Real-Time Rendering (Echtzeitgraphik)

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Walking down the graphics pipeline

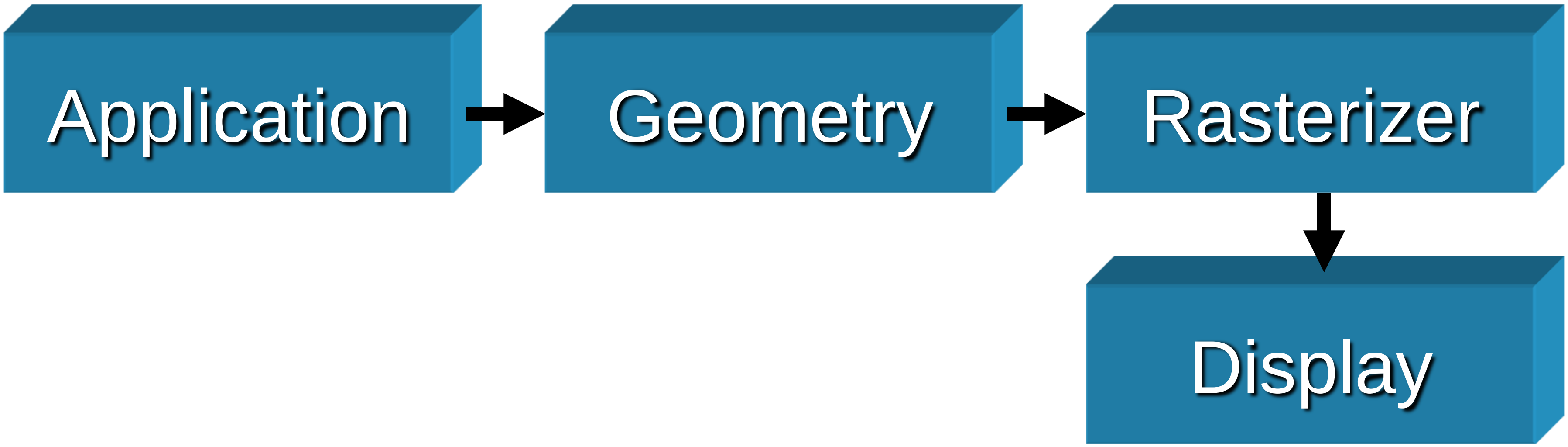
What for?

Understanding the rendering pipeline is the key to real-time rendering!

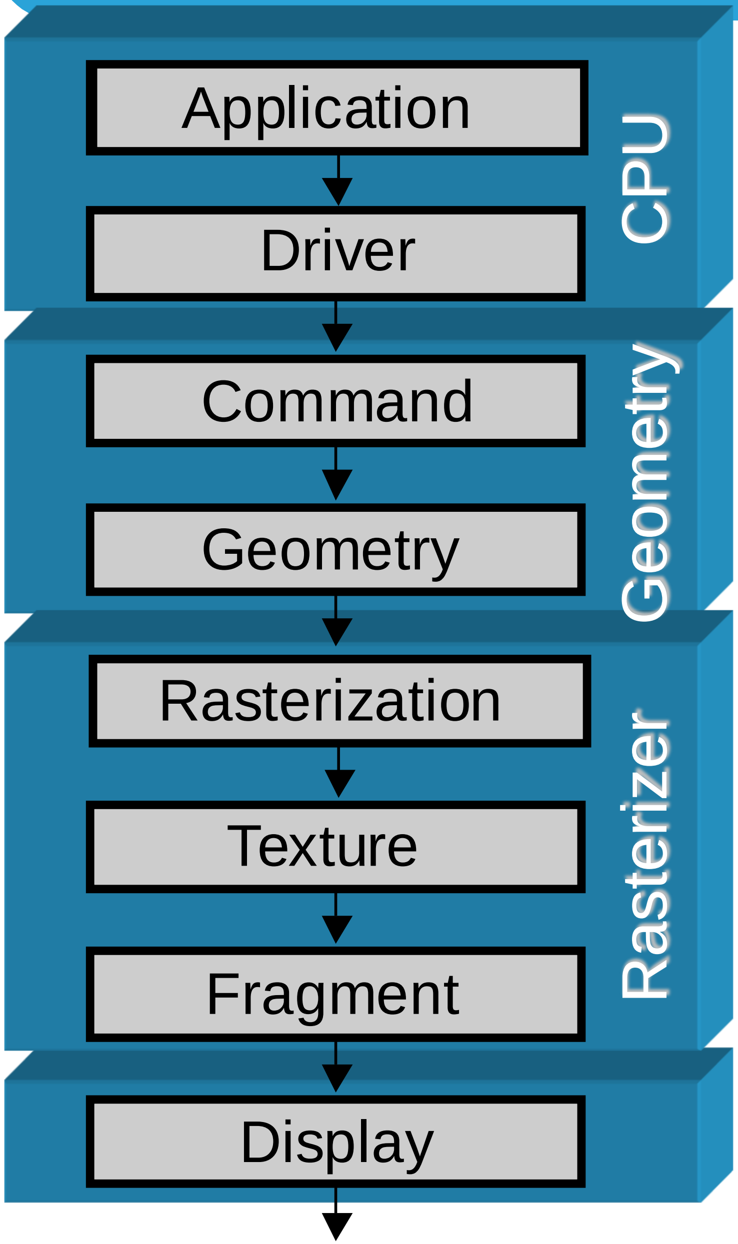
- Insights into how things work
  - Understanding algorithms
- Insights into how fast things work
  - Performance

Simple Graphics Pipeline

- Often found in text books
- Will take a more detailed look into OpenGL



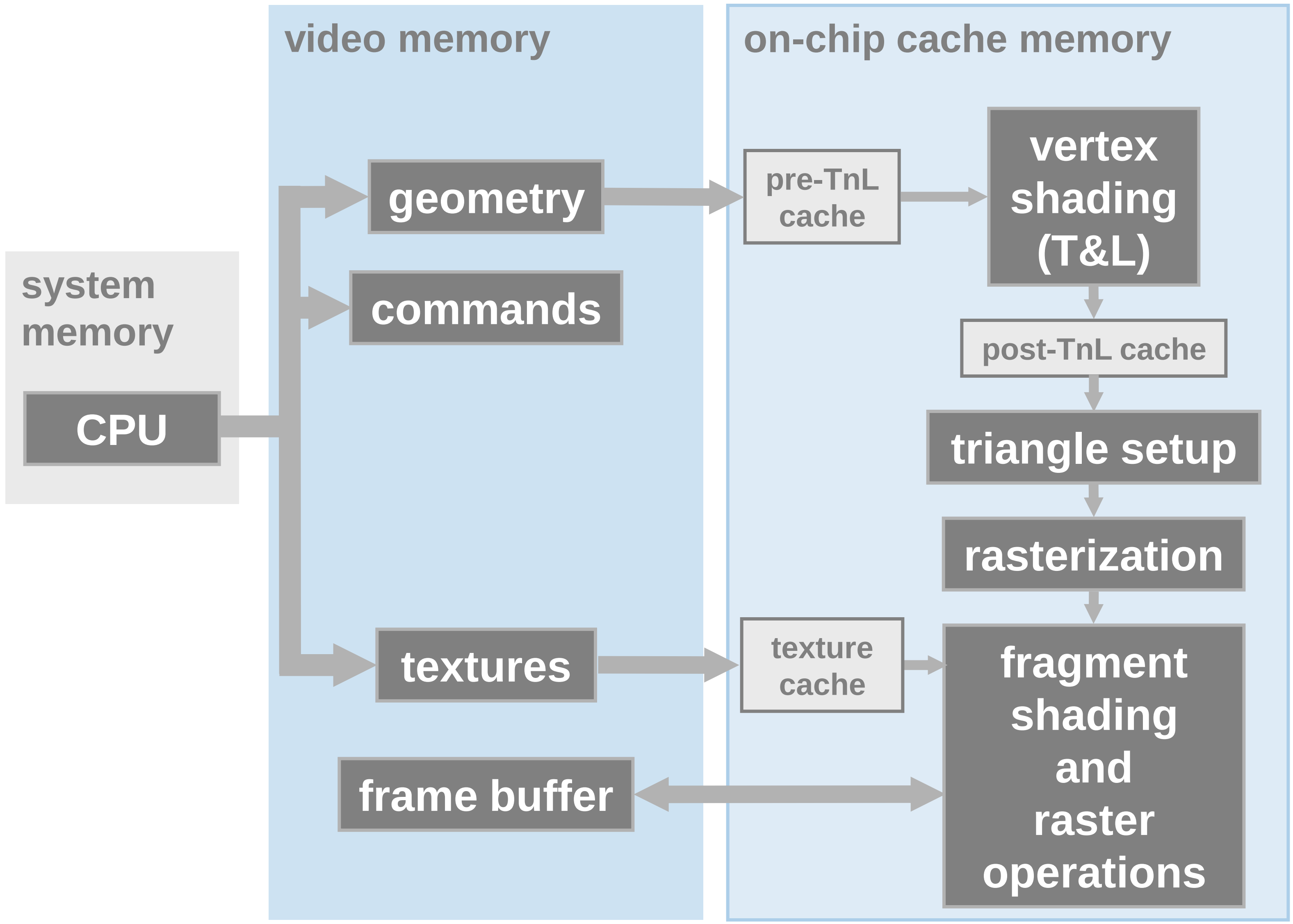
Graphics Pipeline (pre DX10, OpenGL 2)



