3D graphic acceleration – history and architecture

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Advances in computer hardware

- **3D acceleration** common in the consumer sector
- **games**, **multimedia**
- **appearance:** presentation quality, ~photorealistic
  - sophisticated texturing and shading techniques, multi-pass methods, ..
- **very high performance**
  - recent **VLSI technology** (NVIDIA Pascal .. 14-16 nm, AMD .. 1024-bit HBM memory, ..)
  - extreme memory performance (stacked memory), **massive parallelism**
  - very fast **CPU-GPU buses** (NVLink..)

Advances in GPU software

- **two main APIs** for 3D graphics
  - **OpenGL** (SGI, open standard, Khronos)
  - **Direct3D** (Microsoft)
- parameter setup + **efficient data transfer**
  - sharing of data arrays ("buffers")
- **programmable rendering pipeline**
  - revolution in realtime 3D graphics (~2000)
  - ***vertex-shader***: vertex processing
  - ***tesselation and geometry shaders***: geometry processing on the GPU (new primitives "on the fly")
  - ***fragment-shader*** (*pixel-shader*): pixel appearance

Development tools

- for developers and artists
- **high level shader programming**
  - [Cg (NVIDIA)], **HLSL** (DirectX), **GLSL** (OpenGL)
  - Cg is almost equal to **HLSL**
- **effect composition**
  - compact definition of the effect (GPU programs, data references, parameters..) in one source file/script
  - DirectX **.FX** format, NVIDIA **CgFX** format
  - tools: Effect Browser (Microsoft), **FX Composer** (N-VIDIA), **RenderMonkey** (ATI)

History I: Silicon Graphics

- first commercial graphical workstations
  - hardware-accelerated graphical subsystem (depth-buffer)
  - SW tools, libraries (Iris GL, Inventor), “graphics = SGI”
- selected workstations `(http://www.g-lenerz.de/)`
  - 1983: **Iris 1000** – graphical terminal to VAX (Motorola 68k @ 8MHz, Geometry Engine, ..)
  - 1984: **Iris 2000** (graphical station, Clark GE), Iris 3000
  - 1986: **Professional Iris 4D** (first MIPS processors)
  - 1988: Power series, **GTX**, **Personal Iris 4D**

History II: Silicon Graphics, SGI

- other workstations and graphical systems:
  - 1991: **Iris Indigo** (most popular SGI workstation)
  - 1992: **Iris Crimson**
  - 1992: **Indigo R4000** (64bit), **RealityEngine**
  - 1993: **Iris Indy** (cheap, 3D graphics acceleration option)
  - 1993: **Onyx** (server with RE2)
  - 1993: **Iris Indigo²** (Extreme graphics)
  - 1996: **O2** (cheap workstation), **InfiniteReality** engine
  - 1997: **Octane** (2 CPUs)
  - 2000: **Octane2** (Vpro graphics)
  - 2002: **Fuel**, 2003: **Ezro**, 2008: **Virtu** (x86, NVIDIA)

History III: Consumer sector

- 1^{st} **graphic accelerator** for home PC
  - 1996: **3Dfx Voodoo 1**
  - graphic coprocessor (“pass-through”)
  - **Glide API**
- 1^{st} **SLI card** (Scan Line Interleave)
  - 1998: **3Dfx Voodoo²**
- **NVIDIA**
  - 1997: NVIDIA **Riva 128**
  - 1998: NVIDIA Riva TNT (“TwiNTexel”)
- 1^{st} **HW T&L** (“transform & lighting”)
  - 1999: NVIDIA **GeForce 256**

History IV: Consumer sector

- 2000
  - NVIDIA **GeForce2**
  - **ATI Radeon**
- 2001: **GPU programming**
  - **DirectX 8.0** (vertex shaders, fragment shaders, 1.0, 1.1)
  - NVIDIA **GeForce3**, GeForce3 Titanium
  - DirectX 8.1 (PS 1.2, 1.3, 1.4)
  - ATI Radeon **8500** (TruForm)
- 2002: **advanced GPU programming**
  - **DirectX 9.0** – VS, PS **2.0**
  - NVIDIA **GeForce4 Titanium**
  - ATI Radeon **9000, 9700** [Pro]

History V: Consumer sector

- 2003: **affordable DX9**
  - cheap **DirectX 9.0** – compatible cards (VS, PS 2.0)
  - NVIDIA **GeForce FX** 5200-5800
  - ATI Radeon **9800**
- 2004: **extended shader programming**
  - **DirectX 9.0c** (VS, PS 3.0), **OpenGL 2.0** (at last!)
  - NVIDIA **GeForce 6800**, 6200, 6600
  - ATI Radeon **X800**
- 2005: **HW advances**
  - **PCI-Express** bus
  - twin GPU systems – NVIDIA: **SLI**, ATI: **CrossFire**
  - NVIDIA **GeForce 7800**
  - ATI Radeon **X550, X850**

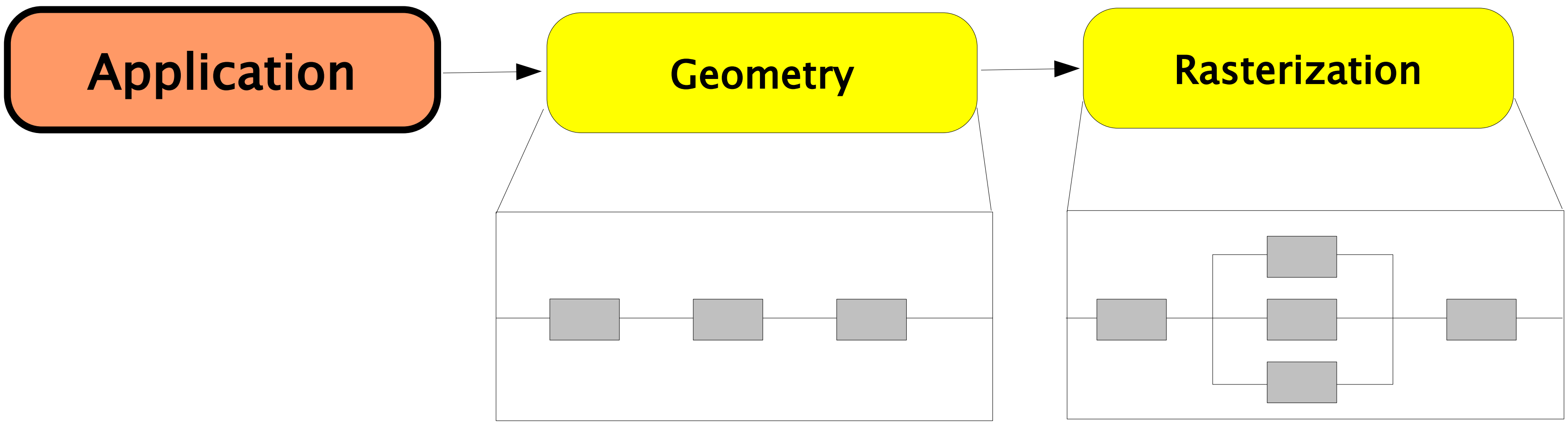
History VI: Consumer sector

- 2006
  - **DirectX 10** (Windows Vista) .. **geometry shaders**
  - NVIDIA **GeForce 7600, 7900**
  - ATI Radeon **X1800, X1900**
- 2007
  - **CUDA** (NVIDIA) – GPGPU programming in C
  - NVIDIA **GeForce 8600, 8800**
  - ATI Radeon **R600** (HD 2400, 3850)
- 2009
  - **OpenGL 3.2**, **DirectX 11**
  - GPU **tesselation**
  - NVIDIA **Fermi**

