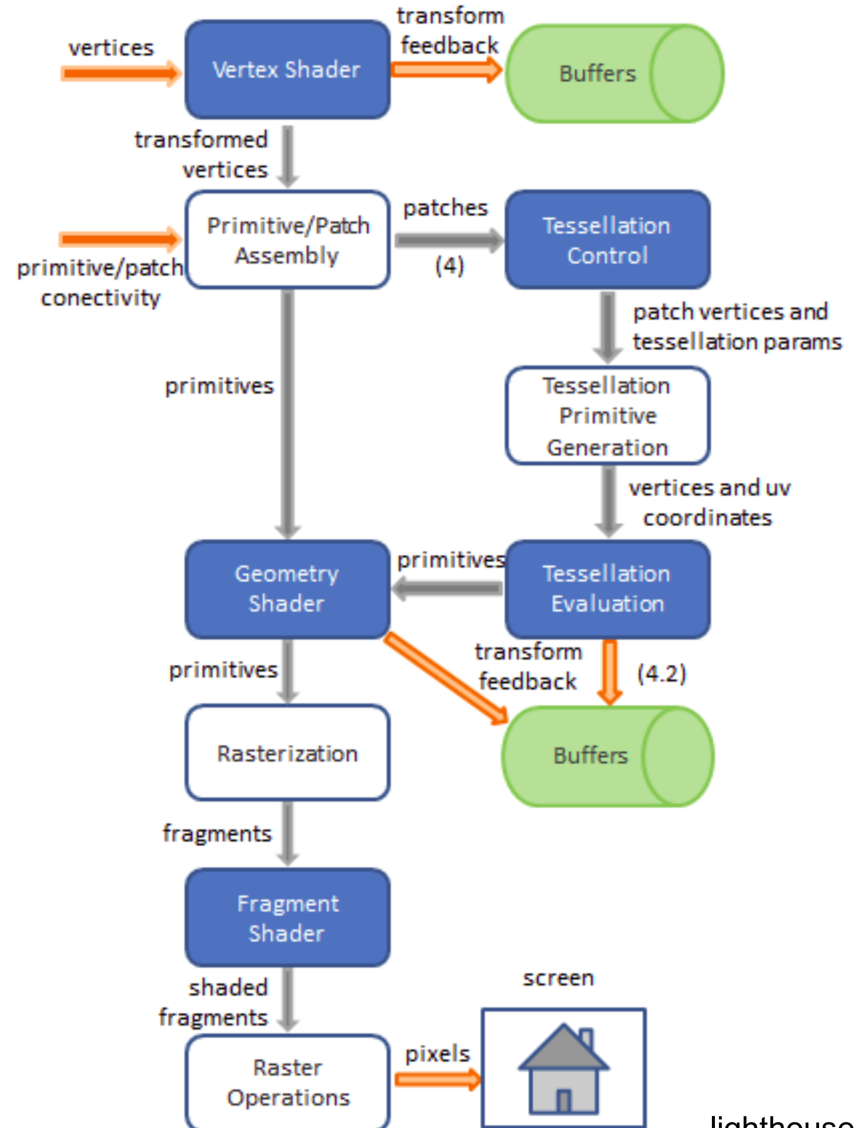
- **glsl (necessary, released in sync with OpenGL, → later)**
  - The OpenGL shading language; defines programmable aspects
- **OpenGL ES (3.2)**
  - Embedded subset (used on most mobile devices)
  - Being better aligned with OpenGL (subset)
- **EGL (GLX, WGL, AGL/CGL)**
  - Glue library to windowing systems, EGL becoming the standard now
- **OpenCL (2.2)**
  - Open Computing Language: Many-core computing
  - Cross-platform version of Nvidia's CUDA
  - SPIR-V as a generic assembler format for GPUs
- **WebGL (2.0)**
  - In the browser, based on OpenGL ES 3.0 (now also WebGPU)
- **GUI-Toolkits**
  - QT: QtGLWidget class, Gtk: GtkGLExt widget
  - GLUT (OpenGL Utility Toolkit, older but still useful)
  - SDL: Simple DirectMedia Layer (more modern than GLUT, w/ audio)

Additional Infos

- **Just a few selected items (not complete)**
- **Books**
  - Real-Time Rendering, Fourth Edition
    - By Tomas Akenine-Moller, Eric Haines, Naty Hoffman, et al.
    - Advanced Techniques
- **Tutorials**
  - Learn OpenGL: https://learnopengl.com/
  - Lighthouse3D (older): http://www.lighthouse3d.com
- **WebGL**
  - WebGL PlayGround: http://webglplayground.net/
    - Try out WebGL directly in the Web-Browser

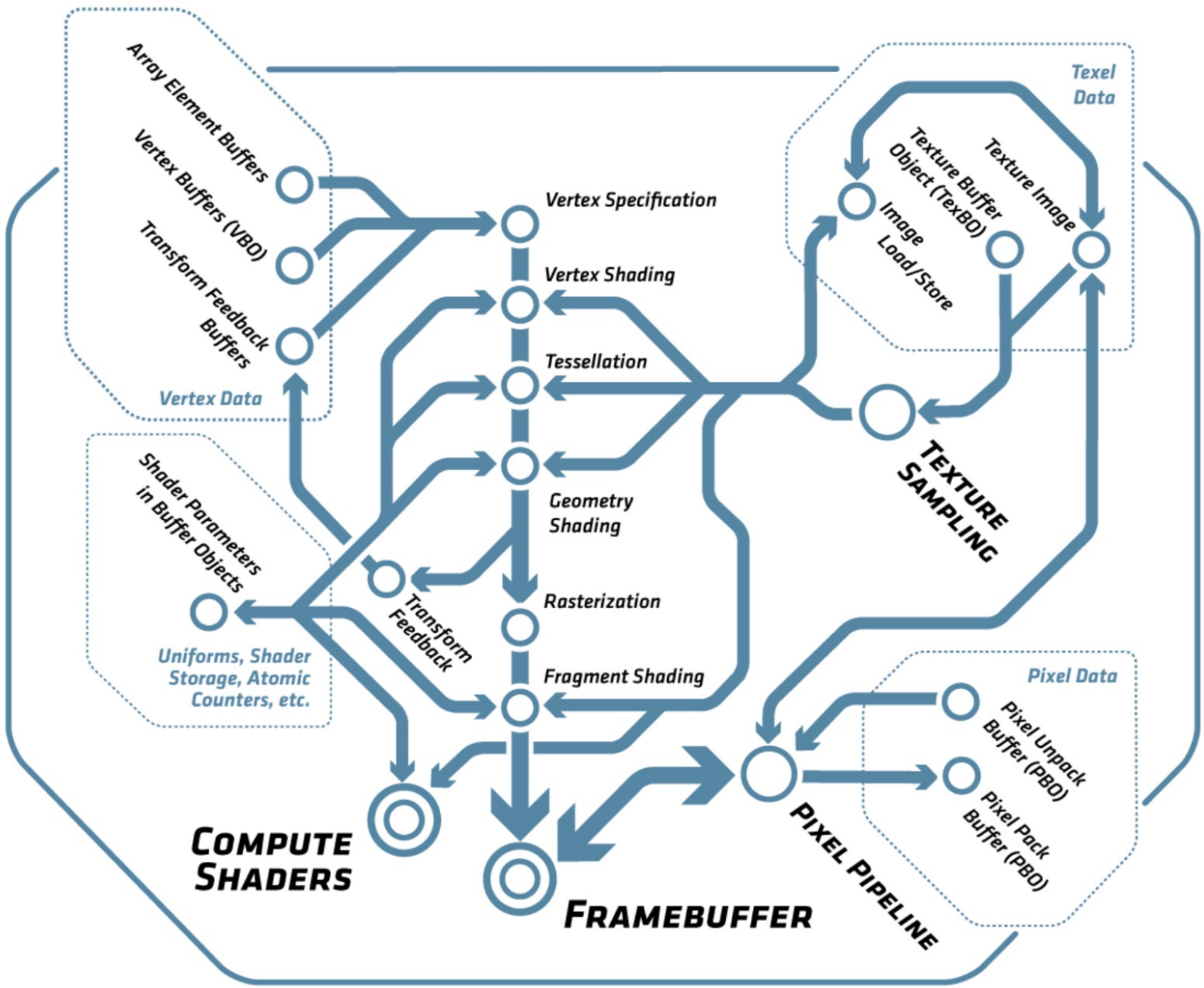
Modern OpenGL Pipeline

- **(Not looking at pixel input and output)**



lighthouse3D.com

Complete OpenGL Pipeline (4.5)