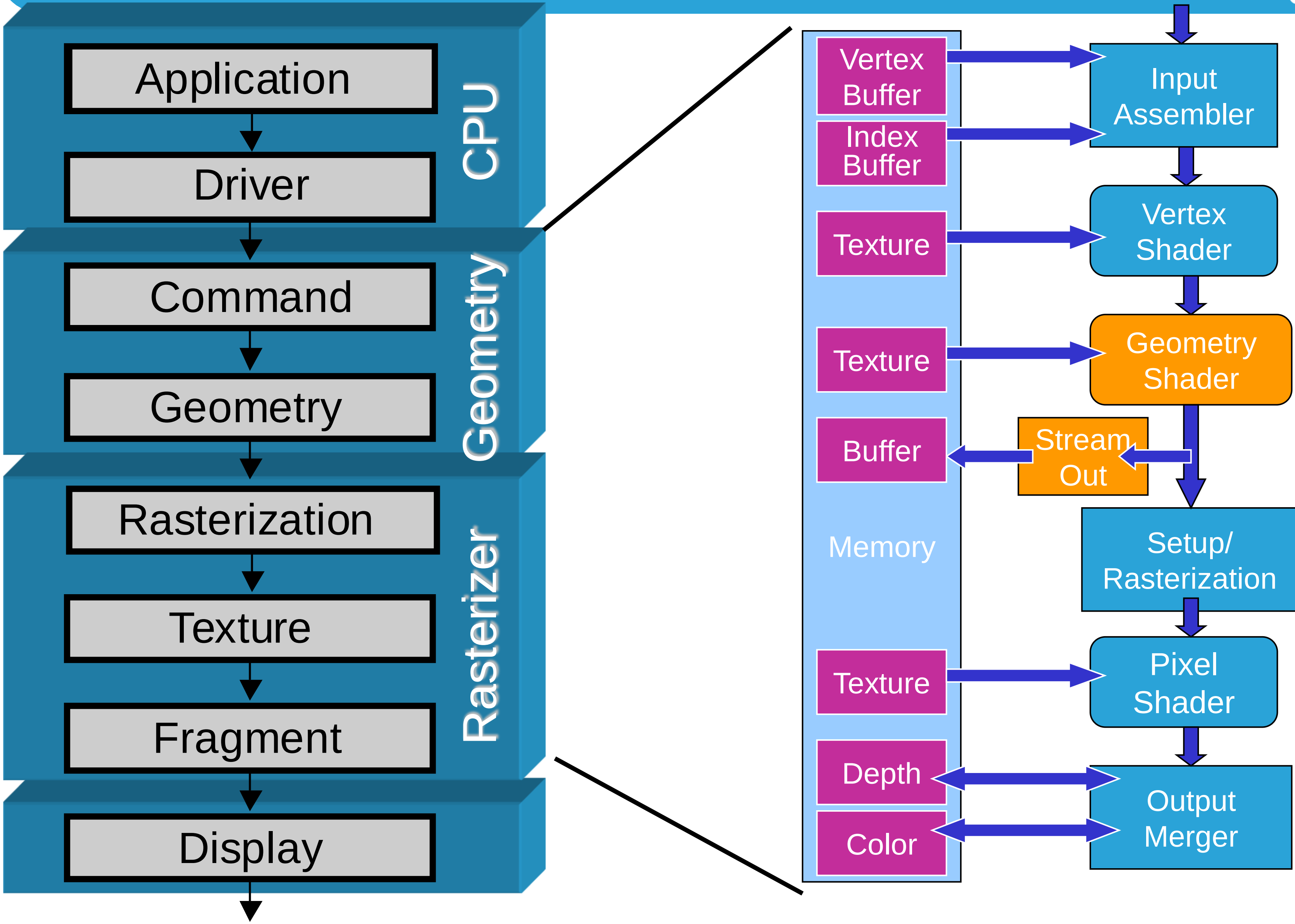
- Nowadays, everything part of the pipeline is hardware accelerated

- Fragment: “pixel”, but with additional info (alpha, depth, stencil, …)

Fixed Function Pipeline – Dataflow View



DirectX10 /OpenGL 3.2 Evolution



OpenGL 3.0

- OpenGL 2.x is not as capable as DirectX 10
  - **But**: New features are vendor specific extensions (geometry shaders, streams…)
  - GLSL a little more restrictive than HLSL (SM 3.0)
- OpenGL 3.0 did not clean up this mess!
  - OpenGL 2.1 + extensions
  - Geometry shaders are only an extension
  - New: depreciation mechanism
- OpenGL 4.x
  - New extensions
  - OpenGL ES compatibility!

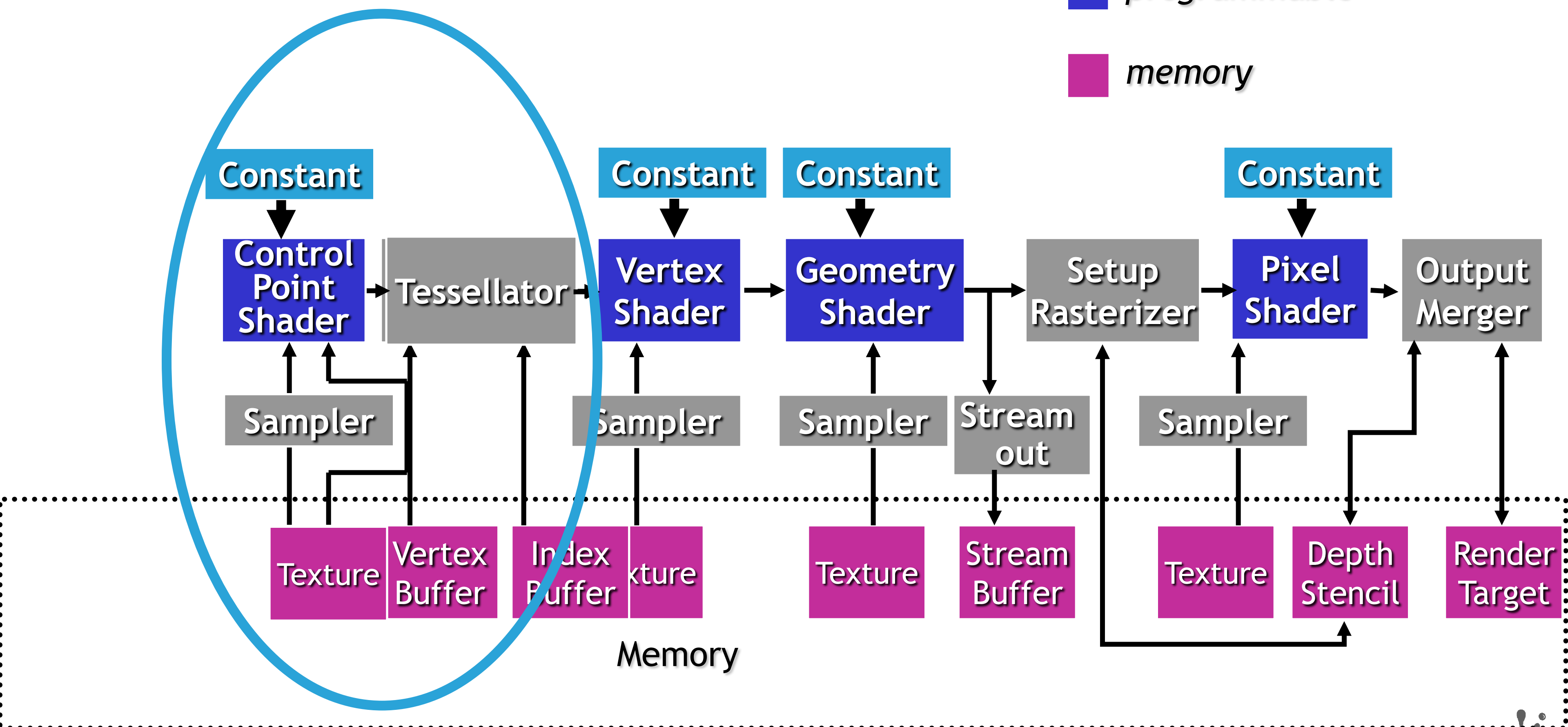
DirectX 11/OpenGL 4.0 Evolution

Not the final place in the pipeline!!!

fixed

programmable

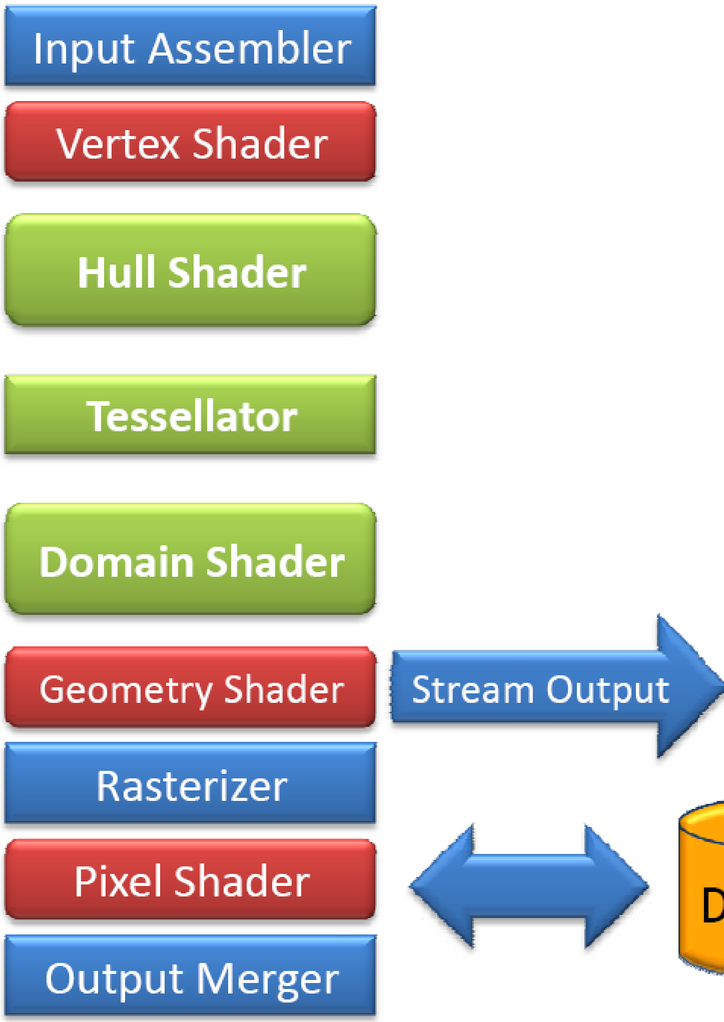
memory



DirectX 11

- Tesselation
  - At unexpected position!
- Compute Shaders
- Multithreading
  - To reduce state change overhead
- Dynamic shader linking
- HDR texture compression
- Many other features...