History VII: Consumer sector

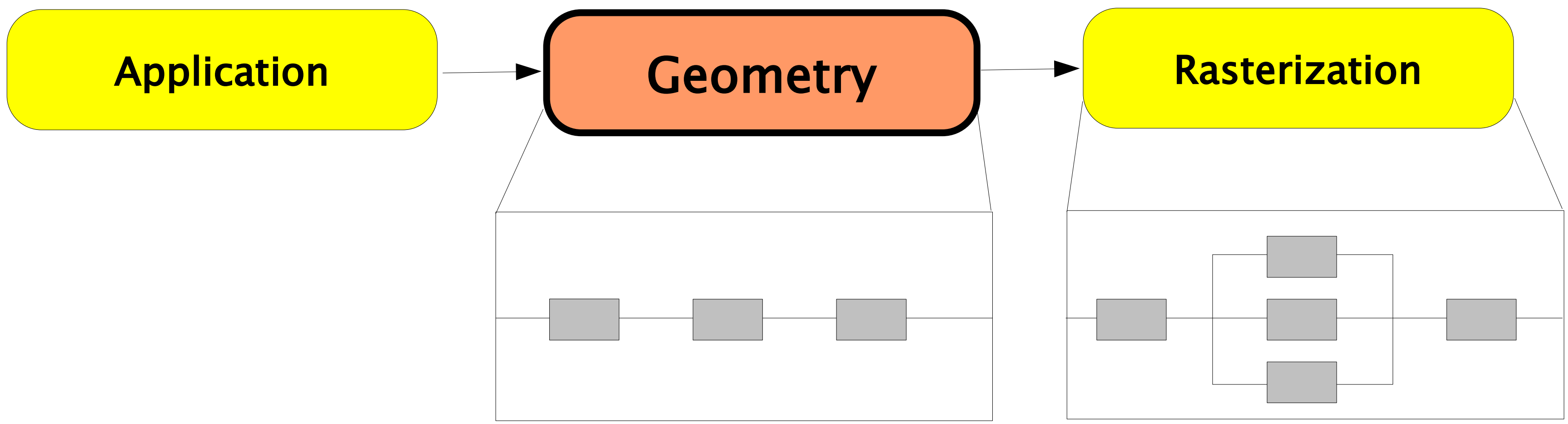
- 2010
  - **OpenGL 4**
  - **OpenCL:** general computing on GPU, multiplatform
- 2011 -
  - **computing servers** using many GPU cards (**NVIDIA Tesla** architecture)
  - **OpenGL 4.6**
  - **DirectX 12** (Windows 10, Xbox One)
  - **OpenGL ES** for mobile platforms (GLES 3.2)
- **other manufacturers**
  - Past: Matrox, 3DLabs, S3, PowerVR (Kyro), SiS
  - **Intel:** very good integrated GPUs

3D graphics pipeline I



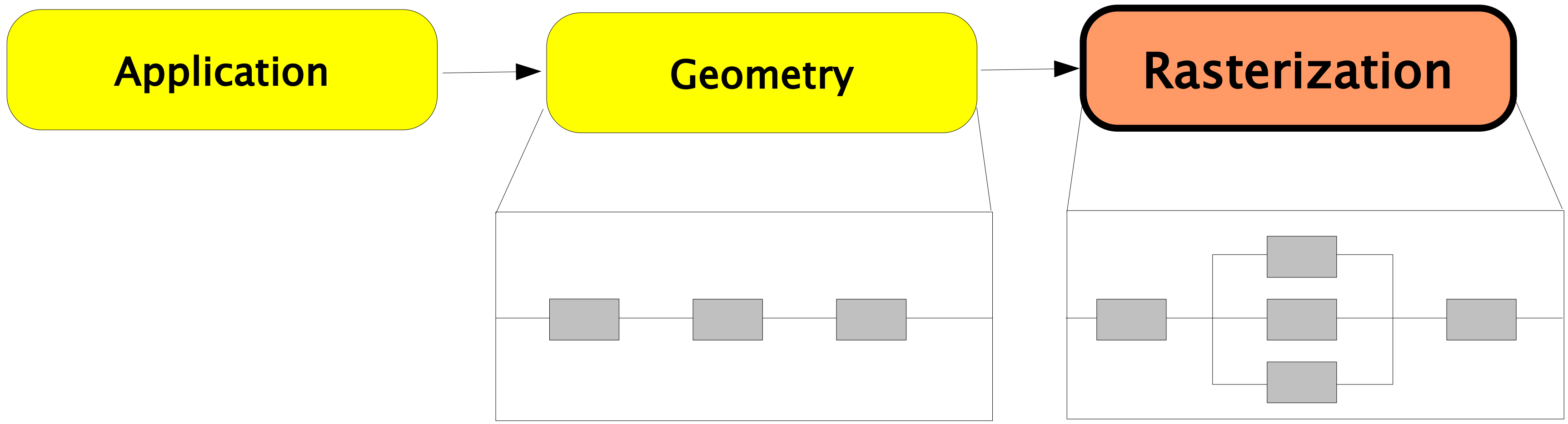
- **Application**
  - **3D data representation** (virtualization, disk + memory), parametrization, templates, ..
  - **object behavior**: physical simulation, AI
  - **interaction**: collisions, deformations, ..

3D graphics pipeline II



- **Geometry** (“*HW T&L*”)
  - **modeling transforms** (application support)
  - **projection transforms** (perspective), **clipping**
  - **tesselation** (creating primitives “on the fly”)
  - **lighting** (at least pre-computing of data for lighting)
  - very long pipeline