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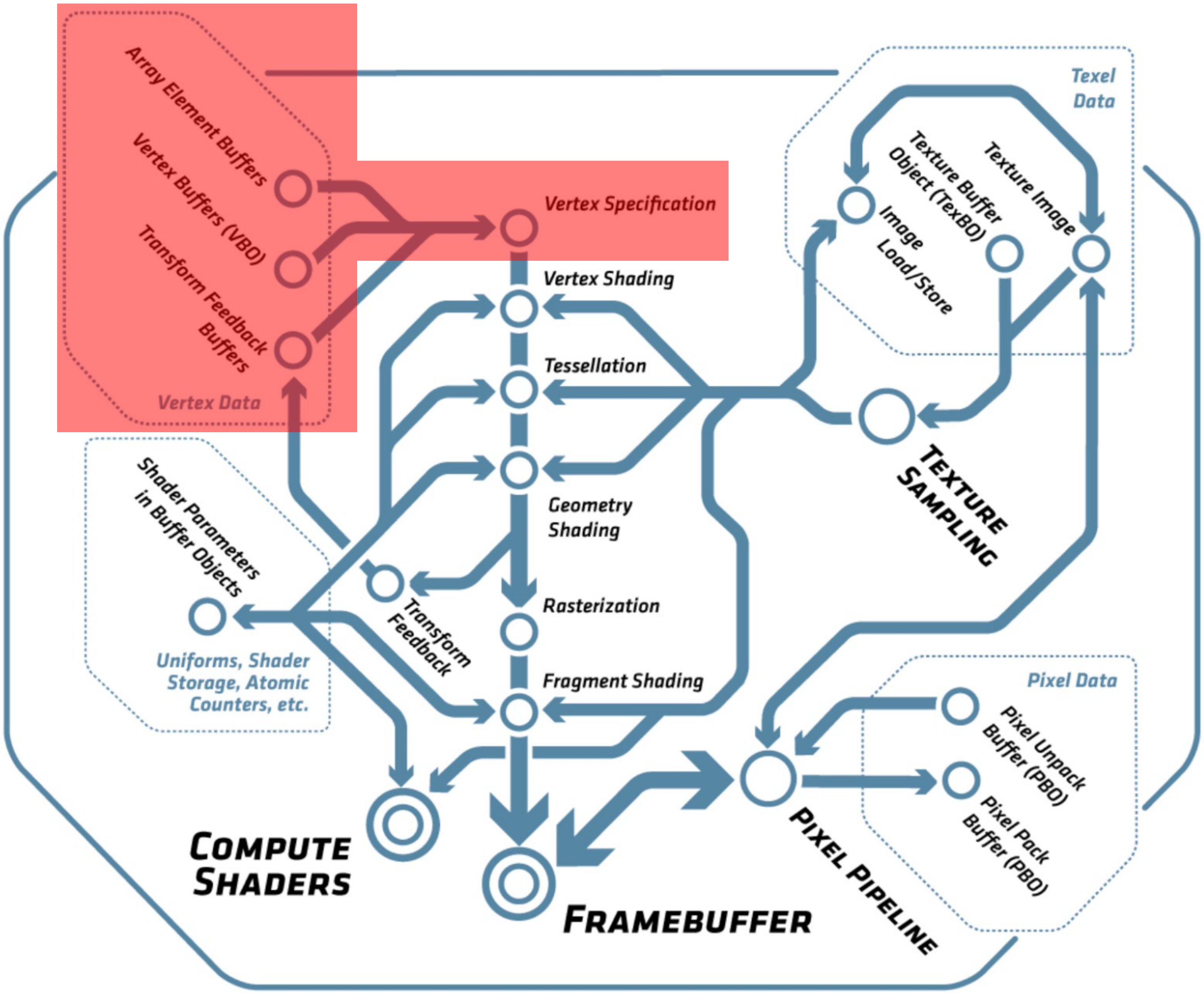


OpenGL Rendering

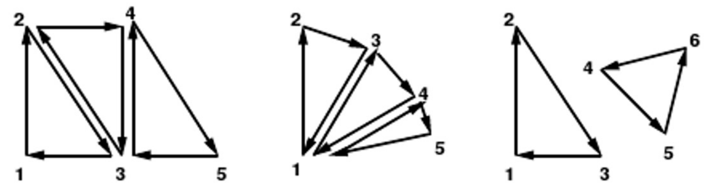
- **OpenGL draws primitives**
  - Primitive types: points, lines, and triangles
  - Drawing subject to selectable *modes* (w/ their state) and *shaders*
  - Commands: Set modes, change parameters, send primitives
    - Data (parameters) is bound when call is made (even for arrays)
  - OpenGL *contexts* encapsulate the state
    - Created, deleted, and changed by *windowing system* (!)
  - Window system also controls display of frame buffer content
    - E.g., gamma correction tables, bit depth, etc.
- **Frame buffers**
  - Default frame buffer (configured by window system, displayed)
  - Plus an arbitrary number of application created frame buffers

Specifying Primitives

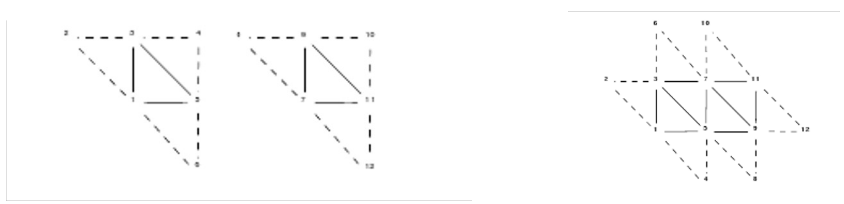
- **Geometric primitives**
  - Defined by vertices and their attributes
  - Vertices processed individually, all in the same way and in order
    - Until primitive assembly and rasterization
    - Clipping may change primitives before rasterization (add/delete)
- **Providing Data Through Vertex Arrays**
  - Each vertex consists of the *position data* plus N *attribute slots*
  - glEnable/DisableVertexAttribArray(slot)
    - Enable use of array for specific slot (geometry always in slot 0)
    - Fixed static value can be specified via glVertexAttrib(slot, …)
  - glVertexAttribPointer(slot, size, type, normalized, stride, data)
    - *Slot* defines which attribute is specified
    - *Size* specifies number of components (1D, 2D, 3D, 4D, BGRA)
    - *Type* data type in the array
      - Byte, short, int, float, half, double (+ unsigned integers)
    - *Stride* specifies the distance in bytes between two elements
    - *Data* points to the beginning of array with the data
    - (*Normalized* defines how integer data is converted to float)

Primitive Types

- **Modes for Vertex Arrays**
  - Points
  - Lines: Strips (connected), Loops (closed), Lines (separate)
  - Triangle: Strips (shared common edge), Fans (shared first vertex), Triangles (separate)



- **Advanced geometry types** **(seldomly used, obsolete with Mesh Shaders)**
  - With adjacency: Additional vertices around a primitive
    - Lines, Line Strips, Triangles, TriangleStrips



  - Patches with a fixed number of vertices per patch
    - Must be used with tesselation shaders

Specifying Primitives

- **Drawing from Vertex Array**
  - glDrawArrays(mode, first, count)
    - Sends *count* vertices starting from *first* index
  - glMultiDrawArrays(mode, first[], count[], elements)
    - Same but executes *elements* times by iterating through *first* and *count*
  - glDrawElements (mode, count, type, indices[])
    - Indexes into vertex arrays via array of *indices* of given *type* (int, short, etc.)
  - glMultiDrawElements (mode, count[], type, indices[][], elements)
    - Similar to MultiDrawArrays() but with indices
  - glDrawArraysInstanced(mode, first, count, elements)
    - Calls glDrawArrays *elements* times, incrementing a shader variable *instanceID* for each instance. Shader may have different transform each
  - glDrawElementsInstanced(mode, count, type, indices[], elements)
    - As expected …
  - Main issue reducing the number of API calls to draw a scene
  - Several other & more efficient draw calls available and being designed as extensions
  - (Complex calls may now be replaced by mesh shaders)

Buffers

- **Buffers store data on the server (GPU) side**
  - glGenBuffers(n, out bufferIds[]), glDeleteBuffers(…)
    - Allocates and deletes buffer objects
- **Types of BufferBindings**

Target name	Purpose	Described in section(s)
ARRAY_BUFFER	Vertex attributes	2.9.6
COPY_READ_BUFFER	Buffer copy source	2.9.5
COPY_WRITE_BUFFER	Buffer copy destination	2.9.5
DRAW_INDIRECT_BUFFER	Indirect command arguments	2.9.8
ELEMENT_ARRAY_BUFFER	Vertex array indices	2.9.7
PIXEL_PACK_BUFFER	Pixel read target	4.3.1, 6.1
PIXEL_UNPACK_BUFFER	Texture data source	3.7
TEXTURE_BUFFER	Texture data buffer	3.8.7
TRANSFORM_FEEDBACK_BUFFER	Transform feedback buffer	2.17
UNIFORM_BUFFER	Uniform block storage	2.11.7

Table 2.8: Buffer object binding targets.