DirectX 11 Pipeline



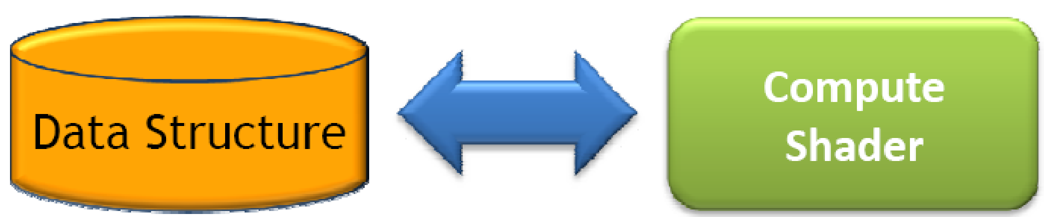
Direct3D 10 pipeline

Plus

Three new stages for Tessellation

Plus

Compute Shader



DirectX 12/Vulkan/AMD Mantle/Apple Metal

- Reduce driver overhad
  - Indirect drawing
  - Pipeline state objects
  - Command lists/bundles
  - Partly possible already in OpenGL 4.3+
- Other features
  - Conservative rasterization (for culling)
  - New blend modes
  - Order-independent transparency

Application

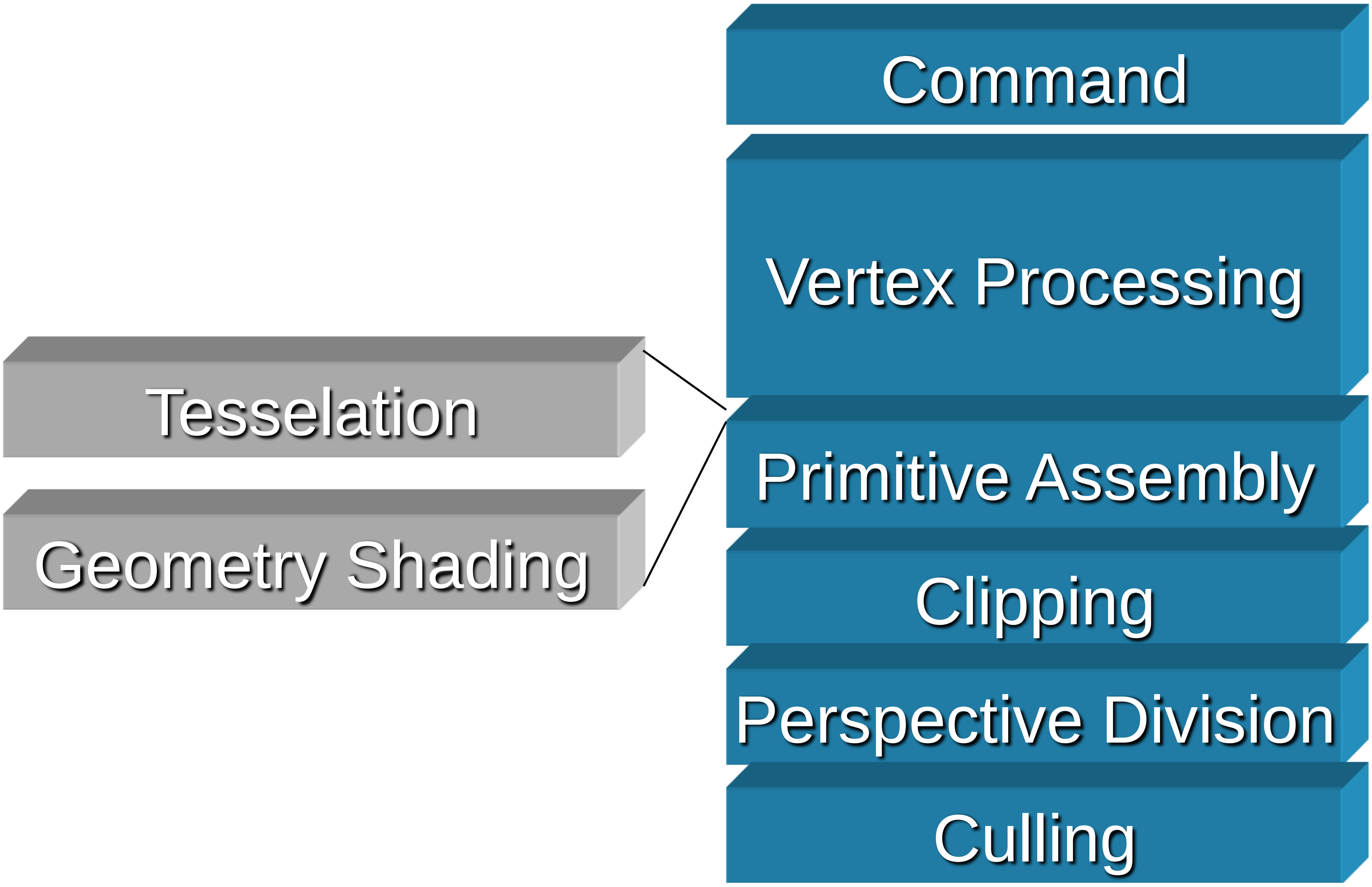
- Generate database (Scene description)
  - Usually only once
  - Load from disk
  - Build acceleration structures (hierarchy, …)
- Simulation (Animation, AI, Physics)
- Input event handlers
- Modify data structures
- Database traversal
- Shaders (vertex,geometry,fragment)

Driver

- Maintain graphics API state
- Command interpretation/translation
  - Host commands → GPU commands
- Handle data transfer
- Memory management
- Emulation of missing hardware features

- Usually huge overhead!
  - Significantly reduced in DX10

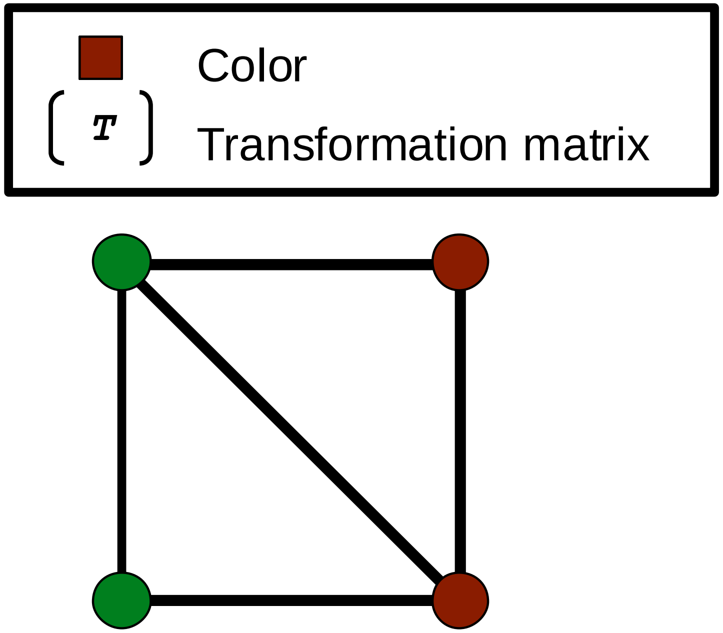
Geometry Stage



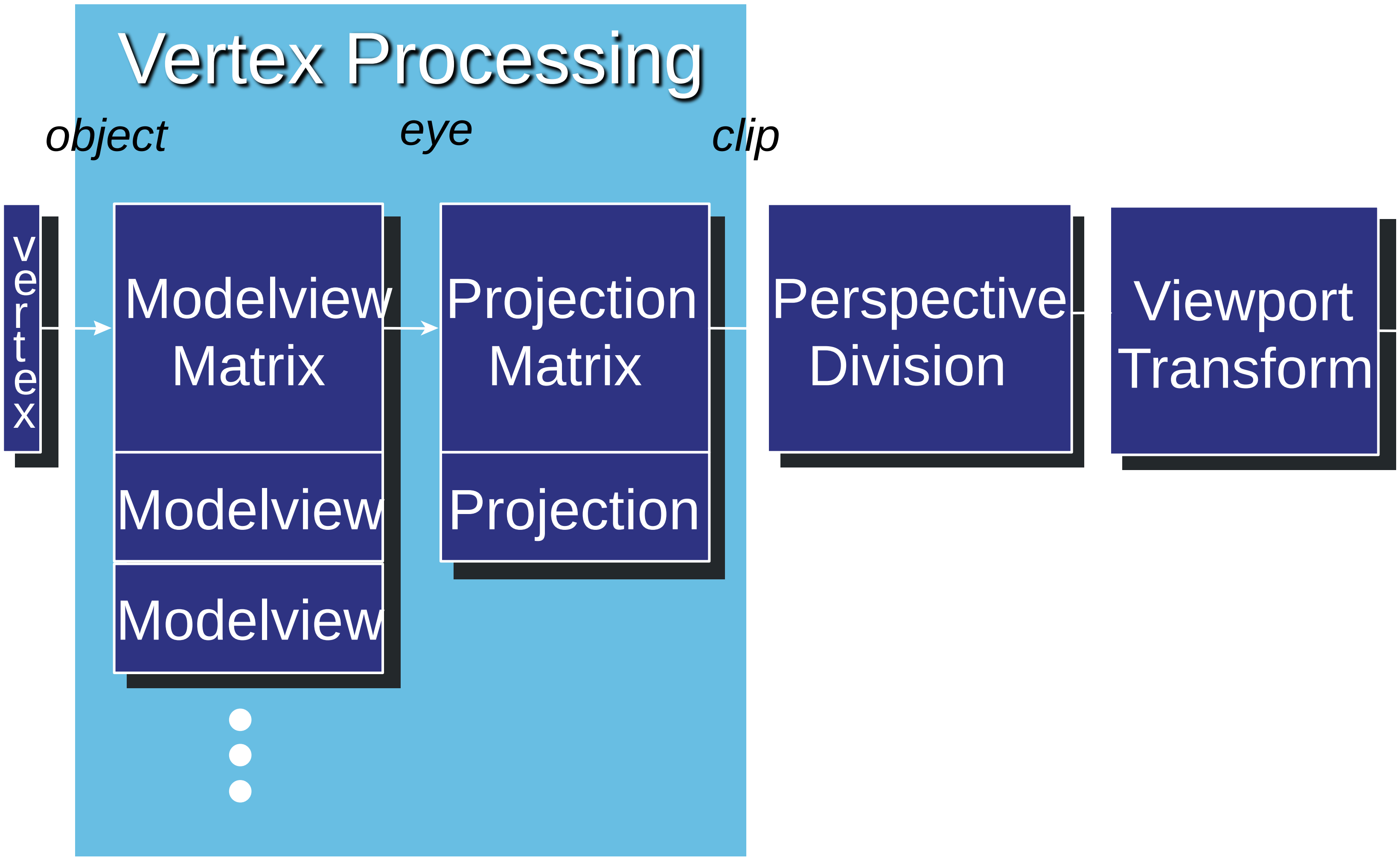
Command

- Command buffering (!)
- Command interpretation
- Unpack and perform format conversion (“Input Assembler”)

```
glLoadIdentity( );
glMultMatrix( T );
glBegin( GL_TRIANGLE_STRIP );
glColor3f ( 0.0, 0.5, 0.0 );
glVertex3f( 0.0, 0.0, 0.0 );
glColor3f ( 0.5, 0.0, 0.0 );
glVertex3f( 1.0, 0.0, 0.0 );
glColor3f ( 0.0, 0.5, 0.0 );
glVertex3f( 0.0, 1.0, 0.0 );
glColor3f ( 0.5, 0.0, 0.0 );
glVertex3f( 1.0, 1.0, 0.0 );
glEnd( );
```