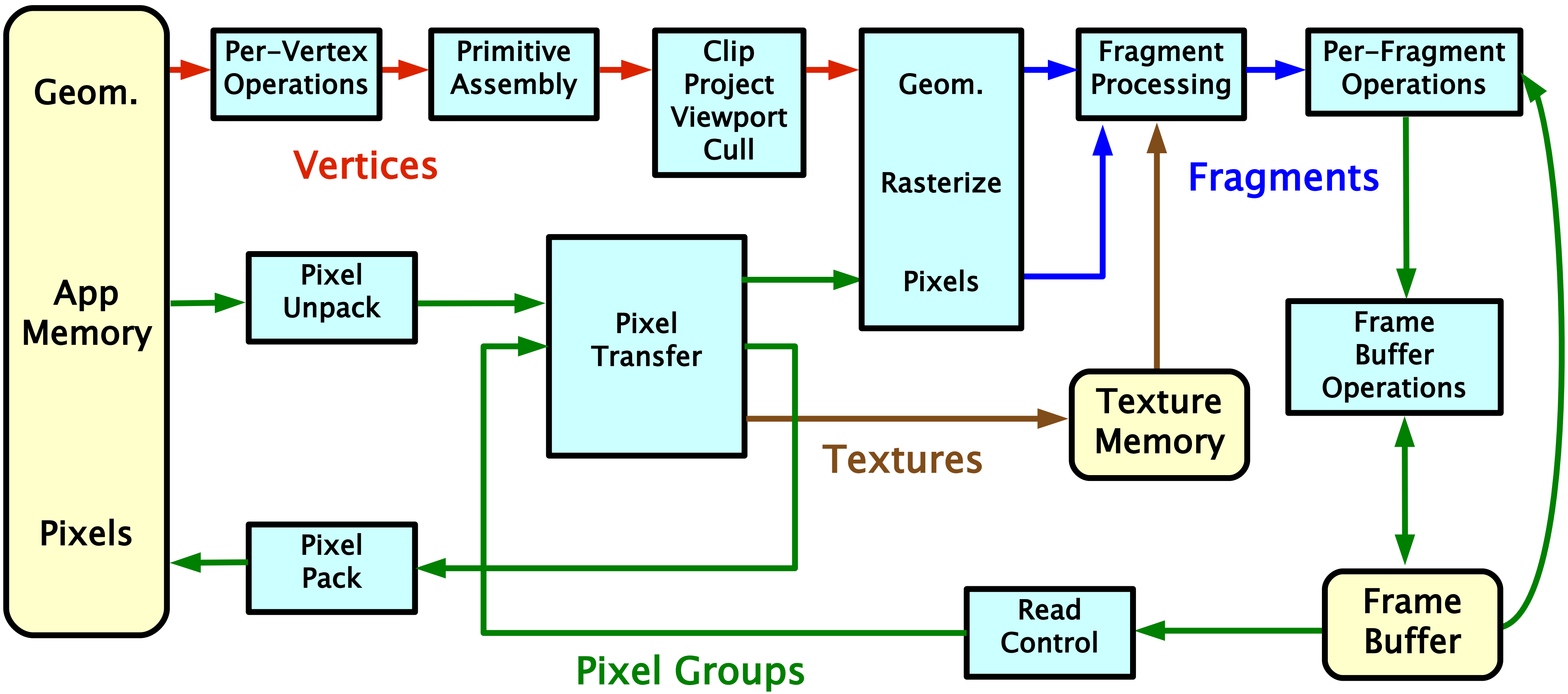
3D graphics pipeline III



- **Rasterization** (raster rendering)
  - primitives are converted into **fragments**, attribute interpolation
  - visibility ("*depth-buffer*"), **texture mapping**, shading effects, transparency, fog, ..
  - **parallelism** (independent processing of fragments)

OpenGL (FFP scheme)

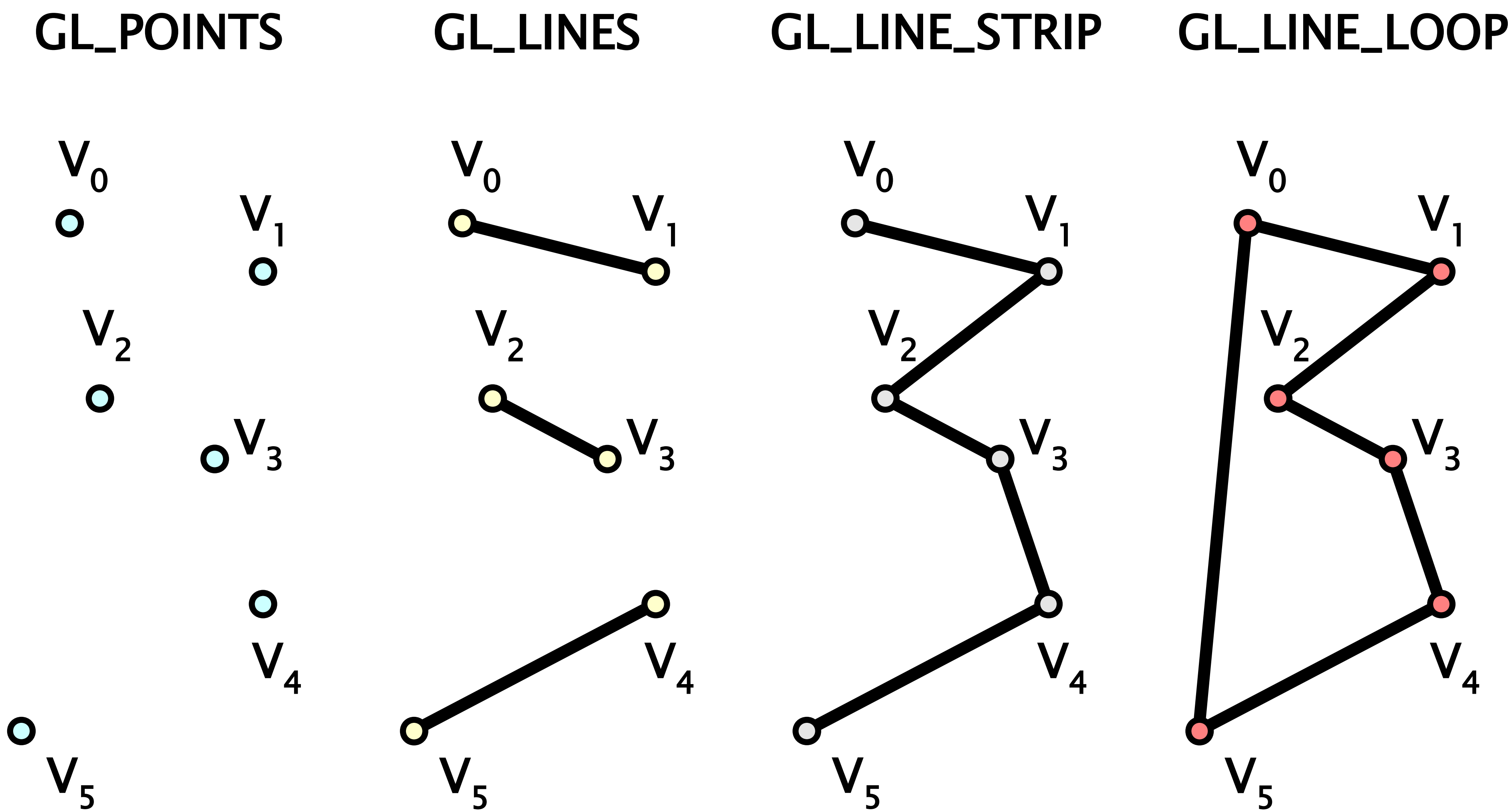
- OpenGL Fixed Functionality Pipeline:



OpenGL: geometric primitives

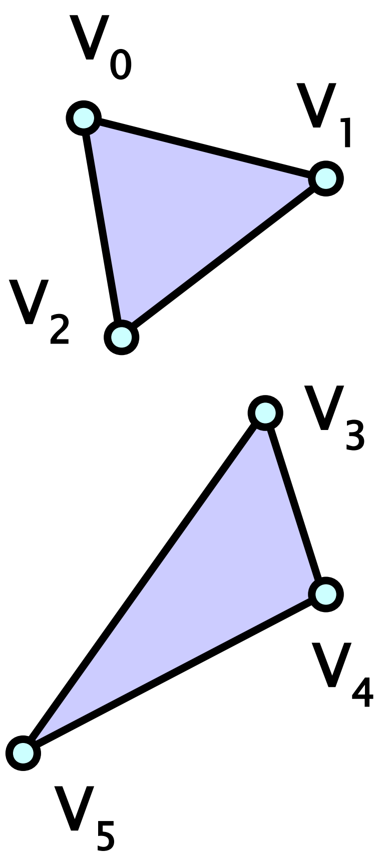
- types of geometric primitives:
  - **point**, **line**, polyline, closed polyline
  - polygon, **triangle**, triangle strip, triangle fan, quadrangle, quad strip
- **immediate** vertex processing **mode**
  - glVertex, glColor, glNormal, glTexCoord, ...
  - <u>not efficient</u> (many gl*() calls)
- **vertex arrays**
  - glDrawArrays, glMultiDrawArrays, <u>glDrawElements</u>, ...
  - glColorPointer, glVertexPointer, ... or **interleaving**