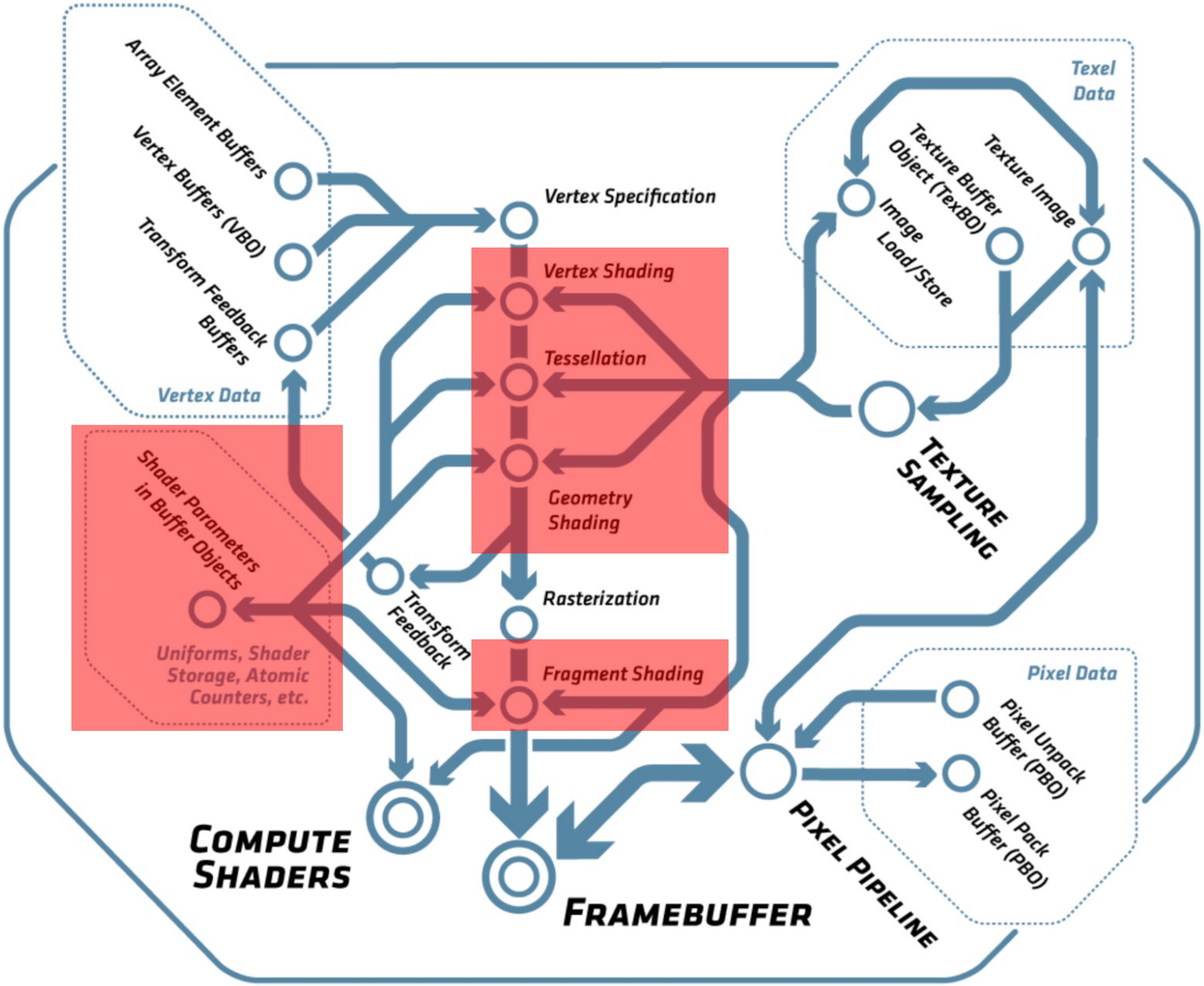
- **glBindBuffers(target, bufferId)**
  - Binds a buffer object (with or without data) to a specific target
- **glBufferData(target, size, data, usage)**
  - Assigns data to a buffer object (and allocates memory for it)
  - *Usage* provides hints how the data may be used in future
- **glMapBuffer<Range>(target, <offset, length,> access)**
  - Maps/Copies (a range of) the buffer to address space of the client
  - Must glUnmapBuffer() before use of buffer in OpenGL
    - May use copy or mapping of virtual memory

Using Buffers

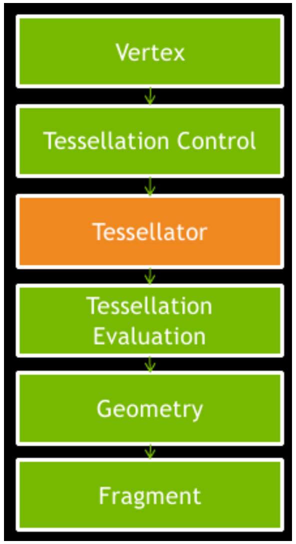
- **glVertexAttribPointer and all drawing calls use the currently bound buffer (if any)**
  - ARRAY_BUFFER for the vertex data
  - ELEMENT_ARRAY_BUFFER for the index data
  - All *data (pointers)* are interpreted as integers that provide offsets into these buffers (so are typically zero)

- **Advanced: A complete set of buffer objects for all slots can be specified with a Vertex Array Object (VAO)**
  - glGenVertexArrays(), glDeleteVertexArray()
  - BindVertexArray(array)
    - For setup:
      - Bind all necessary buffers glBindVertexArray()
      - Specify the vertex formats glVertexAttribPointer()
    - Binding a VAO later sets up all buffers in the VAO simultaneously
    - Draw calls can use all associated buffers immediately

Complete OpenGL Pipeline (4.5)



Shaders



- **Shaders compute what gets rendered**
  - Draw commands just provide input for shaders
- **Shaders Stages communicate via interfaces**
- **Vertex Shaders**
  - Are executed for each vertex passed to OpenGL
    - Receives "uniform" parameters for the shader
    - "Attributes" from each vertex (see above)
    - Writes to a set of "varyings" variables
    - Output is rasterized, interpolated, and forms "fragments"
  - The output of a vertex shader can also be recorded (in app)
- **Fragment Shader (after rasterization)**
  - Are executed for every pixel covered by a primitive
    - Receive the interpolated (e.g. across triangle) varying variables
    - Outputs color, depth, other data (to eventually go into frame buffers)
  - Writing to framebuffers is still subject to per-fragment operations

Shaders (II)

- **Geometry Shader**
  - Are executed for every *primitive* that has been assembled
    - Receive an array of vertices (including adjacent vertices, if given)
  - Output primitives of a specific type
    - Generate new primitives by writing to all attribute variables and issuing a EmitVertex() call
    - Plus potentially an EndPrimitive() to start a new primitive
- **Tesselation Control/Evaluation Shader**
  - Advanced topic
  - Can only be used with Patch primitive
  - Control: Determines the parameters of tesselation
  - Fixed function stage does the tesselation
  - Evaluation Shader: generates and outputs new primitives
- **Newest Addition: Mesh (+ task) shaders**
  - Replace initial pipeline until rasterization, use compute model
- **We discuss programming shaders later**

Shaders (III)

- **Shaders specify the programmable parts of a pipeline**
- **Different Types of shaders (vertex, fragment, geometry, etc.)**
  - Must be compiled, combined into a “program”, and linked
- **glGenShader(type)**
  - Create a shader object for a shader of the given type
- **glShaderSource(shader, ...)**
  - Stores shader source code in the object
- **glCompileShader(shader)**
  - Compiles the shader object
- **glShaderBinary(…)**
  - Loads a precompiled shader in some internal format

- **glGenProgram()**
  - Creates a new shader program
- **glAttachShader(program, shader)**
  - Attaches a shader to a program
- **glLinkProgram(program) & glValidateProgram(program)**
  - Sets up the interfaces between the shader stages
- **glUseProgram(program)**
  - Prepare a shader and use it for subsequent drawing calls

Shaders (IV, advanced)

- **New since OpenGL4.1: Program Pipeline Object**
  - Encapsulates a preconfigured pipeline of shaders
- **glGenProgramPipeline(), glDeleteProgramPipeline()**
  - Allocates and deallocates such objects
- **glBindProgramPipeline(id)**
  - Activates the pipeline for draw commands and other operation
- **glUseProgramStages(pipeline, stages, program)**
  - Binds the program to the indicated shader stages of the pipeline
  - Program must be linked as „separable“ (a la „shared library“, DLL)
  - Special rules apply to handling input/output variables of shaders
- **glGetProgramBinary(…)**
  - Obtains back a compiled and linked program as a binary object
- **glProgramBinary(…)**
  - Loads a shader binary into an allocated program object
  - Must have been created on same/„compatible“ HW/SW

Shaders (V)

- **Shaders have uniform parameters (instance variables)**
  - May be set to change shader behavior (diffuse color, matrix, …)
    - May be allocated in blocks, stored in a uniform buffer (on the GPU)
  - glGetUniformLocation(program, variable-name)
    - Returns the uniform *slot* used for a specific named shader variable
  - glUniform*(location, …)
    - Changes that parameter value
- **Per-vertex attributes can be sent to a program**
  - Applications do not necessarily know the shader in advance
  - glGetActiveAttribute(program, index, …)
    - Returns information about the attribute at given index
      - Name, type, size of the specified attribute at "index"
  - glGetAttribLocation(program, name)
    - Returns the *slot* used for a specific named shader variable
    - For sending vertex data to the shader through glVertexAttribPointer()
    - Binding of names to locations can be specified in shader code
  - glBindAttribLocation(program, index, name)
    - Alternative: Assigns the given index to the named attribute
    - Used by next linking process.