- Transformation

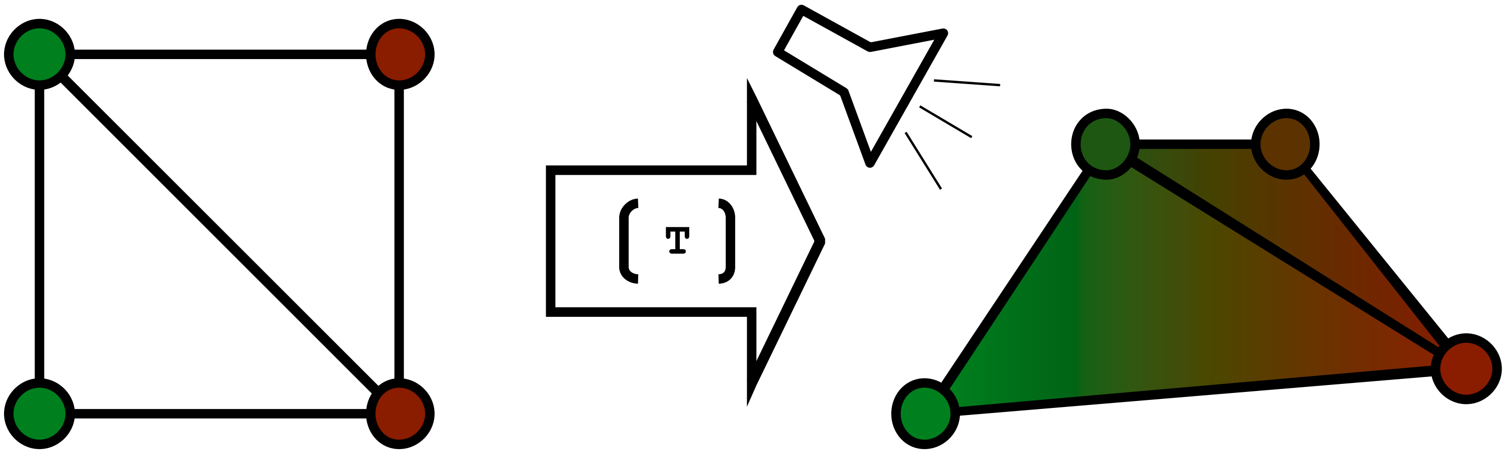


Vertex Processing

- Fixed function pipeline:
  - User has to provide matrices, the rest happens automatically
- Programmable pipeline:
  - User has to provide matrices/other data to shader
  - Shader Code transforms vertex explicitly
    - We can do whatever we want with the vertex!
    - Usually a *gl_ModelViewProjectionMatrix* is provided
    - In GLSL-Shader : *gl_Position = ftransform();*

Vertex Processing

- Lighting
- Texture coordinate generation and/or transformation
- Vertex shading for special effects



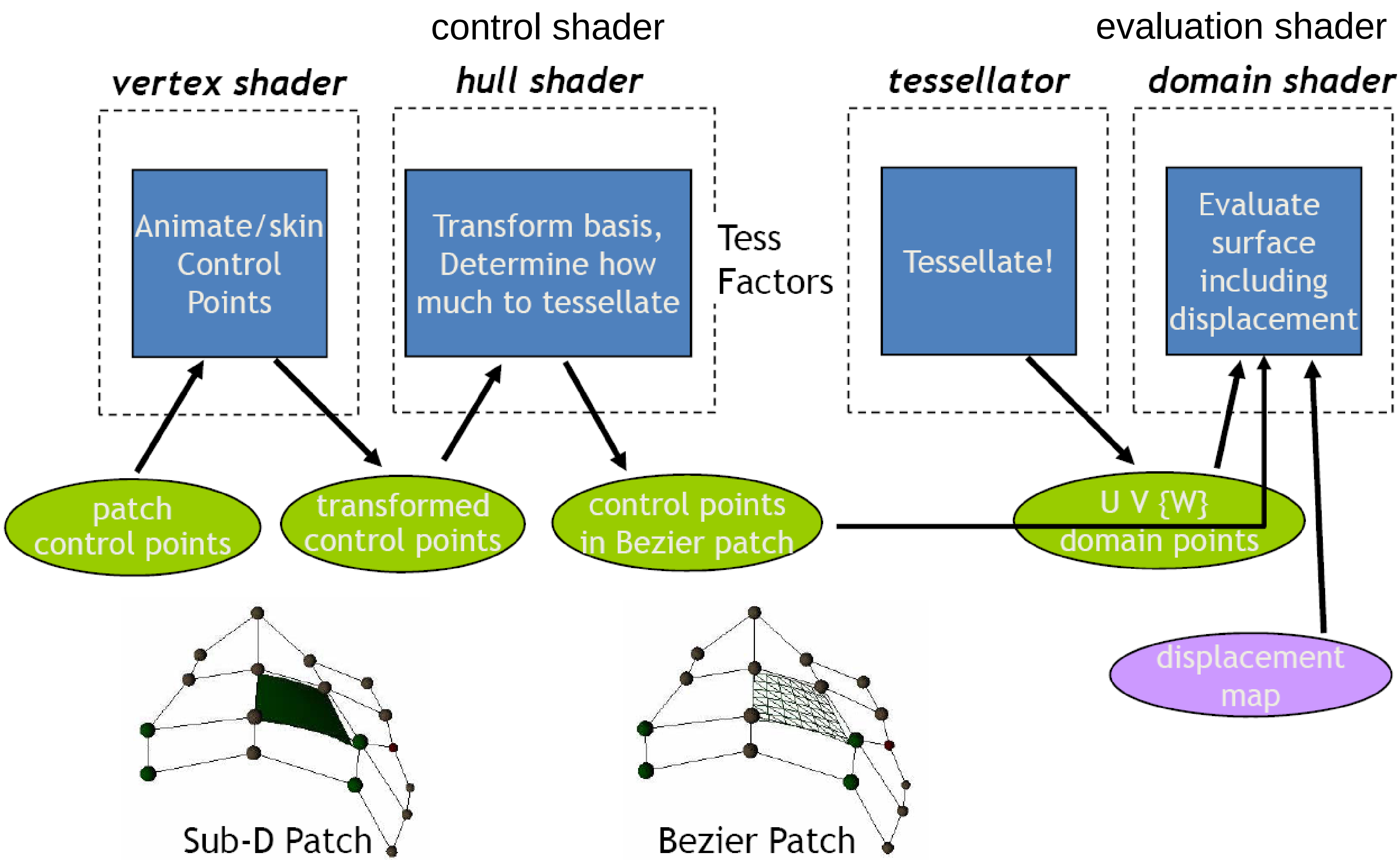
Object-space triangles

Screen-space lit triangles

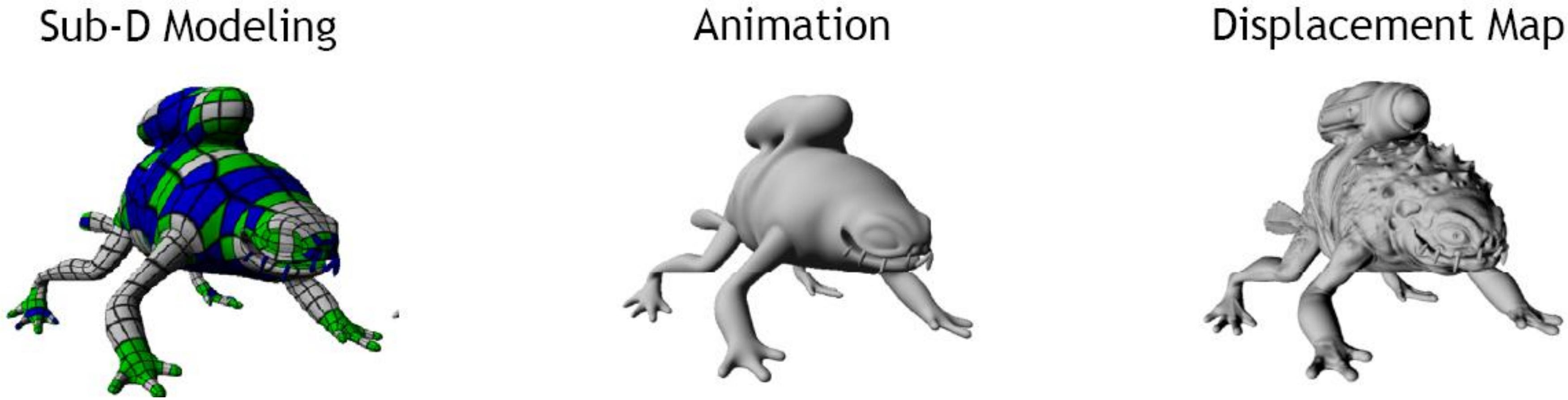
Tesselation

- If just triangles, nothing needs to be done, otherwise:
- Evaluation of polynomials for curved surfaces
- ➢ Create vertices (tesselation)
- DirectX11 specifies this in hardware!
  - 3 new shader stages!!!
  - Still not trivial (special algorithms required)