Geometric primitives I

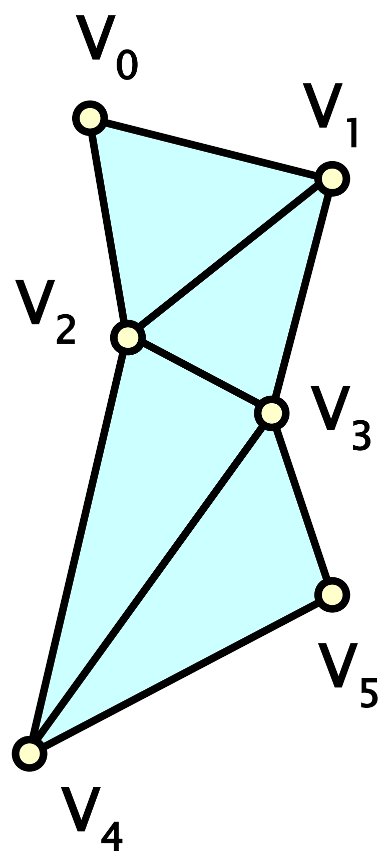


Geometric primitives II

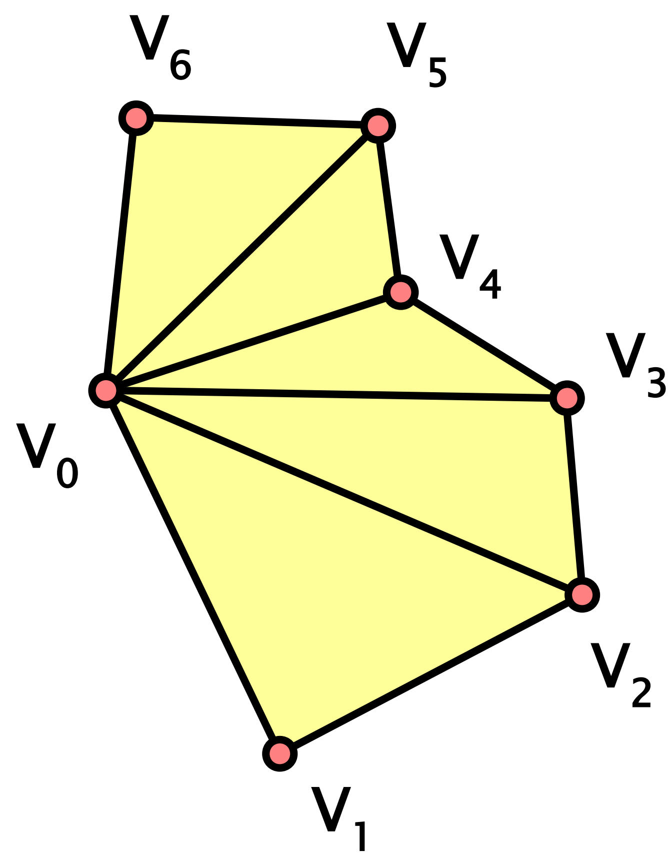
GL_TRIANGLES



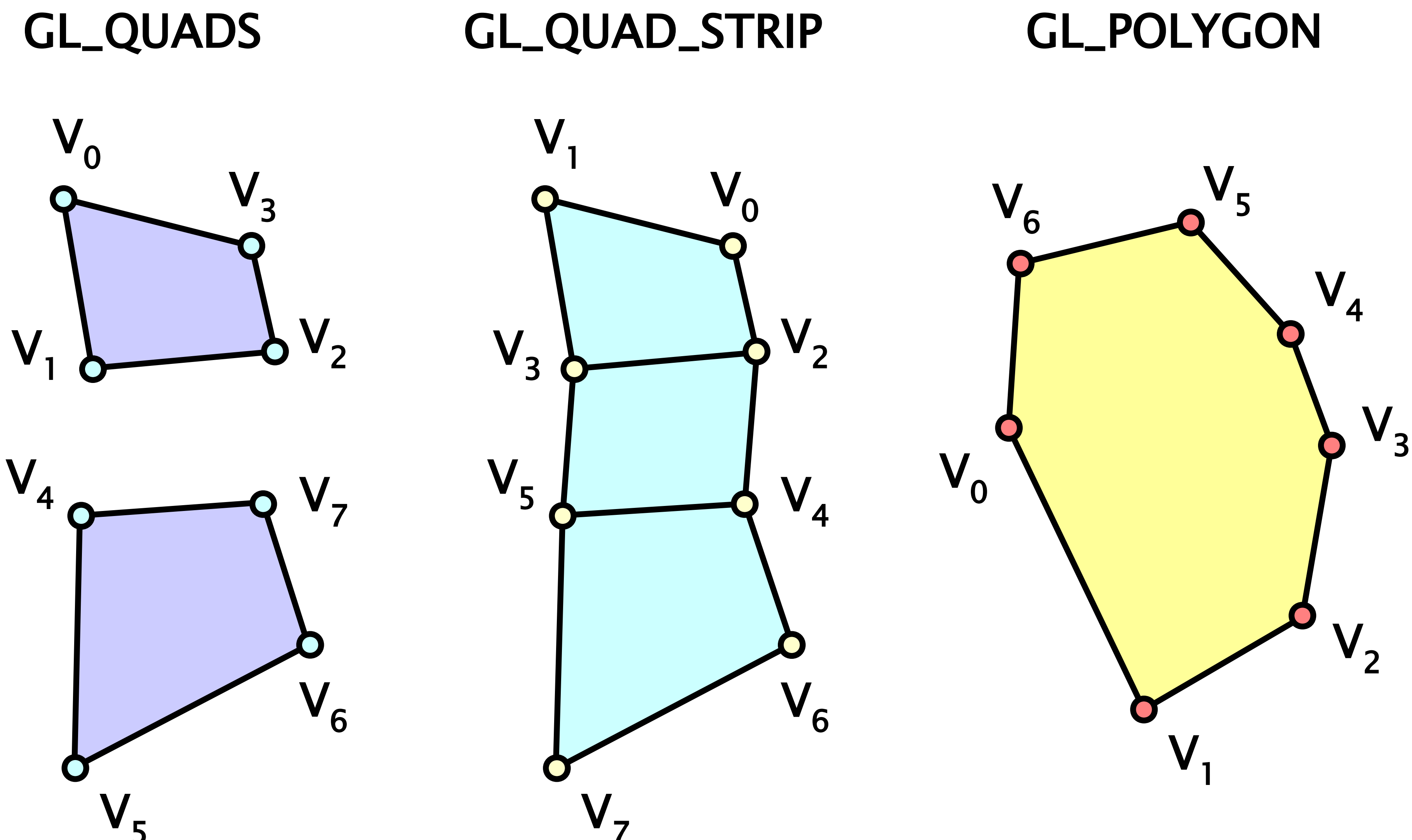
GL_TRIANGLE_STRIP



GL_TRIANGLE_FAN



Geometric primitives III



OpenGL “macros” (Display Lists)

