Lecture 4:
Geometry Processing

Kayvon Fatahalian
CMU 15-869: Graphics and Imaging Architectures (Fall 2011)

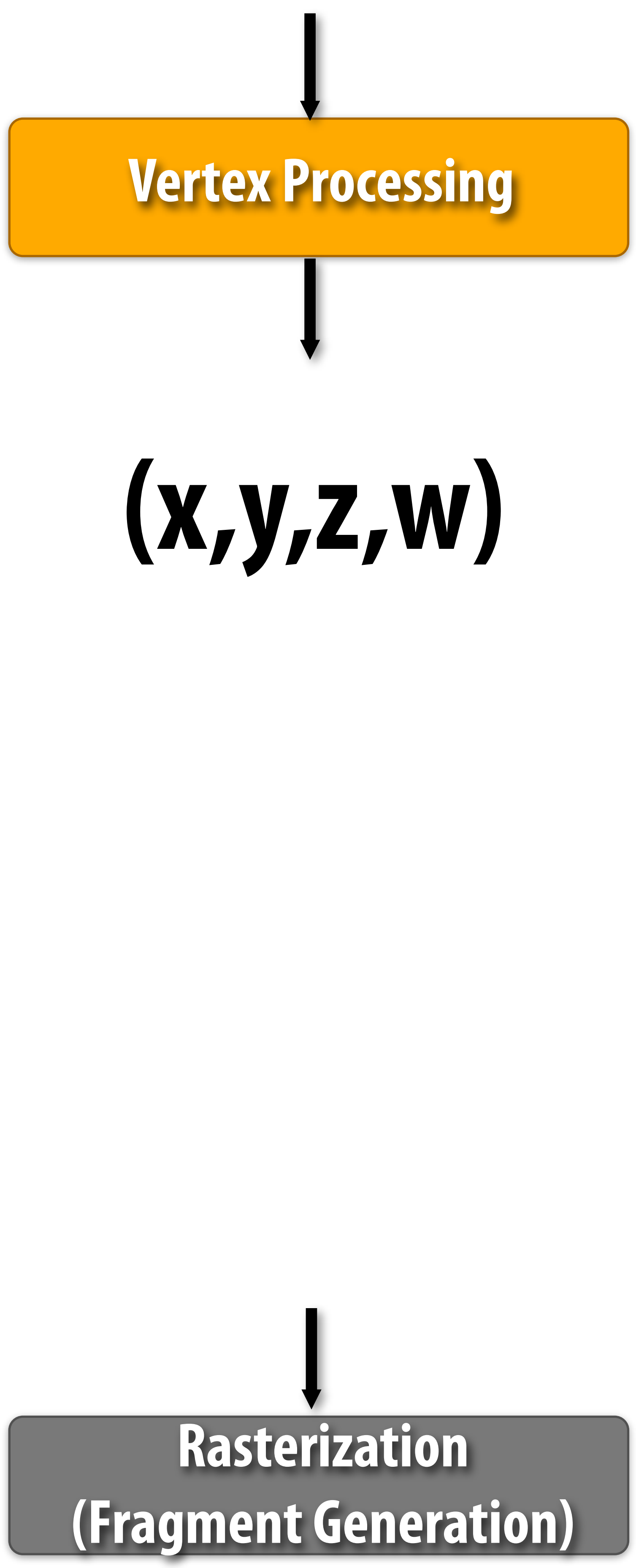
Today

- Key per-primitive operations (clipping, culling)

Various slides credit John Owens, Kurt Akeley, and Pat Hanrahan

- Programmable primitive generation
  - Geometry shader
  - Modern GPU tessellation

Recall: in a modern graphics pipeline, application-specified logic computes vertex positions



Vertex positions emitted by vertex processing (or the geometry shader, if enabled) are represented in homogeneous clip-space coordinates.

Vertex is within the view frustum if:

$-w \leq x \leq w$

$-w \leq y \leq w$

$-w \leq z \leq w$

Vertex's position in euclidian space is (x/w, y/w, z/w)