DirectX11 Tesselation



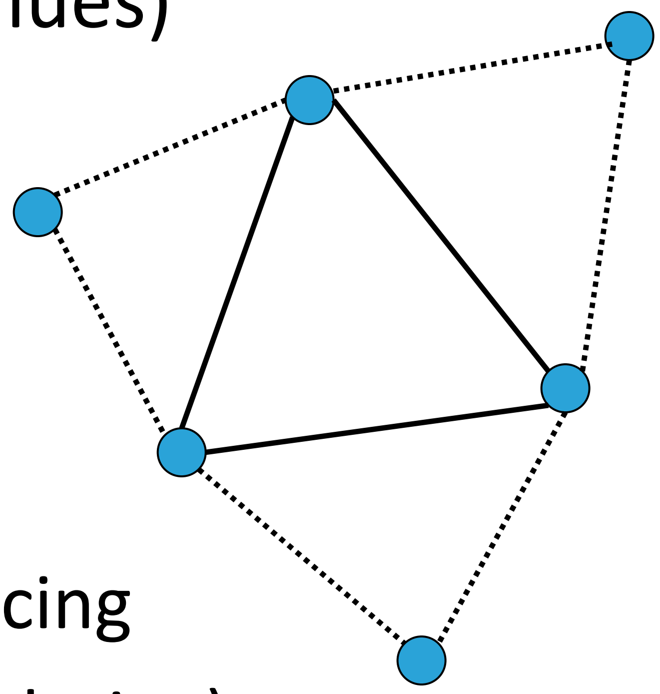
Tesselation Example



Optimally tesslated!

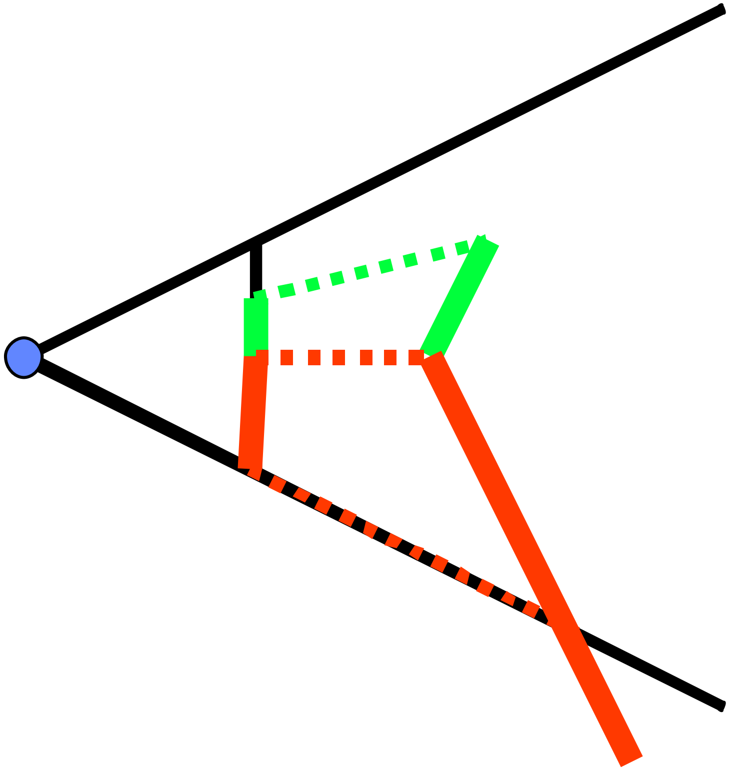
Geometry Shader

- Calculations on a primitive (triangle)
- Access to neighbor triangles
- Limited output (1024 32-bit values)
  - → No general tesselation!
- Applications:
  - Render to cubemap
  - Shadow volume generation
  - Triangle extension for ray tracing
  - Extrusion operations (fur rendering)

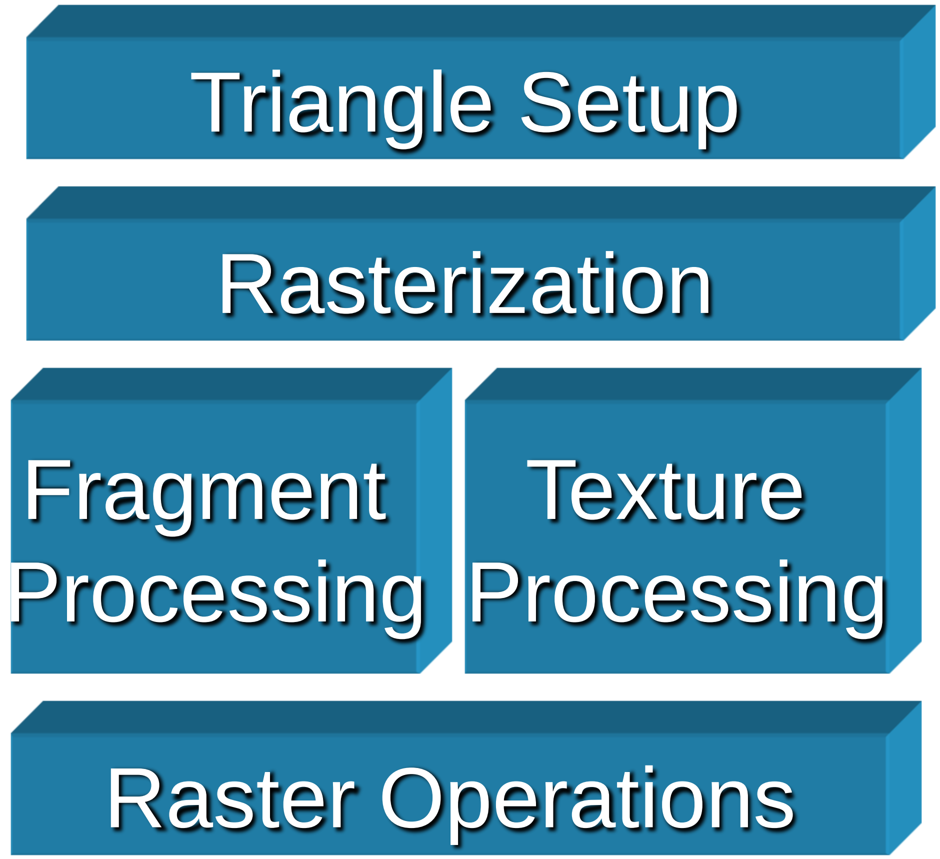


Rest of Geometry Stage

- Primitive assembly
- Geometry shader
- Clipping (in homogeneous coordinates)
- Perspective division, viewport transform
- Culling

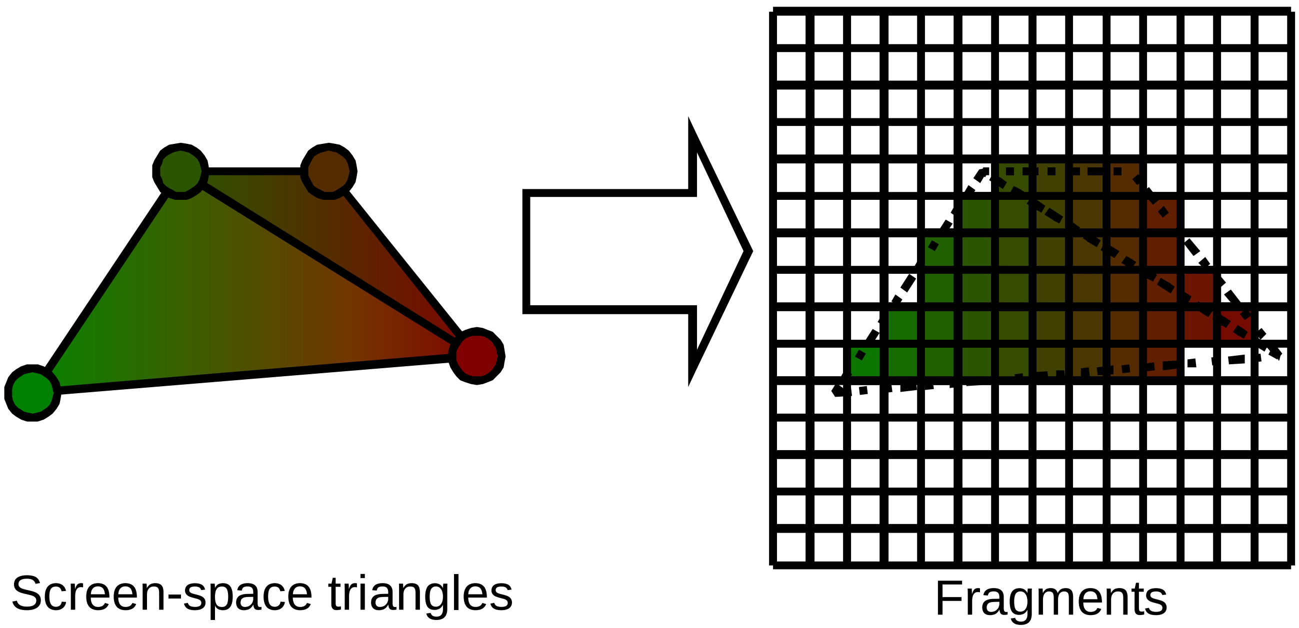


Rasterization Stage



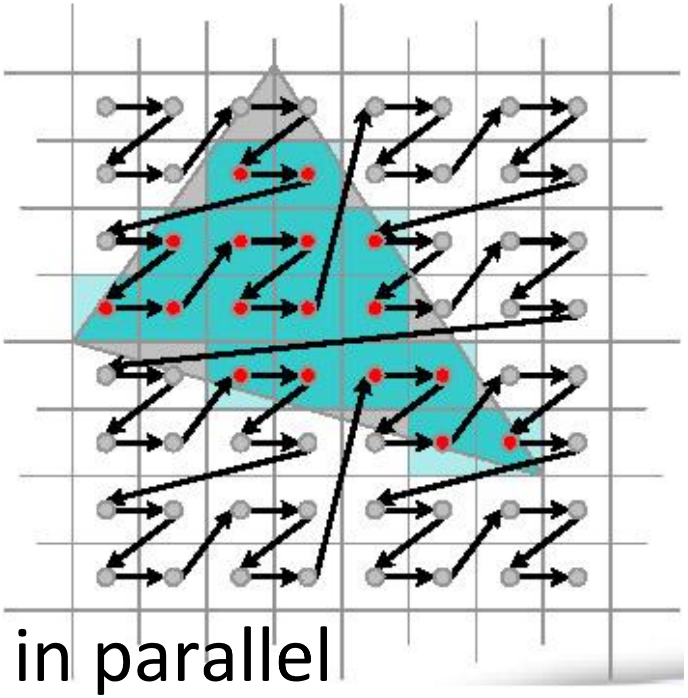
Rasterization

- Setup (per-triangle)
- Sampling (triangle = {fragments})
- Interpolation (interpolate colors and coordinates)