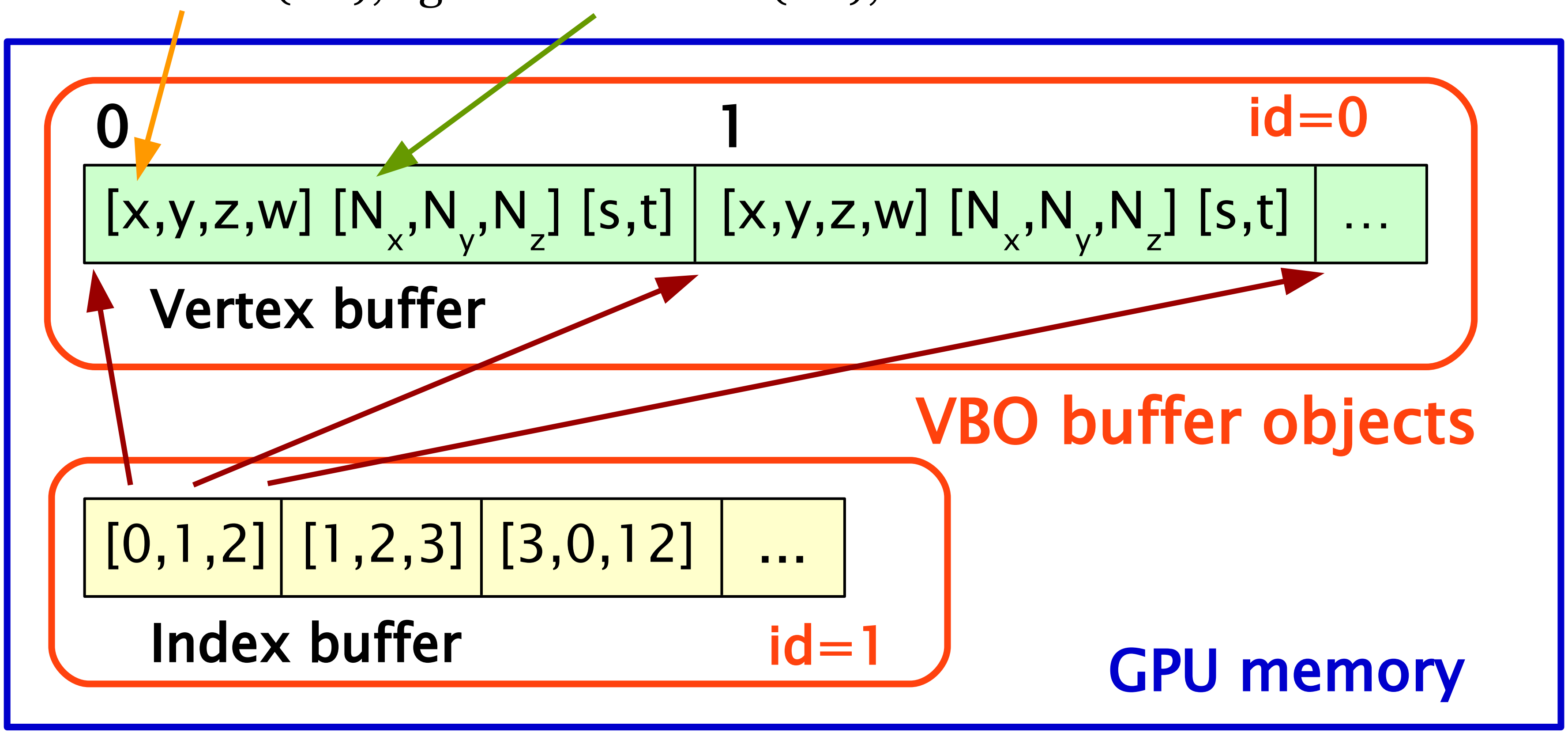
- DISPLAY_LIST_MODE instead of IMMEDIATE_MODE
- **sequence of OpenGL commands** stored in memory
  - glNewList, glEndList
  - a list can be stored on the server side (GPU)
  - idea: “display-list = macro”
- **replay**
  - glCallList, glCallLists
  - could be much more efficient (sequence caching/optimization..)

Geometric data on the server

- since **OpenGL 1.5**
  - **VBO buffer**, currently: **VAO buffer**
- server-side buffers for geometric data
  - buffer management: glCreateBuffers, glBindBuffer
  - data submit: glBufferData, glBufferSubData
  - buffer mapping: glMapBuffer, glUnmap..
- working with **client memory** or **VBO buffer**
  - glColorPointer, glNormalPointer, glVertexPointer, ...

Vertex Buffer Objects

glBindBuffer(GL_ARRAY_BUFFER, **0**);
glVertexPointer(...); glNormalPointer(...); ...



glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, **1**);
glDrawElements(GL_TRIANGLES, ...);

Vertex processing (GL < 3.x)

- **matrix transforms** (model, view, projection matrices)
  - glMatrixMode
  - glLoadIdentity, glLoadMatrix, glMultMatrix
  - glRotate, glScale, glTranslate, ...
- **lighting attributes**
  - glLight, glLightModel, glMaterial

Primitive assembly

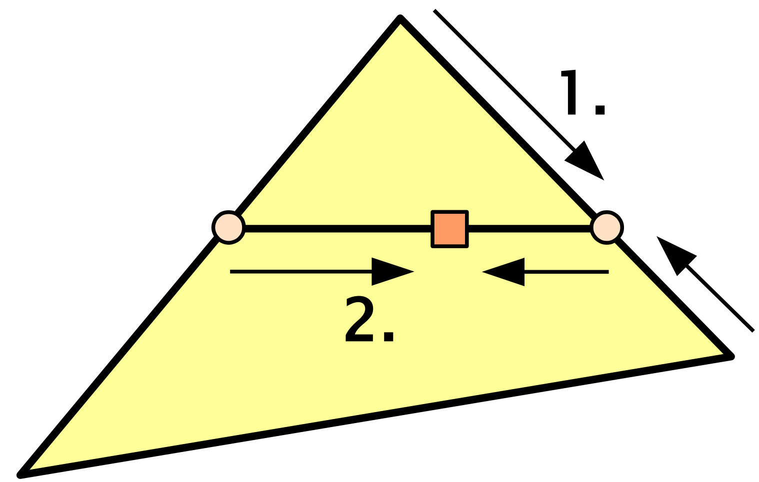
- **primitive assembly**
  - how many vertices the primitive needs
  - assembly and dispatch of the data
- **primitive processing**
  - clipping
  - projection into a frustum, division by "w"
  - projection and clipping into a 2D window ("viewport")
  - optional back-face culling
    - single- vs. double-sided triangles

Rasterization, fragments

- **rasterization**
  - decomposition of a primitive into a set of **fragments**
  - objects: points, line segments, triangles, bitmaps
- **fragment**
  - **raster element**, potentially contributing to a pixel color
  - size: equal or smaller than a pixel (anti-aliasing)
  - “data packet” passing through a raster part of a GPU:
    - input/output: **x**, **y**, **z** (only depth is mutable)
    - optional texture coordinates $\mathbf{t}_0$ to $\mathbf{t}_n$
    - specular & diffuse color, fog coefficient, user data, ...
    - output: **RGB** color and opacity $\boldsymbol{\alpha}$ (further frame-buffer op.)

Fragment data interpolation

- fragment attributes are **interpolated from values in vertices**:
  - depth (**z** or **w**)
  - texture coordinates
  - colors (specular, diffuse color)
  - user attributes, …



- fast **HW interpolators**
- **perspective correct** interpolation
  - only [**x**, **y**] is changing linearly
  - other values need one division per fragment

Fragment processing

- **texturing operations**
  - very good **optimization**
  - data fetch from texture memory
  - texel interpolation
    - mip-mapping, anisotropic filtering, …
  - multi-texturing (many operations for combining colors)
  - special effects (bump-mapping, environment mapping)
- **fog** computation
  - depends on **z** value
- primary & secondary color combination (diff., spec.)