Shaders (VI): Example

- **Shader Variables**

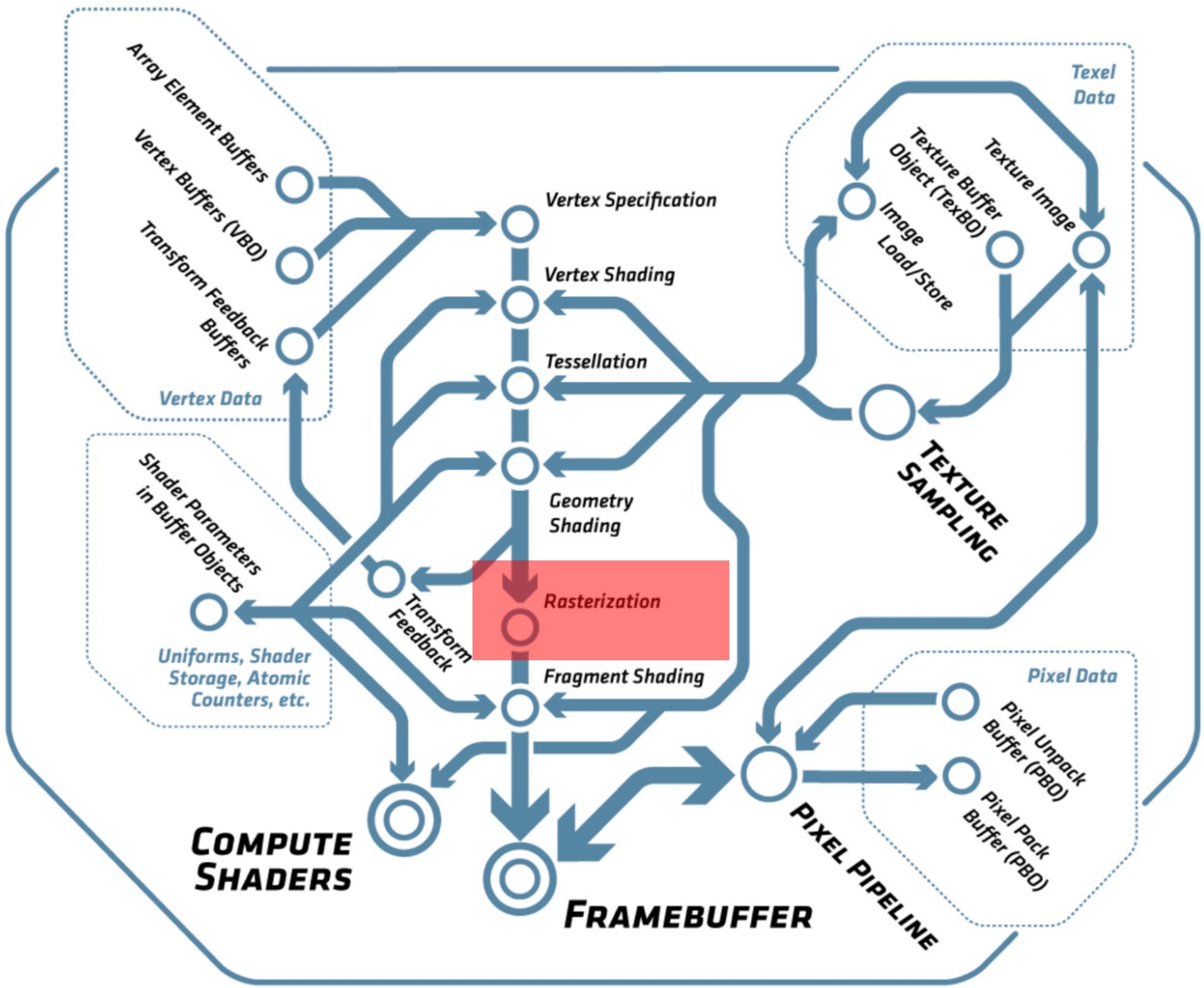
```
uniform float specIntensity;
uniform vec4 specColor;
uniform vec4 colors[3];
```

- **Access from OpenGL *application***

```
GLint loc1, loc2, loc3;
float specIntensity = 0.98;
float sc[4] = {0.8,0.8,0.8,1.0};
float colors[12] = {0.4,0.4,0.8,1.0, 0.2,0.2,0.4,1.0,
   0.1,0.1,0.1,1.0};

loc1 = glGetUniformLocation(program,"specIntensity");
  glUniform1f(loc1, specIntensity);
loc2 = glGetUniformLocation(program,"specColor");
  glUniform4fv(loc2, 1, sc);
loc3 = glGetUniformLocation(program,"colors");
  glUniform4fv(loc3, 3, colors);
```

Complete OpenGL Pipeline (4.5)