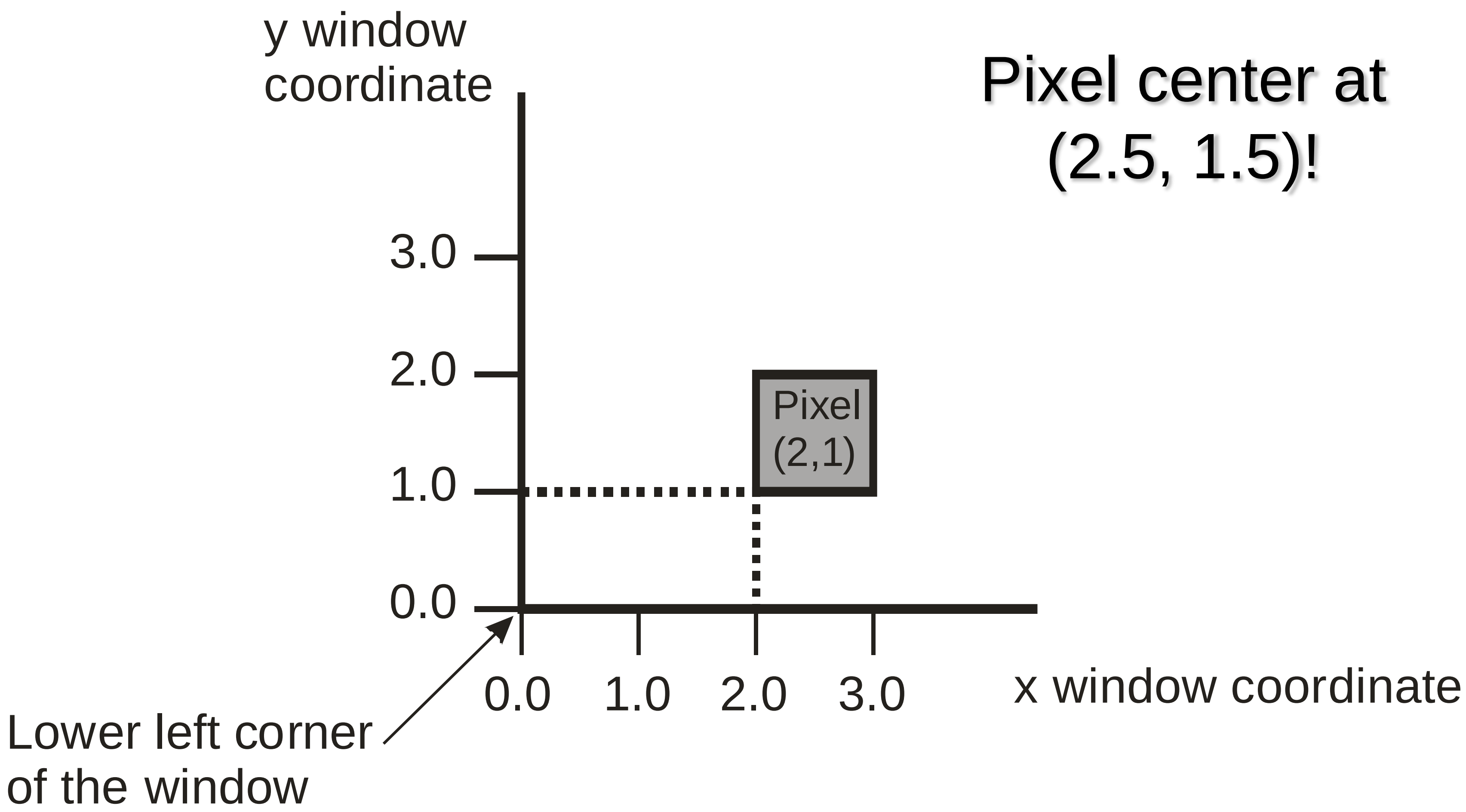
Rasterization

- Sampling inclusion determination
- In tile order improves cache coherency
- Tile sizes vendor/generation specific
  - Old graphics cards: 16x64
  - New: 4x4
  - Smaller tile size favors conditionals in shaders
  - All tile fragments calculated in parallel on modern hardware



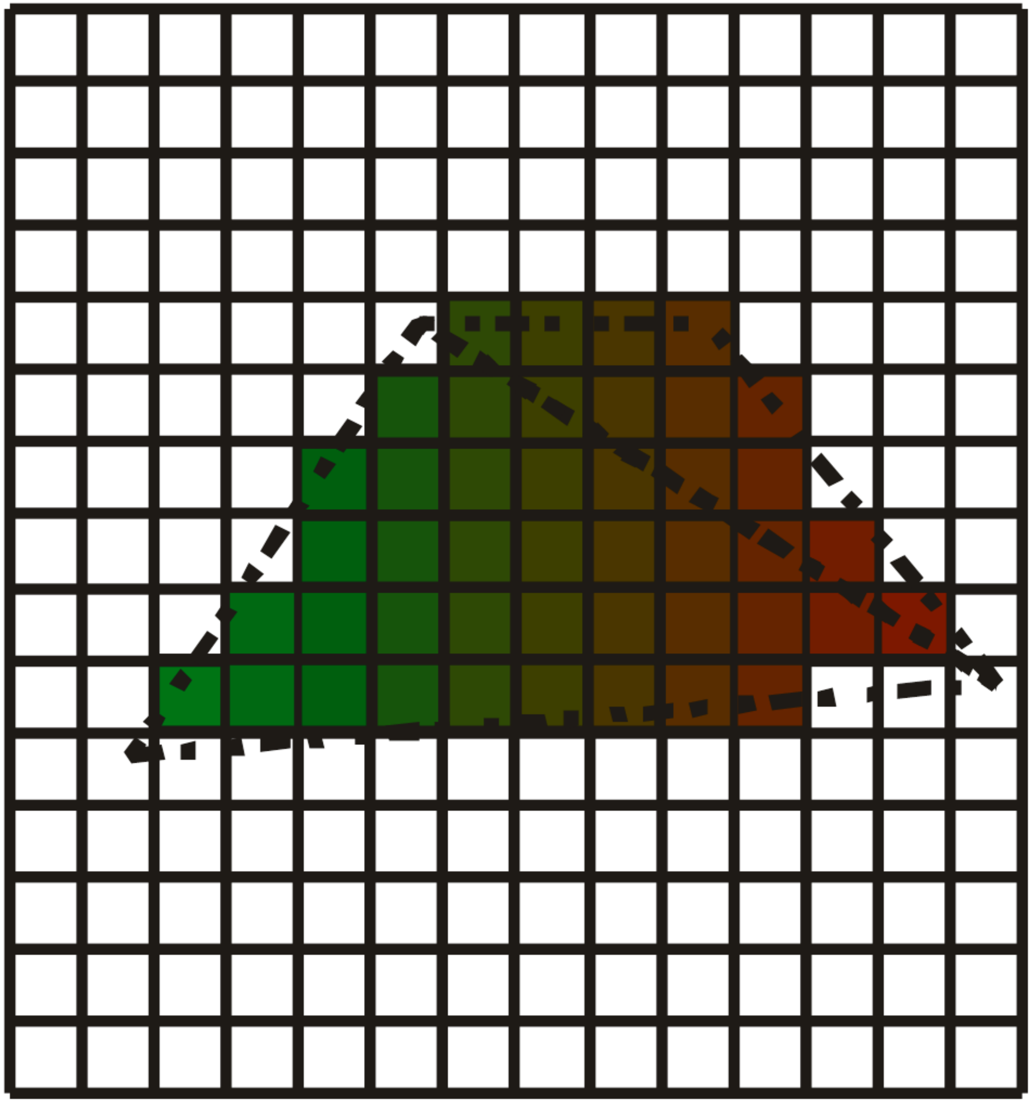
Rasterization – Coordinates

- Fragments represent “future” pixels



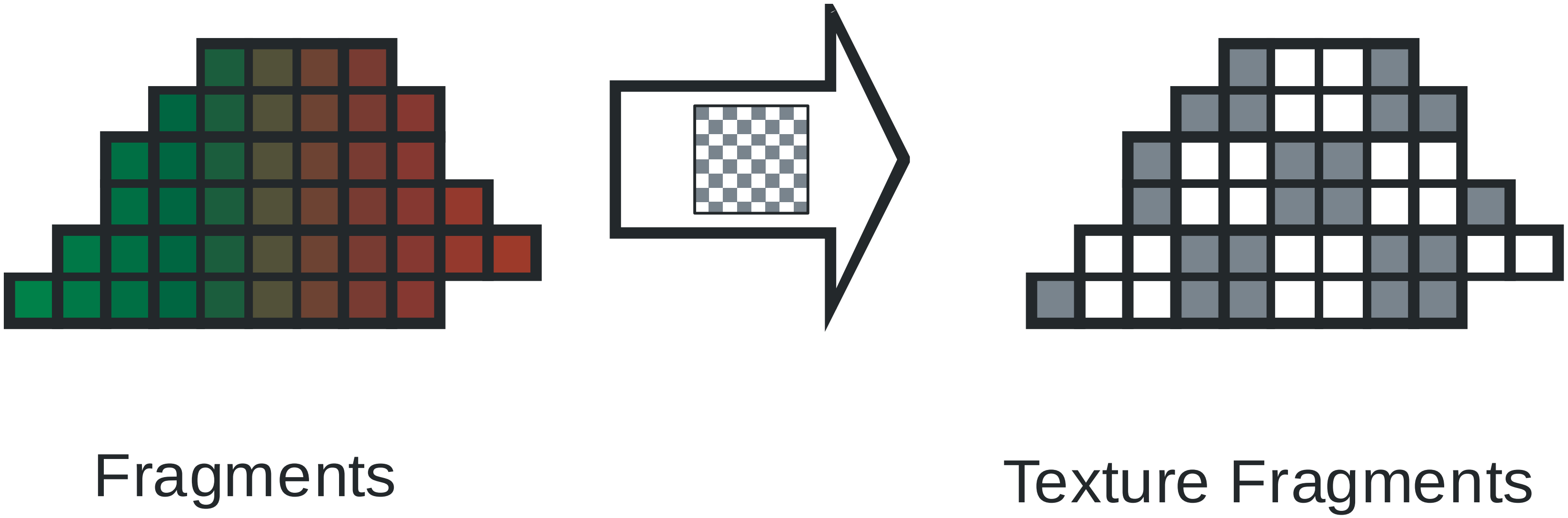
Rasterization – Rules

- Separate rule for each primitive
- Non-ambiguous!
- Polygons:
  - Pixel center contained in polygon
  - On-edge pixels: only one is rasterized