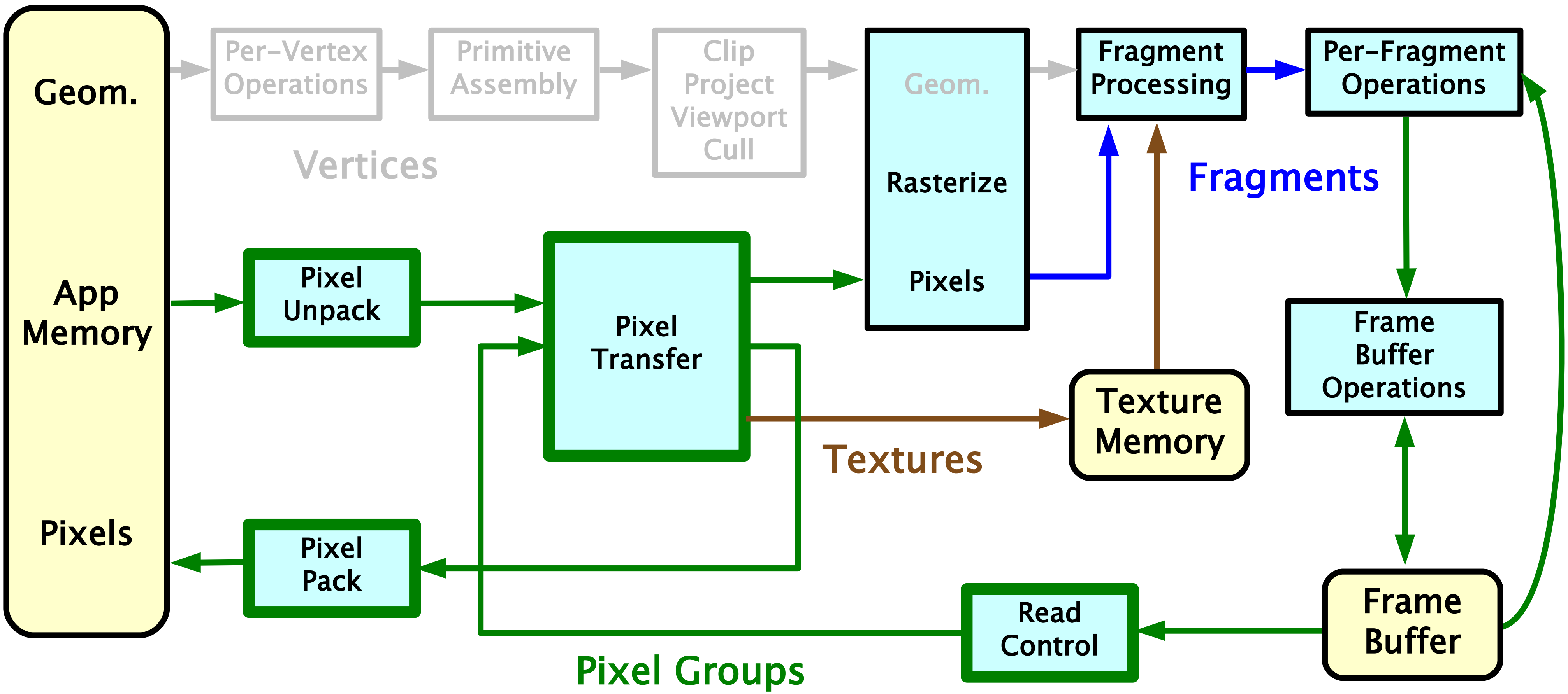
Fragment utilization (“per–fragm. op.”)

- **user area clipping** (glScissor)
- **transparency** rejection test (glAlphaFunc)
- **stencil test** (glStencilOp) * **write**
- **depth test** (glDepthFunc) *
- **color blending** (transparency) *
- **sRGB conversion**
- **dithering** (shallow frame-buffers)
- **logical operation** (glLogicOp) *

Global frame-buffer operations

- **frame-buffers**
  - front, back, left, right, … (double-buffering, stereo)
  - set current rendering buffer (glDrawBuffer)
- **buffer initialization** (glClear)
  - glClearColor, glClearDepth, glClearStencil, glClearAccum
- **graphic server control** operations
  - glFlush: flush all intermediate buffers
  - glFinish: finish all current-context rendering

Raster images in OpenGL



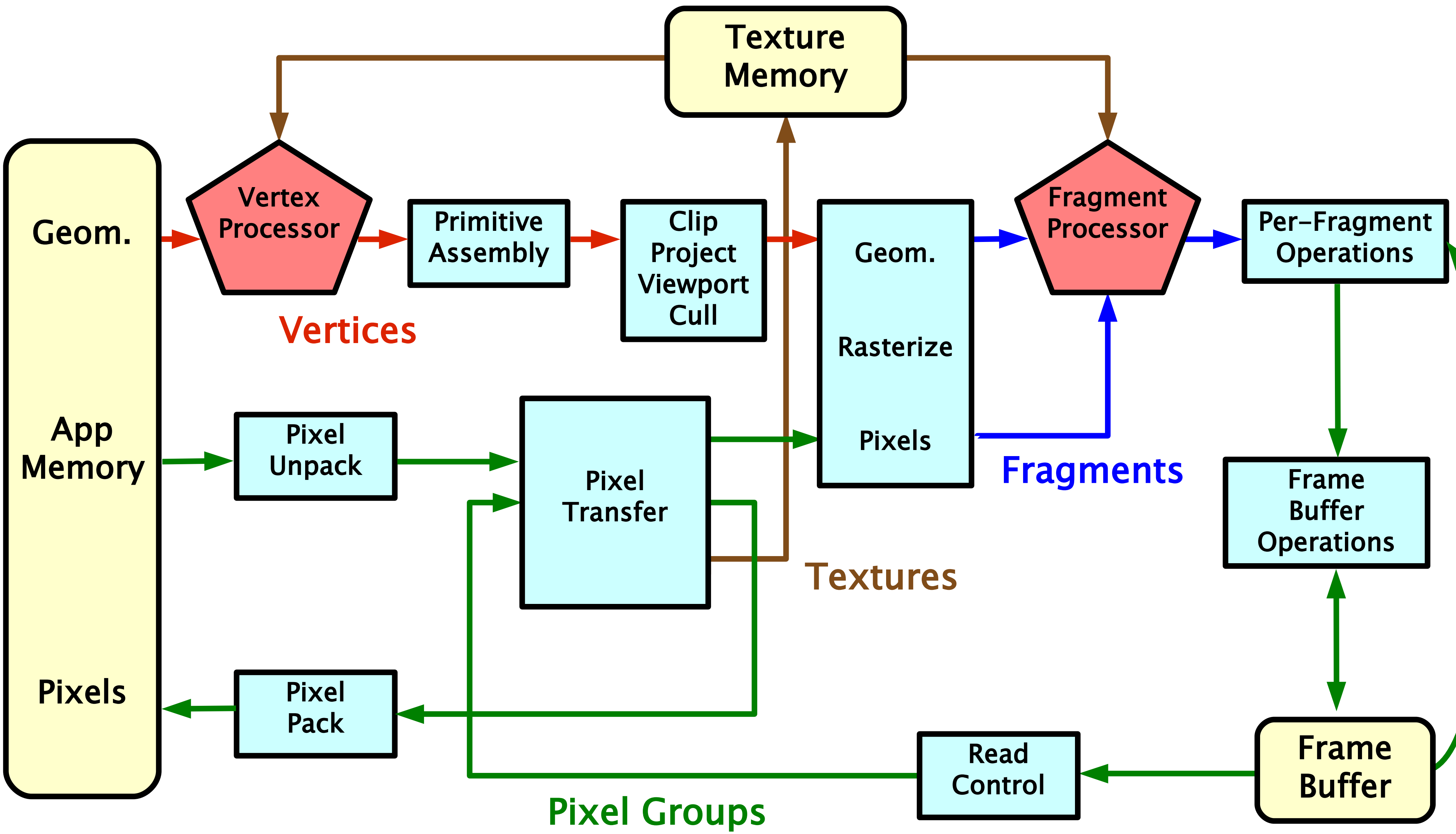
Raster image transfer

- **application memory → frame-buffer**
  - by rasterization (convert bitmap to fragments)
  - glDrawPixels, glBitmap
- **application memory → texture memory**
  - only using “unpacking” and “pixel transfer”
  - glTexImage, glTexSubImage
- **transfer inside GPU**
  - glCopyPixels: for frame-buffer[s]
  - glCopyTexImage, glCopyTexSubImage: target = texture
- **frame-buffer → application memory**
  - glReadPixels: used to be very slow operation (≤AGP)

Raster conversions and other op.