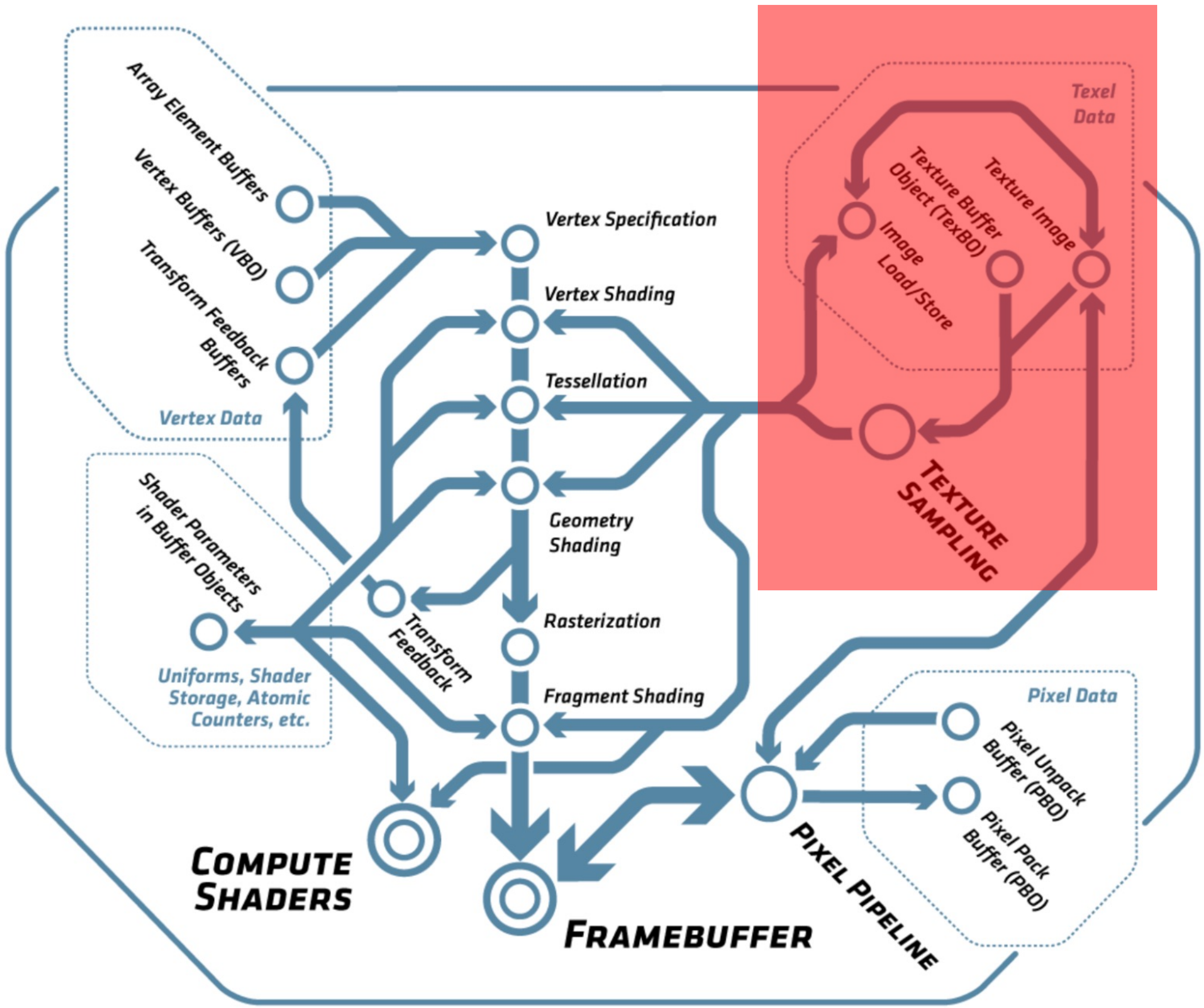
Rasterization

- **Rasterization: Generating *fragments* from *primitives***
  - For every covered pixel
    - And potentially many subpixel “samples” within a pixel
  - Computes fragment data by interpolation over triangle
    - All attributes and Z/depth
    - At center (*centroid*) or at true sample position
    - Can be perspectively correct (*smooth*) or *linear in image* space
- **Different rasterization approaches**
  - For points, lines, and triangles (see spec)
- **Backface culling of triangles**
  - Mode must first be enabled by glEnable(GL_CULL_FACE)
  - glFrontFace(dir)
    - Defines which triangles are front facing *CLW*/*CCW* (in screen space)
  - glCullFace(mode)
    - Defines which triangles are culled: *FRONT*, *BACK*, both

Rasterization (II)

- **Strict ordering**
  - Primitives are rasterized as they proceed through the pipeline
    - But pipeline may be implemented by multiple parallel HW engines
  - Results must be as if rasterized in order as send by application
    - Requires synchronization between HW pipelines
    - Complicates scalability in HW
    - Requirement can be ignored by OpenGL if order does not matter

Complete OpenGL Pipeline (4.5)



Texturing

- **Generating a new texture object**
  - glGenTexture(count, &texture)
- **Each shader can have up N "textures image units" (128)**
  - Selected with glActiveTexture(GL_TEXTURE0 + i)
- **Binding of texture objects to a unit**
  - glBindTexture(target, texture)
    - Target: one of
      - TEXTURE_1D, TEXTURE_2D, TEXTURE_3D, TEXTURE_1D_ARRAY, TEXTURE_2D_ARRAY, TEXTURE_RECTANGLE, TEXTURE_BUFFER, TEXTURE_CUBE_MAP, TEXTURE_2D_MULTISAMPLE, and TEXTURE_2D_MULTISAMPLE_ARRAY
- **Assignment to "sampler" variable in shader with**
  - `idx= GlGetUniformLocation(prog, name)`
  - `glUniform1i(idx, texture)`
- **How textures are used is solely the job of the shader**

Specifying Content for a Texture

- **Definition of Layout in Memory**
  - glPixelStore(param_name, value)
    - See table below for which parameters define the layout
- **Defining texture data**
  - glTexImage3D(target, level, internal_fmt, w, h, d, 0, format, type, data)
  - glTexImage2D(target, level, internal_fmt, w, h, 0, format, type, data)
  - glTexImage1D(target, level, internal_fmt, w, 0, format, type, data)
  - *SubImage*: (Re-)define only a part of the texture at given offset
    - level: Mipmaps, array index, or face of a cubemap
    - internal_fmt: One of many formats for storing texture internally on GPU
    - w, h, d: width, height, depth; (0 for border width, which *must* be zero)
    - format, type: see below
- **Copying texture data to a GL from buffer**
  - glCopyTex(Sub)Image{1, 2, 3}D(target, level, internal_fmt, …)
    - Copy from the frame buffer bound to GL_READ_FRAMEBUFFER
- **Advanced:**
  - Compressed and multisampled formats
  - Rendering directly from texels in a buffer: glTexBuffer()

Texture Types, Formats, Layouts

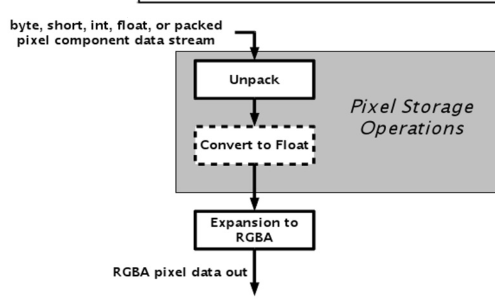
Parameter Name	Type	Initial Value	Valid Range
UNPACK_SWAP_BYTES	boolean	FALSE	TRUE/FALSE
UNPACK_LSB_FIRST	boolean	FALSE	TRUE/FALSE
UNPACK_ROW_LENGTH	integer	0	$[0, \infty)$
UNPACK_SKIP_ROWS	integer	0	$[0, \infty)$
UNPACK_SKIP_PIXELS	integer	0	$[0, \infty)$
UNPACK_ALIGNMENT	integer	4	1,2,4,8
UNPACK_IMAGE_HEIGHT	integer	0	$[0, \infty)$
UNPACK_SKIP_IMAGES	integer	0	$[0, \infty)$

Image layout in user memory (PixelStore)

Format Name	Element Meaning and Order	Target Buffer
STENCIL_INDEX	Stencil Index	Stencil
DEPTH_COMPONENT	Depth	Depth
DEPTH_STENCIL	Depth and Stencil Index	Depth and Stencil
RED	R	Color
GREEN	G	Color
BLUE	B	Color
RG	R, G	Color
RGB	R, G, B	Color
RGBA	R, G, B, A	Color
BGR	B, G, R	Color
BGRA	B, G, R, A	Color
RED_INTEGER	iR	Color
GREEN_INTEGER	iG	Color
BLUE_INTEGER	iB	Color
RG_INTEGER	iR, iG	Color
RGB_INTEGER	iR, iG, iB	Color
RGBA_INTEGER	iR, iG, iB, iA	Color
BGR_INTEGER	iB, iG, iR	Color
BGRA_INTEGER	iB, iG, iR, iA	Color

Texture data *format* in user memory (incomplete)

type Parameter Token Name	Corresponding GL Data Type	Special Interpretation
UNSIGNED_BYTE	ubyte	No
BYTE	byte	No
UNSIGNED_SHORT	ushort	No
SHORT	short	No
UNSIGNED_INT	uint	No
INT	int	No
HALF_FLOAT	half	No
FLOAT	float	No
UNSIGNED_BYTE_3_3_2	ubyte	Yes
UNSIGNED_BYTE_2_3_3_REV	ubyte	Yes
UNSIGNED_SHORT_5_6_5	ushort	Yes
UNSIGNED_SHORT_5_6_5_REV	ushort	Yes
UNSIGNED_SHORT_4_4_4_4	ushort	Yes
UNSIGNED_SHORT_4_4_4_4_REV	ushort	Yes
UNSIGNED_SHORT_5_5_5_1	ushort	Yes
UNSIGNED_SHORT_1_5_5_5_REV	ushort	Yes
UNSIGNED_INT_8_8_8_8	uint	Yes
UNSIGNED_INT_8_8_8_8_REV	uint	Yes
UNSIGNED_INT_10_10_10_2	uint	Yes
UNSIGNED_INT_2_10_10_10_REV	uint	Yes
UNSIGNED_INT_24_8	uint	Yes
UNSIGNED_INT_10F_11F_11F_REV	uint	Yes
UNSIGNED_INT_5_9_9_9_REV	uint	Yes
FLOAT_32_UNSIGNED_INT_24_8_REV	n/a	Yes



Texture data *type* in user memory (incomplete)

Texture Types, Formats, Layouts

Sized internal color formats continued from previous page						
Sized Internal Format	Base Internal Format	*R* bits	*G* bits	*B* bits	*A* bits	Shared bits
RG8_SNORM	RG	s8	s8			
RG16	RG	16	16			
RG16_SNORM	RG	s16	s16			
R3_G3_B2	RGB	3	3	2		
RGB4	RGB	4	4	4		
RGB5	RGB	5	5	5		
RGB565	RGB	5	6	5		
RGB8	RGB	8	8	8		
RGB8_SNORM	RGB	s8	s8	s8		
RGB10	RGB	10	10	10		
RGB12	RGB	12	12	12		
RGB16	RGB	16	16	16		
RGB16_SNORM	RGB	s16	s16	s16		
RGBA2	RGBA	2	2	2	2	
RGBA4	RGBA	4	4	4	4	
RGB5_A1	RGBA	5	5	5	1	
RGBA8	RGBA	8	8	8	8	
RGBA8_SNORM	RGBA	s8	s8	s8	s8	
RGB10_A2	RGBA	10	10	10	2	
RGB10_A2UI	RGBA	ui10	ui10	ui10	ui2	
RGBA12	RGBA	12	12	12	12	
RGBA16	RGBA	16	16	16	16	
RGBA16_SNORM	RGBA	s16	s16	s16	s16	
SRGB8	RGB	8	8	8		
SRGB8_ALPHA8	RGBA	8	8	8	8	
R16F	RED	f16				
RG16F	RG	f16	f16			
RGB16F	RGB	f16	f16	f16		
RGBA16F	RGBA	f16	f16	f16	f16	
R32F	RED	f32				
RG32F	RG	f32	f32			
RGB32F	RGB	f32	f32	f32		
RGBA32F	RGBA	f32	f32	f32	f32	
R11F_G11F_B10F	RGB	f11	f11	f10		
Sized internal color formats continued on next page						