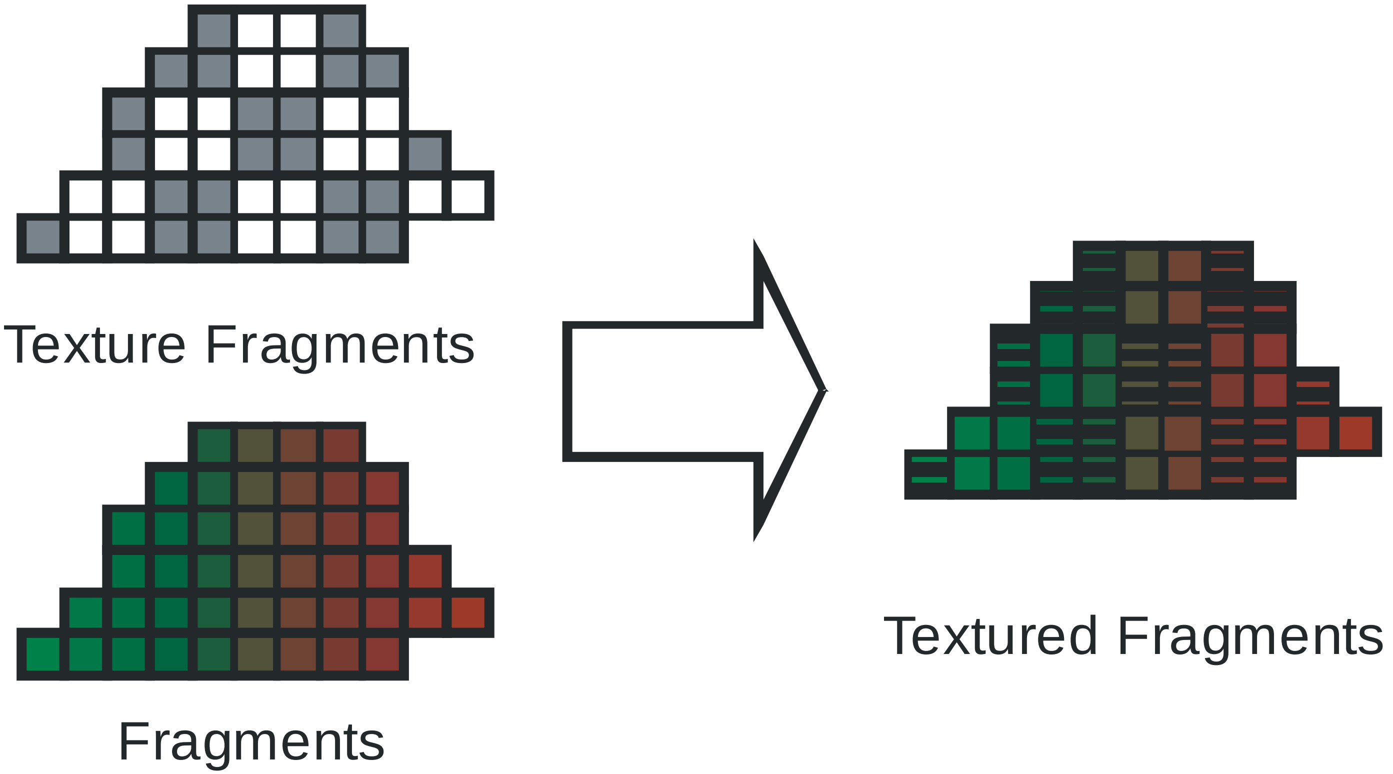
Texture

- Texture “transformation” and projection
  - E.g., projective textures
- Texture address calculation (programmable in shader)
- Texture filtering



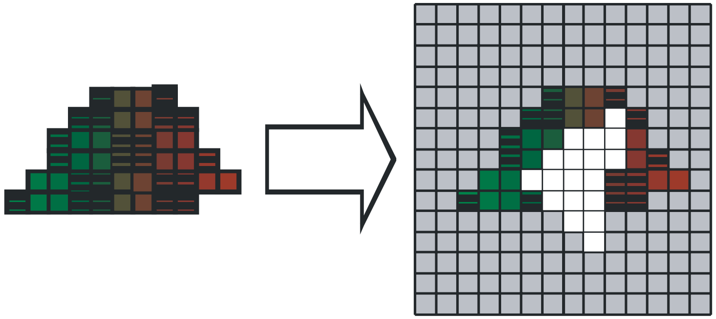
Fragment

- Texture operations (combinations, modulations, animations etc.)



Raster Tests

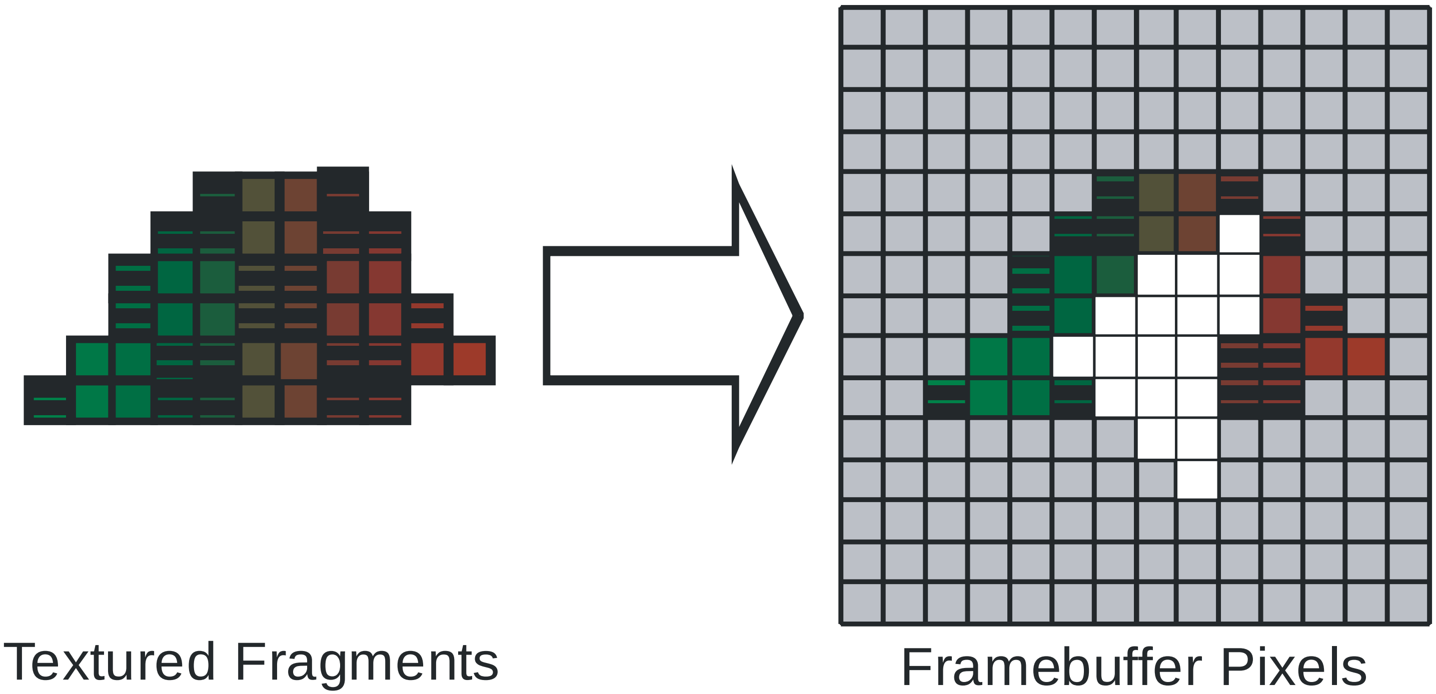
- **Ownership**
  - Is pixel obscured by other window?
- **Scissor test**
  - Only render to scissor rectangle
- **Depth test**
  - Test according to z-buffer
- **Alpha test**
  - Test according to alpha-value
- **Stencil test**
  - Test according to stencil buffer