- “**pixel unpacking**”
  - conversion from app format to OpenGL format (“coherent stream of pixels”, „group of pixels”)
  - { RGB[α] | depth | stencil } [][]
  - source format, scanline length (stride), offsets, ...
  - setting: glPixelStore
- “**pixel packing**”
  - OpenGL format → app format
- “**pixel transfer**”
  - change: scale, intensity, general “LuT” operation
  - setting: glPixelTransfer, glPixelMap
  - extensions: convolution, other filters, histograms, ...

OpenGL (Programmable Pipeline)



Vertex processor

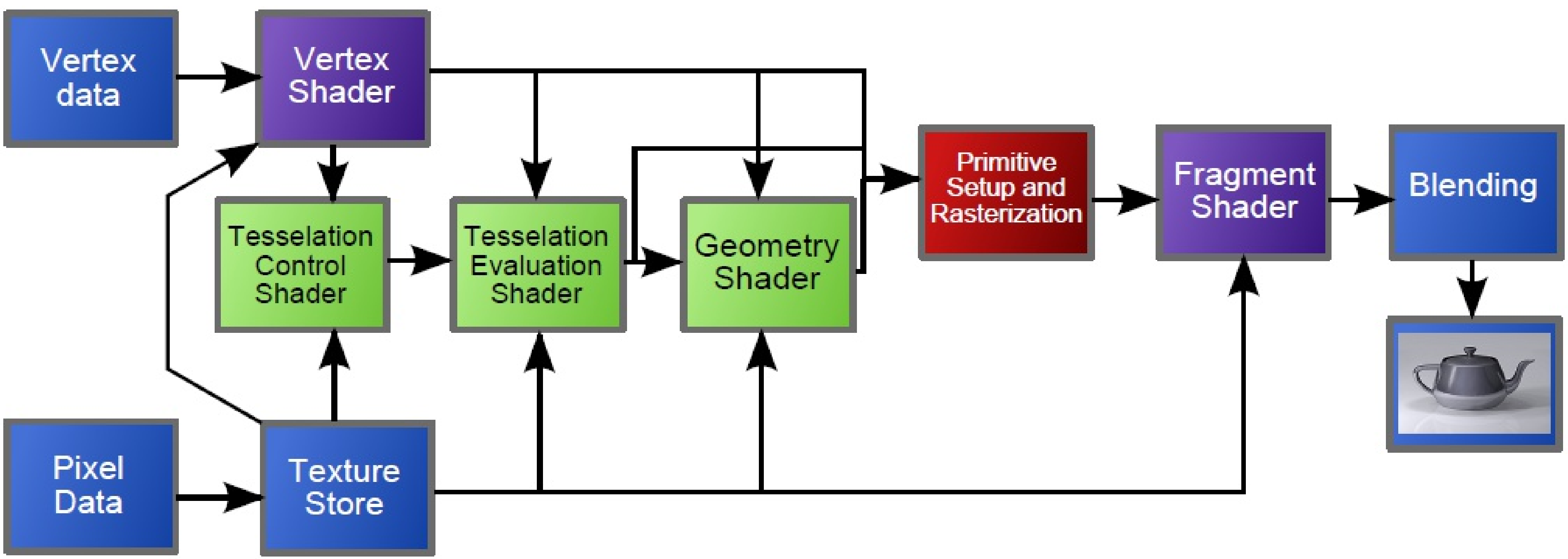
- replaces the **vertex processing unit** in FFP
  - vertex coordinate transform
  - normal vector transform and normalization
  - computing/transformation of texturing coordinates
  - lighting vectors
  - setup of material attributes
- **cannot modify**
  - **number of vertices**
    - partial solution: primitive degeneration
  - type / topology of geometric primitives

Fragment processor

- replaces **fragment processing unit** in FFP
  - arbitrary arithmetic on fragment attributes
  - texture data fetch and application (color, etc.)
  - fog computation
  - output fragment color synthesis
  - fragment depth can be modified
- **cannot modify**
  - **number of fragments** (except for the "discard" operation)
  - **fragment position** within the viewport [x,y]

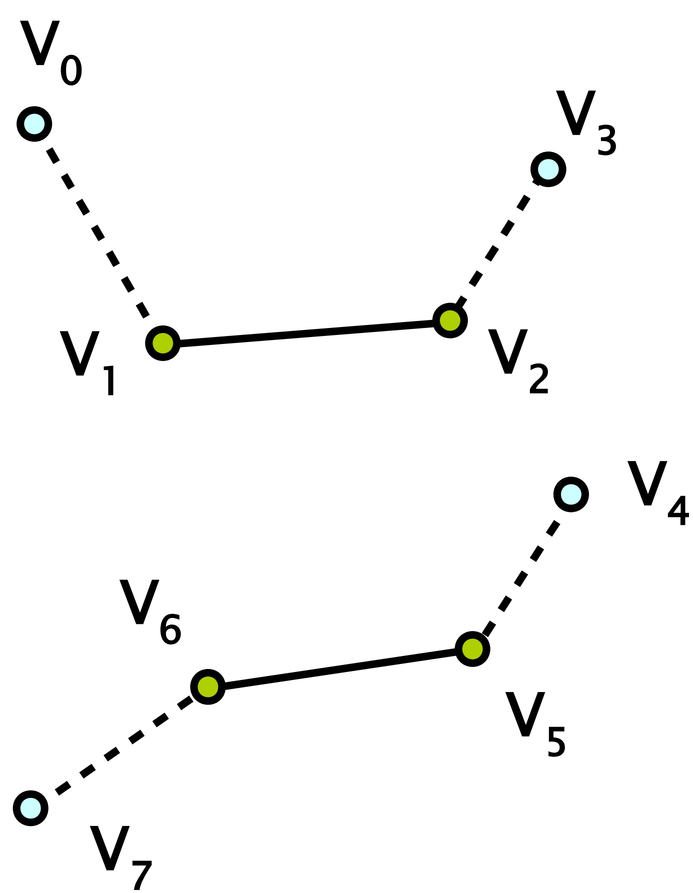
Recent innovations (2009–2010)

- two more **geometry processing steps on a GPU**
  - geometry shader (OpenGL 3.2)
  - tesselation shaders (OpenGL 4.0)