- **Special cases for compressed textures**
  - Not covered here

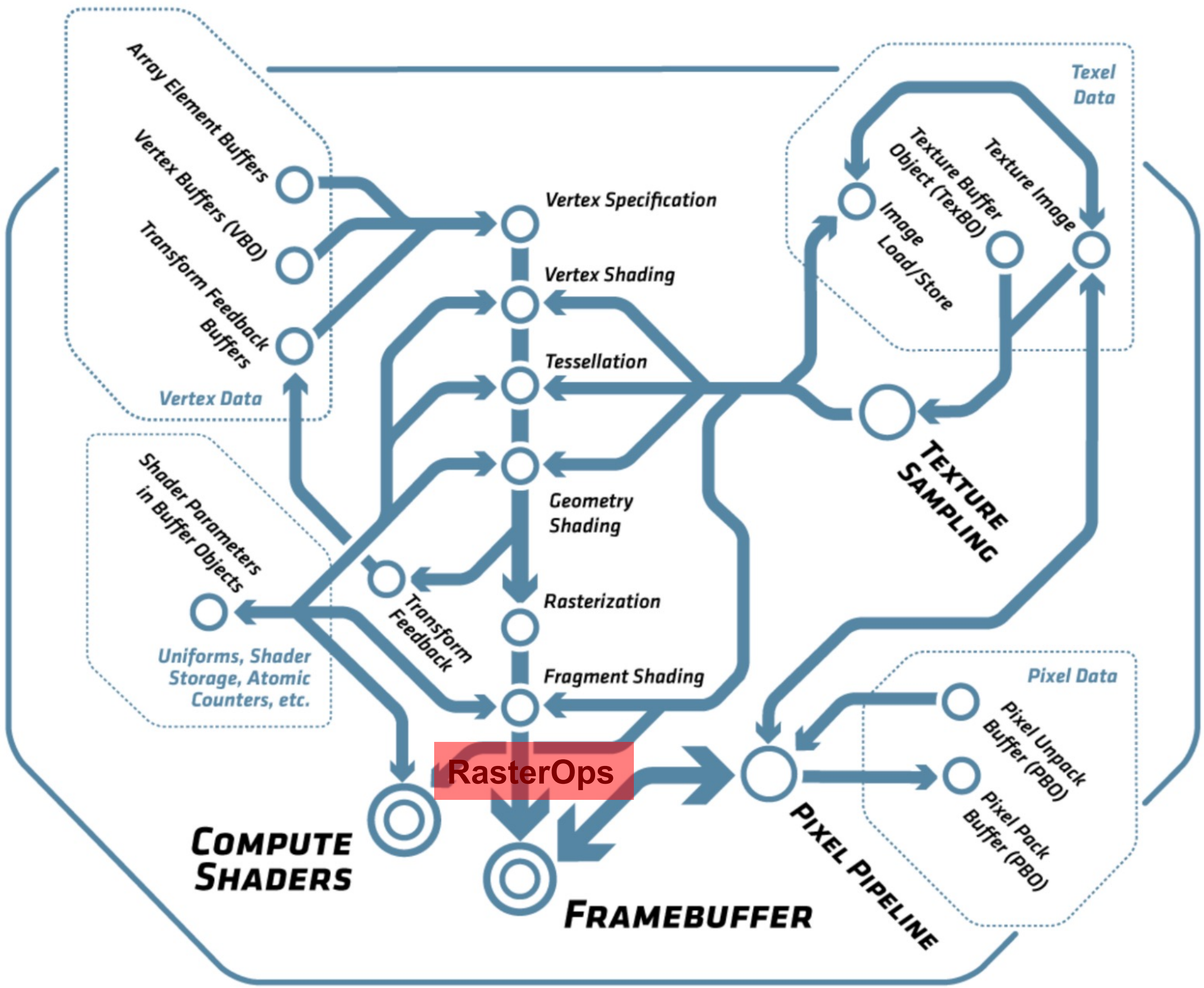
Texture Parameters & Objects

- **Changed via**
  - glTexParam*(target, param_name, value)
- **Type of parameters**
  - Wrap-mode in s, t, r: clamp (edge/border), repeat, mirror (alternately)
  - Min_Filter: NEAREST, LINEAR, NEAREST_MIPMAP_NEAREST, to LINEAR_MIPMAP_LINEAR
  - Mag_Filter: NEAREST, LINEAR
  - LOD/Mipmap parameter
  - Compare function for Z comparison (depth texture only)
- **But see Texture Sampler on next slide**

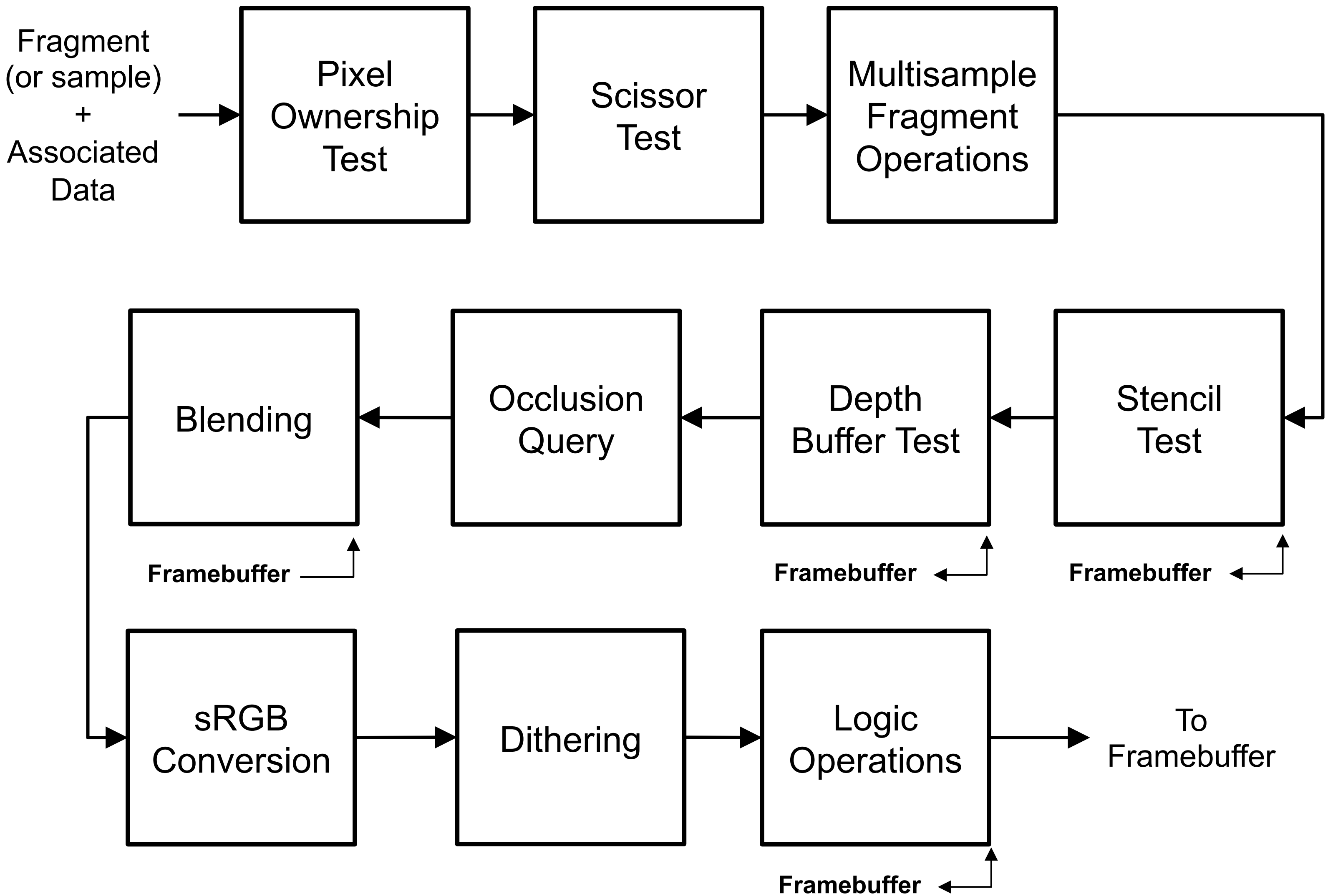
Texture Samplers

- **New in OpenGL 4.X**
  - Two aspects of a texture: The data itself & how it is to be used
  - Previously a texture object specified both
  - Better reuse if they can be separated
- **Texture Sampler**
  - Specify how the texture data (in a Texture Object) should be used
  - Single Sampler can be attached to many units – or vice versa
- **Allocate new/delete texture Sampler**
  - glGenSampler(…), glDeleteSampler()
- **Bind a Sampler to a Texture**
  - glBindSampler(unit, sampler)
  - Its parameters supersedes those of the texture object
- **Specify Sampler parameters**
  - glSamplerParameter(…)
  - Defines: Wrap mode, Filter, LOD, depth comparison