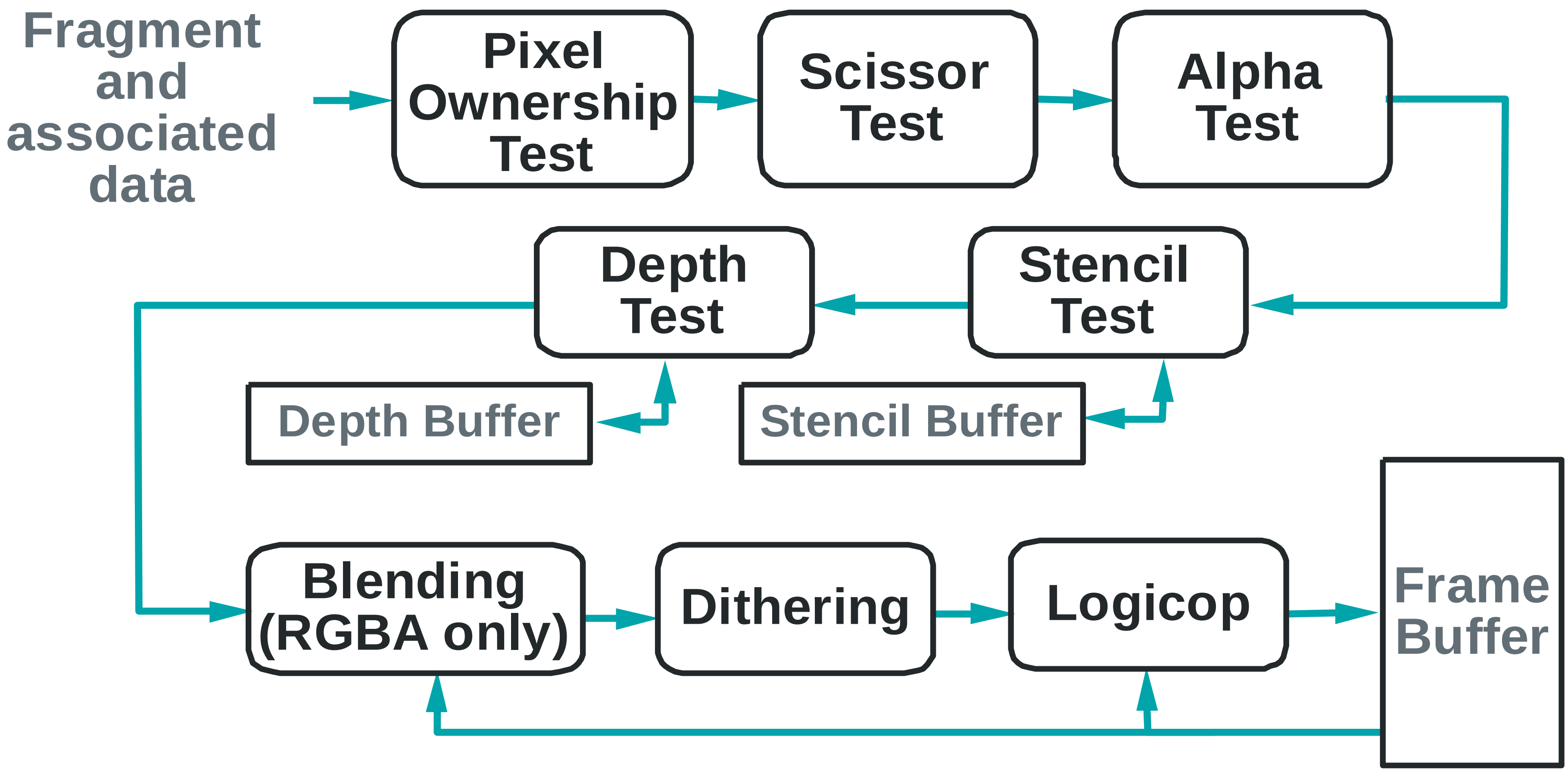
Textured Fragments   Framebuffer Pixels

Raster Operations

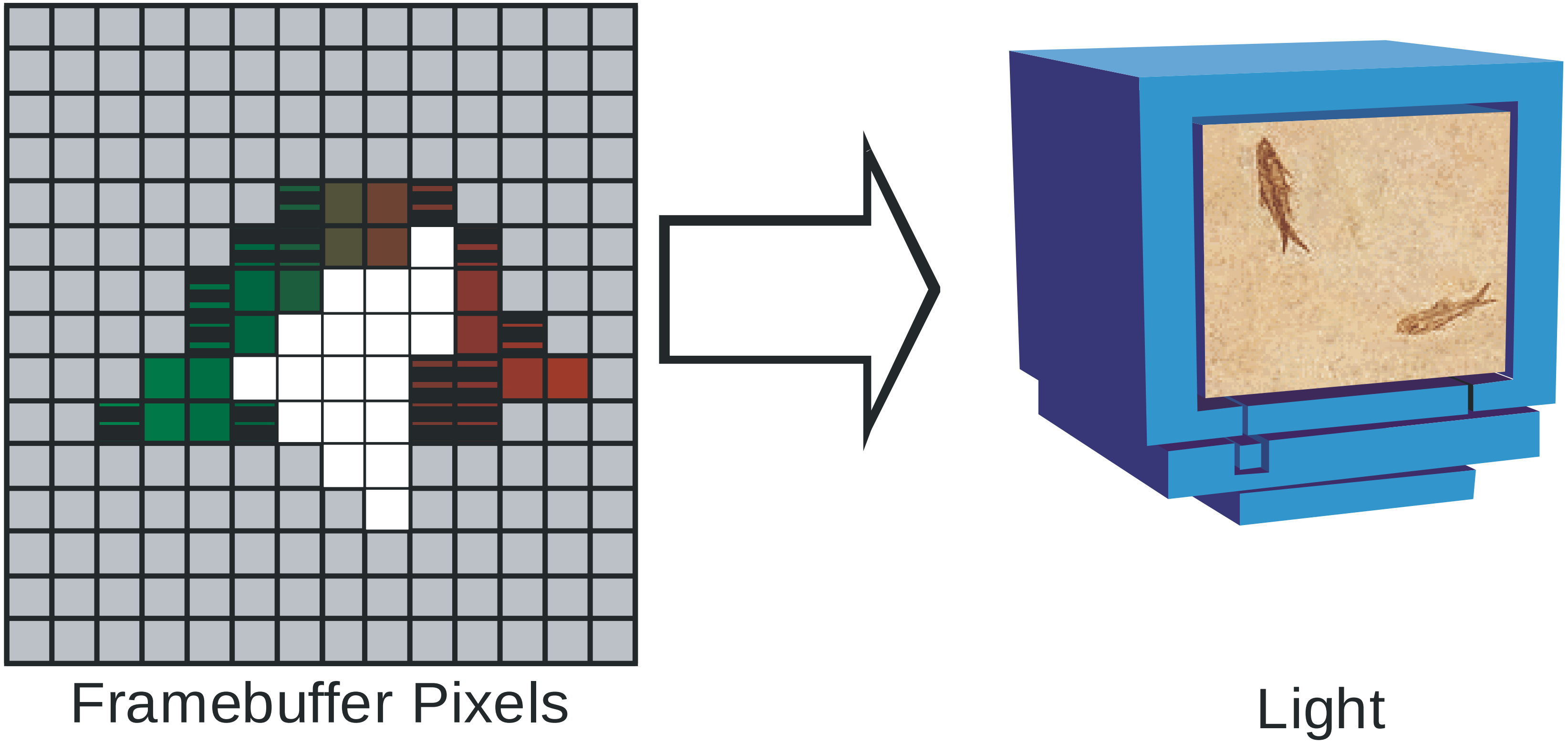
- Blending or compositing
- Dithering
- Logical operations



- After fragment color calculation ("Output Merger")



- Gamma correction
- Digital to analog conversion if necessary



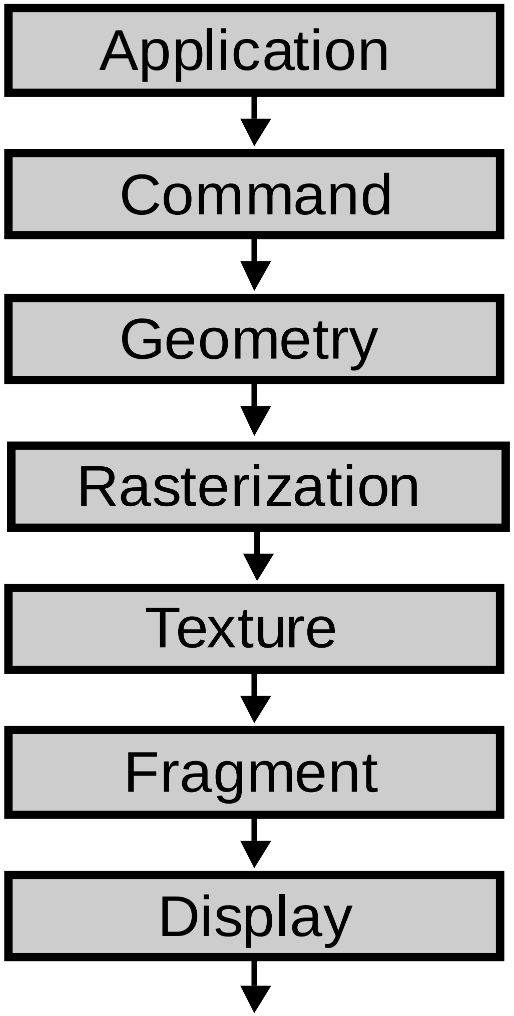
Display

- Frame buffer pixel format:
  RGBA vs. index (obsolete)
- Bits: 16, 32, 128 bit floating point, …
- Double buffered vs. single buffered
- Quad-buffered for stereo
- Overlays (extra bit planes) for GUI
- Auxiliary buffers: alpha, stencil

Functionality vs. Frequency

- Geometry processing = per-vertex
  - Transformation and Lighting (T&L)
  - Historically floating point, complex operations
  - Today: fully programmable flow control, texture lookup
  - 20-1500 million vertices per second
- Fragment processing = per-fragment
  - Blending and texture combination
  - Historically fixed point and limited operations
  - Up to 50 billion fragments (“Gigatexel”/sec)
  - Floating point, programmable complex operations

Computational Requirements



- Assume typical non-trivial fixed-function rendering task
  - 1 light, texture coordinates, projective texture mapping
  - 7 interpolants (z,r,g,b,s,t,q)
  - Trilinear filtering, texture-, color blending, depth buffering
- Rough estimate:

	ADD	CMP	MUL	DIV
Vertex	102	30	108	5
Fragment	66	9	70	1

Communication Requirements

- Vertex size:
  - Position x,y,z
  - Normal x,y,z
  - Texture coordinate s,t

  → $8 \cdot 4 = 32$ bytes
- Texture:
  - Color r,g,b,a, 4 bytes
- Display:
  - Color r,g,b, 3 bytes
- Fragment size (in frame buffer):
  - Color r,g,b,a
  - Depth z (assume 32 bit)

  → 8 bytes, but goes both ways (because of blending!)

Communication Requirements