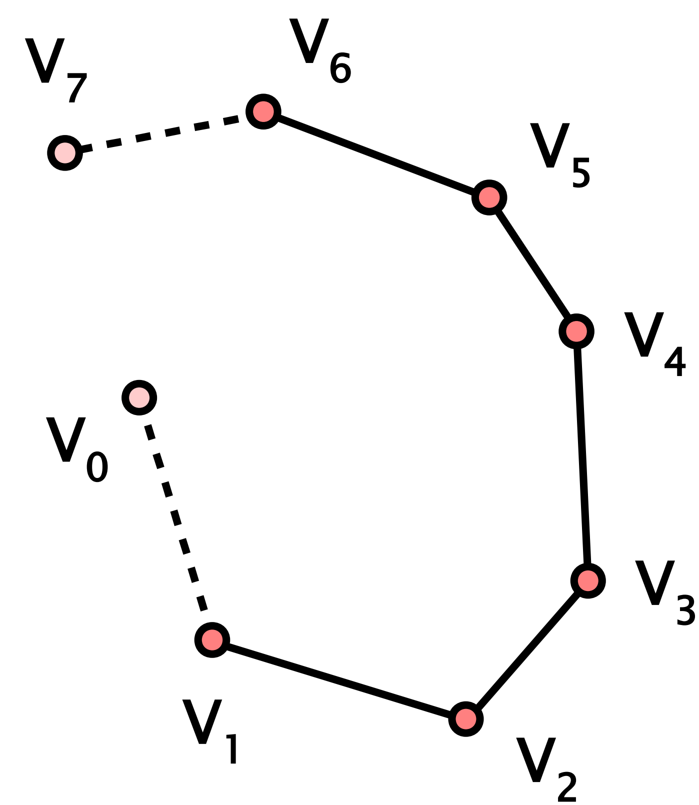


Geometric primitives IV

GL_LINES_ADJACENCY

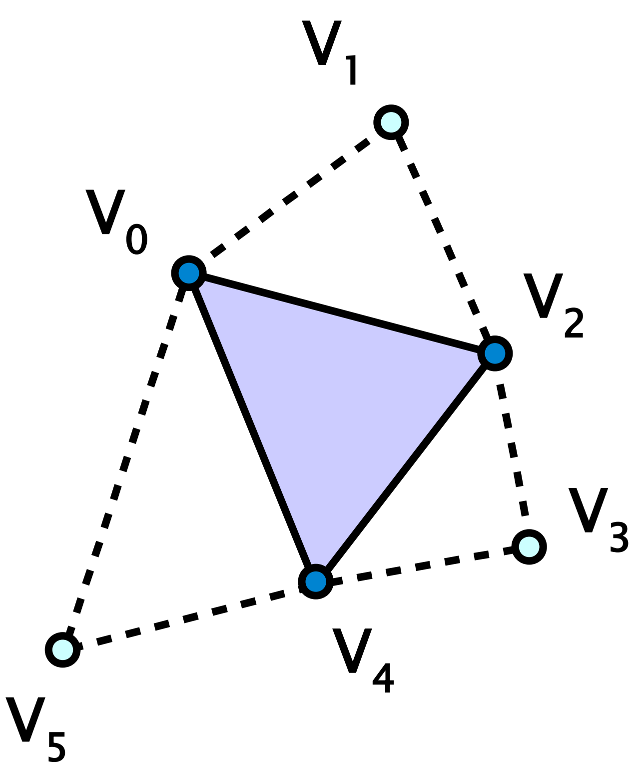


GL_LINE_STRIP_ADJACENCY

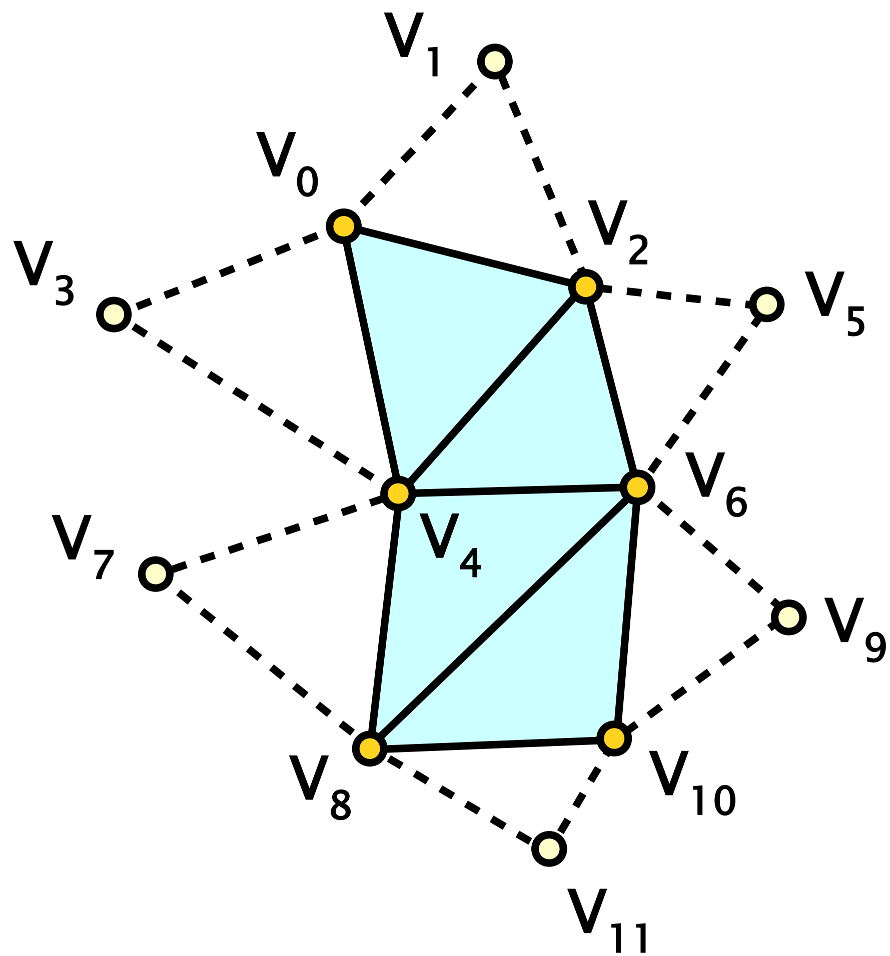


Geometric primitives V

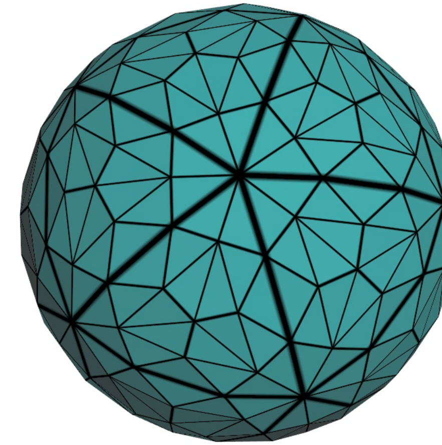
GL_TRIANGLES_ADJACENCY



GL_TRIANGLE_STRIP_ADJACENCY



Geometric processors



- **“Tesselation shaders”**
  - new in OpenGL 4.0
  - HW-supported surface division, subdivision (spline patches..)
  - new shaders: “tesselation control“ and “tesselation evaluation“
  - the former defines topology, the later actually computes new geometry (coefficients)
- **“Geometry shader”**
  - since OpenGL 3.2
  - just before primitive assembly & rasterizer
  - capability to create/discard vertices and primitives
  - more general than TS but less efficient (unadvisable for simple [sub]division schemes)

GPU programming

- **“Vertex shader”, “Fragment shader”**, …
  - custom machine code executed in a vertex-, fragment-, … processor
- application programmer is able to deploy his own code
  - **HW independent*** programming languages
  - **microcode for GPU** is compiled at run-time and can be effectively optimized (various profiles/versions, ..)
  - low-level instructions (assembler-like code)
  - or **high-level languages** Cg, HLSL, GLSL (similar)

NVIDIA Microsoft OpenGL

OpenGL 3.x

- **removed: FFP and immediate mode** (glBegin/glEnd)
- **new:** contextual profiles for future removal of obsolete functionality
- **new:** floating-point textures
- **new:** HW instancing
- **new:** geometry shaders (creating/discarding geometric primitives on the GPU)
- **GLSL 1.3-1.5**
  - native bitwise operations, integer arithmetic, ...

OpenGL 4.x

- **new:** HW tesselation
  - Tesselation Control Shaders, Tesselation Evaluation Shaders
  - GL_PATCHES, GL_TRIANGLES_ADJACENCY primitives
- **new:** direct connection to external computing API (OpenCL) w/o CPU intermediation
- **new:** binary storage of compiled shaders
- **GLSL 4.0**
  - 64-bit floating point computing support
  - shader subroutines
  - separable shader programs

Sources

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- OpenGL Architecture Review Board: ***OpenGL Programming Guide: The Official Guide to Learning OpenGL***, Addison-Wesley, latest edition (8th edition for the OpenGL 4.1)
- Christophe Riccino: **OpenGL reviews**, http://www.g-truc.net/post-opengl-review.html