Complete OpenGL Pipeline (4.5)



Per-Fragment Operations



Per-Fragment Operations

- **Consists of multiple steps**
- **Pixel ownership test (internal)**
  - Does the pixel belong to this window (might be covered by others)
- **Scissor test**
  - Is the pixel within a box defined by glScissor(l, b, r, t)
- **Multi-sample Fragment Operations**
  - Merge the information of sub-samples in a pixel into a final value
  - Includes an “alpha test” (binary transparency)
    - Ignores (sub-)fragments with an alpha value below some threshold
- **Stencil Operation (see below)**
- **Depth Buffer Test**
  - Tests if the fragment z value passes the depth stored at the pixel
- **Occlusion Query (see below)**
- **Blend operations (see below)**
  - Merge fragments with content of the frame buffer

Stencil and Depth Test

- **Function**
  - Compares value stored in stencil and depth buffer for each fragment/pixel
  - If test fails, fragment is discarded
  - Finally, applies stencil operation based on three possible tests
    - *sfail*: Stencil tests failed
    - *dfail*: Stencil test passed, but depth test failed
    - *dpass*: Stencil and depth test passed
  - E.g., used for ShadowVolume algorithms (e.g., counting f/b-facing fragments)
- **Specification**
  - glStencilFunc(enum func, int ref, uint mask)
    - *func*: ALWAYS, NEVER, LESS, LEQUAL, GEQUAL, GREATER, NOTEQUAL
    - *ref*: reference value
    - *mask*: ANDed with both stencil and reference value before comparison
  - glStencilOp(sfail, dfail, dpass)
    - Operations: KEEP, ZERO, REPLACE, INC, DEC, INVERT, INCR_WRAP, DEC_WRAP
- **Depth Test**
  - Comparison to the per-pixel value stored in depth buffer
  - glDepthFunc(func)
    - Compares fragment z with the content of depth buffer (func: same as stencil)
    - If test passes, overwrites old depth value with fragment depth

Fragment Tests

- **Fragment tests (like stencil and Z)**
  - Require per pixel read operations (high bandwidth)
  - May require per pixel write operations
    - Read-Modify-Write operations – can be expensive (but cached in tiles)
    - Again: synchronization issues with multiple, parallel pipelines
  - Tests occur late in the pipeline
  - Might have spend significant processing on the data already
    - Should perform tests earlier without violating OpenGL semantics
    - Often can be conservatively pulled forward
  - Early Z test, right after rasterization
    - E.g., some form of hierarchical Z-buffer (often called "Early-Z-test")
    - Can cull fragments if known to be occluded (some addition cost)
    - Best if rendering is front-to-back (and Z is not modified in shader!)
- **Occlusion *culling* (e.g., ViewFrustum Culling)**
  - Must be done at application level (not in HW on GPU)
    - Replicated visibility computation in the application (mostly coarse)
    - Avoids bandwidth to graphics engine completely, but uses CPU
    - *Can now be implemented on GPU with new mesh shaders!*

Occlusion *Queries*

- **Counting the number of passed depth tests**
  - Generate Counters: glGenQueries(int n, int* ids)
  - Wrap drawing calls in glBeginQuery(id)/glEndQuery(id)
    - E.g., for drawing of bounding box of a complex part of the scene
  - Can later query the value with glGetQueryiv()
- **Use for conditional rendering**
  - Wrap drawing calls that should be omitted if OQ fails in:
    - glBeginConditionalRender(), glEndConditionalRender()
      - E.g., drawing of complex part of the scene
    - Will be skipped if OQ failed (no fragments passed the depth test)
    - Can specify what happens if OQ not ready yet (wait, draw)
    - OQ must happen early enough that results are avail. in time
  - Can be used to do (limited) frustum culling on the GPU

Blending

- **Merging fragment and frame buffer pixel**
  - Weighted combination of *source* (S, fragment) and *destination* (D, frame buffer pixel)
  - E.g., used for semi transparent rendering (ordered in depth!)
- **Specifying the blend equation, function, and constant**
  - glBlendEquation{,Separate}(mode {,alpha_mode})
  - glBlendFunc{,Separate}(src, dst {,alpha_src, alpha_dst})
  - glBlendColor(red, green ,blue, alpha) specifies constant *C*
  - *Separate* allows to set blending separately for color/alpha

Mode	RGB Components	Alpha Component
FUNC_ADD	$R = R_s * S_r + R_d * D_r$ $G = G_s * S_g + G_d * D_g$ $B = B_s * S_b + B_d * D_b$	$A = A_s * S_a + A_d * D_a$
FUNC_SUBTRACT	$R = R_s * S_r - R_d * D_r$ $G = G_s * S_g - G_d * D_g$ $B = B_s * S_b - B_d * D_b$	$A = A_s * S_a - A_d * D_a$
FUNC_REVERSE_SUBTRACT	$R = R_d * D_r - R_s * S_r$ $G = G_d * D_g - G_s * S_g$ $B = B_d * D_b - B_s * S_b$	$A = A_d * D_a - A_s * S_a$
MIN	$R = \min(R_s, R_d)$ $G = \min(G_s, G_d)$ $B = \min(B_s, B_d)$	$A = \min(A_s, A_d)$
MAX	$R = \max(R_s, R_d)$ $G = \max(G_s, G_d)$ $B = \max(B_s, B_d)$	$A = \max(A_s, A_d)$

S_i and D_i are the weights from blend functions →

Function	RGB Blend Factors (S_r, S_g, S_b) or (D_r, D_g, D_b)	Alpha Blend Factor S_a or D_a
ZERO	$(0, 0, 0)$	0
ONE	$(1, 1, 1)$	1
SRC_COLOR	(R_s, G_s, B_s)	A_s
ONE_MINUS_SRC_COLOR	$(1, 1, 1) - (R_s, G_s, B_s)$	$1 - A_s$
DST_COLOR	(R_d, G_d, B_d)	A_d
ONE_MINUS_DST_COLOR	$(1, 1, 1) - (R_d, G_d, B_d)$	$1 - A_d$
SRC_ALPHA	(A_s, A_s, A_s)	A_s
ONE_MINUS_SRC_ALPHA	$(1, 1, 1) - (A_s, A_s, A_s)$	$1 - A_s$
DST_ALPHA	(A_d, A_d, A_d)	A_d
ONE_MINUS_DST_ALPHA	$(1, 1, 1) - (A_d, A_d, A_d)$	$1 - A_d$
CONSTANT_COLOR	(R_c, G_c, B_c)	A_c
ONE_MINUS_CONSTANT_COLOR	$(1, 1, 1) - (R_c, G_c, B_c)$	$1 - A_c$
CONSTANT_ALPHA	(A_c, A_c, A_c)	A_c
ONE_MINUS_CONSTANT_ALPHA	$(1, 1, 1) - (A_c, A_c, A_c)$	$1 - A_c$
SRC_ALPHA_SATURATE[1]	$(f, f, f)^2$	1

sRGB, Dithering, Logic Ops

- **sRGB conversion**
  - Performed if the frame buffer is specified to be in sRGB
    - Non-linear mapping with overall gamma ~ 1/2.2 (with linear base)
    - Inverse conversion used for input from textures in sRGB format
- **Dithering**
  - Round each color component
    - Round to either the larger or smaller representable value
    - Decision threshold based on pixel position (rounding bias)
  - Trades color resolution versus spatial resolution
    - Eye averages over neighboring pixels anyway
  - Enable Mode: glEnable/Disable(GL_DITHER)
- **Logic Ops**
  - Combine fragment (s) and frame buffer pixel (d) with logic operation
    - glLogicOp(op)

Argument value	Operation
CLEAR	0
AND	$s \wedge d$
AND_REVERSE	$s \wedge \neg d$
COPY	s
AND_INVERTED	$\neg s \wedge d$
NOOP	d
XOR	s xor d
OR	$s \vee d$
NOR	$\neg(s \vee d)$
EQUIV	$\neg(s$ xor $d)$
INVERT	$\neg d$
OR_REVERSE	$s \vee \neg d$
COPY_INVERTED	$\neg s$
OR_INVERTED	$\neg s \vee d$
NAND	$\neg(s \wedge d)$
SET	all 1's

OpenGL and Frame Buffers

- **OpenGL system frame buffers**
  - Provide memory for storing data for every pixel
    - Color and optionally: depth (Z), stencil, window-id, and others
  - Format must be fixed before windows are opened
    - Window-System specific, e.g.: glXGetFBConfigs(), eglGetConfigs()
- **Color buffers**
  - RGBA (RGB+Alpha)
    - Alpha stores transparency/coverage information
    - Today often 8/8/8(/8) bits (10 or even 12 bit becoming more popular)
    - Recent GPUs also support 16 bit fix and 16/24/32 bit float components
  - Double buffering option (back- and front buffer)
    - Animations: draw into back, display front buffer
    - No flashing or tearing artifacts when swapped in between frames
    - Swap buffers during *vertical retrace* (glXSwapBuffers()) or asap.
    - New monitors support “Adaptive Sync” to send FB when ready (w/ limits)
      - No longer limited to fixed frame rate; extensions even allow controlled timing
  - Stereo option (possibly quad buffered)
    - Left and right buffers (also with DB), e.g., for two projectors
    - Requires support from GUI

OpenGL and Frame Buffers

- **Depth/Z buffer**
  - Stores depth/Z coordinate of visible geometry per pixel
  - Used for occlusion test (Z-test)
- **Stencil buffer**
  - Small integer variable per pixel
  - Used for masking fragment operations
  - Write operations based on fragment tests
    - Set/increment/decrement variable
- **Application-defined frame buffers**
  - Application can define any number of additional pixel buffer objects
  - And bind them to frame buffer objects

Draw Buffers

- **Specifying which buffer to render to**
  - glDrawBuffer(enum buffer)
  - glDrawBuffers(int size, enum* buffers)
    - All drawing operation will be directed to the indicated buffers
- **Enabling specific color planes**
  - glColorMask(bool r, g, b, a)
  - glColorMask(uint r, g, b, a)
  - glDepthMask(bool mask)
  - glStencilMask{,Separate}(mask)
- **Clearing the Buffer**
  - glClear(mask)
    - With combination of COLOR_BUFFER_BIT, DEPTH_BUFFER_BIT, and STENCIL_BUFFER_BIT
  - glClearColor(r, g, b, a), glClearDepth(depth), glClearStencil(int s)
    - Specifies the color to set the buffer when performing a clear
  - Must be extremely efficient as it would have to touch all pixel but does nothing useful (special HW in the memory path for this)

Symbolic Constant	Front Left	Front Right	Back Left	Back Right
NONE				
FRONT_LEFT	•			
FRONT_RIGHT		•		
BACK_LEFT			•	
BACK_RIGHT				•
FRONT	•	•		
BACK			•	•
LEFT	•		•	
RIGHT		•		•
FRONT_AND_BACK	•	•	•	•

For default framebuffers

Symbolic Constant	Meaning
NONE	No buffer
COLOR_ATTACHMENT*i* (see caption)	Output fragment color to image attached at color attachment point *i*

For app defined frame buffers

Frame Buffer & Render Buffer

- **Definition**
  - Render buffer: Memory for color, stencil, or depth buffer
  - Frame buffer: A combination of the above
- **Generate/delete own RenderBuffer object**
  - glGenRenderBuffer (int n, int* ids), glDeleteRenderBuffers(n, ids)
- **Binding**
  - glBindRenderBuffer(GL_RENDERBUFFER, id)
- **Allocate memory for a Renderbuffer**
  - glRenderBufferStorage(GL_RENDERBUFFER, format, w,h)

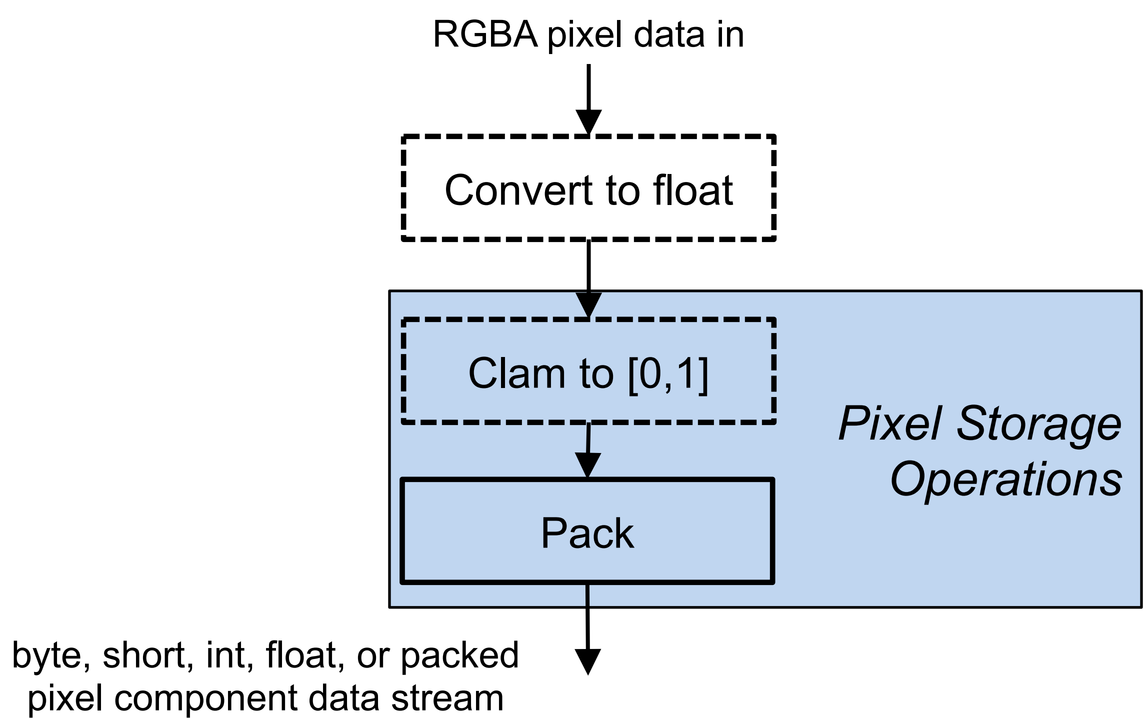
- **Generate/delete a new Framebuffer object**
  - glGenFramebuffers(int n, int* ids) glDeleteFramebuffers(n , ids)
- **Bind a Framebuffer object for rendering**
  - glBindFramebuffer(fb_target, fb_id)
    - fb_target == GL_DRAW_FRAMEBUFFER/GL_READ_FRAMEBUFFER
      - Framebuffer will be used for drawing into or reading from it
    - Default frame buffer has id == 0

Framebuffer Attachement

- **Attaching a render buffer to a frame buffer**
  - glFramebufferRenderbuffer(fb_target, attach, rb_target, rb_id)
    - attach: GL_{COLOR, DEPTH, STENCIL, DEPTH_STENCIL}_ATTACHMENT
    - fb_target: GL_{DRAW, READ}_FRAMEBUFFER
    - rb_target: GL_RENDERBUFFER
- **Attaching a texture to a frame buffer**
  - glFramebufferTexture(fb_target, attach, texture_id, level)
    - Level: Mipmaplevel, side of a cube, z-layer in 3D texture
  - Undefined behavior results if
    - A texture is bound for an active frame buffer and to a texture unit
    - A texture is bound for reading and writing in a copy operation

Reading Pixels Back

- **Reading from the framebuffer**
  - glReadPixels(x, y, w, h, format, type, data)
  - Reads from the framebuffer bound to GL_READ_FRAMEBUFFER



Special Functions

- **glFlush()**
  - Makes sure that all previous commands get send to the GPU
- **glFinish()**
  - Waits until all previous commands have executed
- **sync= glFenceSync(cond, 0)**
  - Send a sync command in the pipeline
    - cond = SYNC_GPU_COMMANDS_COMPLETE
  - Creates sync object that can later be waited upon with
- **glClientWaitSync(sync, flags, timeout)**
- **glWaitSync(sync, flags, timeout)**
  - Waits in the client or the server (GPU)
  - Wait in the server is more efficient as commands can already be sent
- **glHint(target, hint)**
  - Allows to tell OpenGL what quality we would like to see
- **glGet*(...)**
  - Querying the state of OpenGL

OpenGL Guaranties

- **Non-Guaranties**
  - Many rules as how things must be rendered, but …
  - No exact rule for implementation of graphics operations
    - Such as number of bits, coverage by a primitive, etc.
  - Different implementations can differ on a per-pixel basis
    - Within clearly specified limits/rules
- **Guaranty of Invariants**
  - Invariants within an implementation
    - Same output when given the same input
    - Fragment values are independent of
  - Content of frame buffer
  - Active color buffer, ...
    - Independence of parameter values (e.g., for stencil / blending)
  - No invariance when switching options on and off (glDis/Enable())
    - E.g., depth test, stencil, texturing, ...
    - On-screen versus off-screen buffers