Per primitive operations

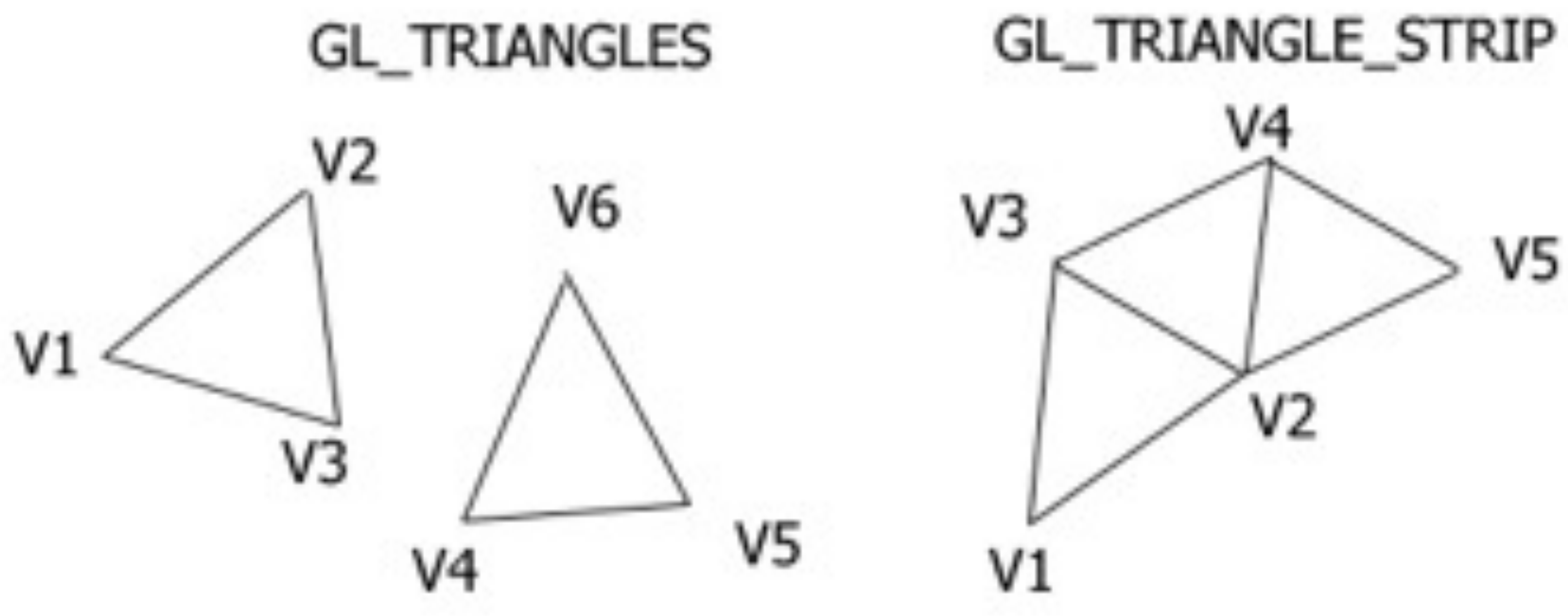
Assemble vertices into primitives

Clip primitive against view frustum

For each resulting primitive

- Divide by w
- Apply viewport transform
- Discard back-facing primitives [optional, depends on config]

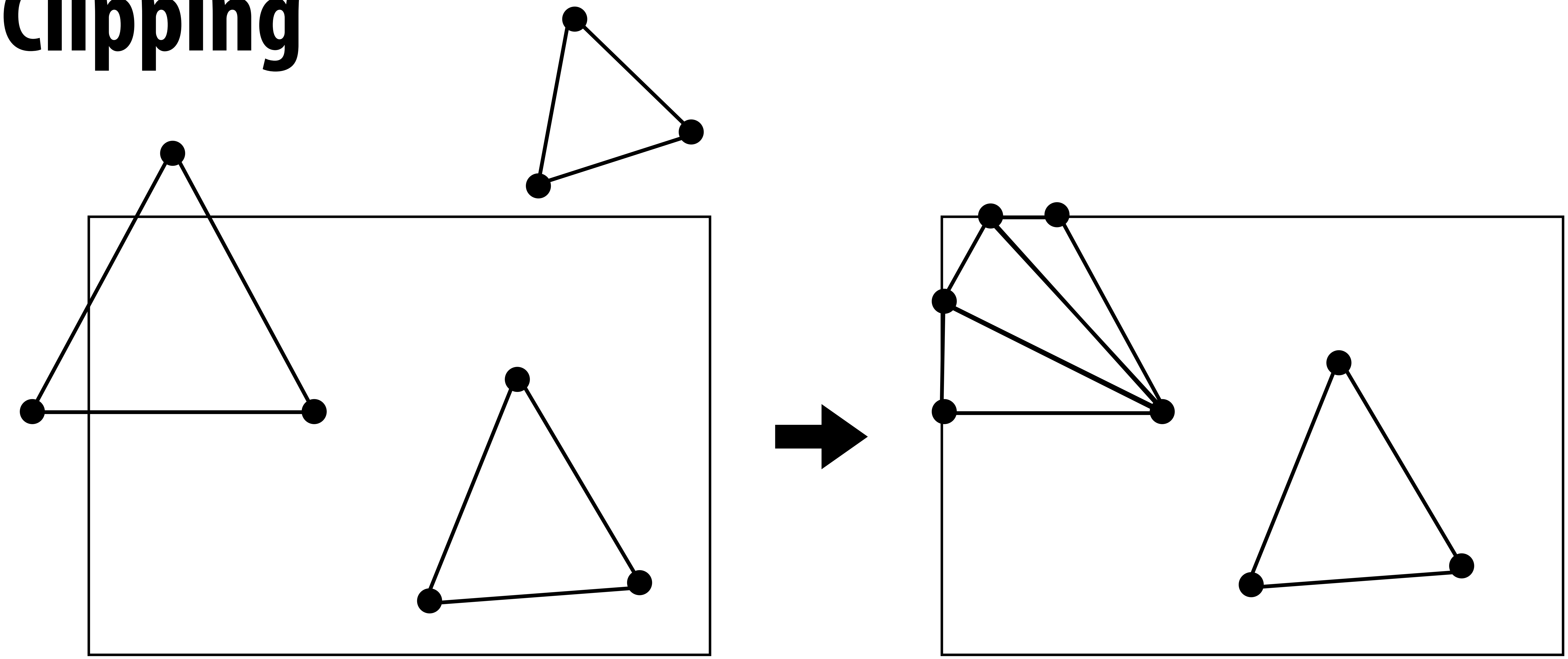
Assembling vertices into primitives



How to assemble is part of graphics state (specified by draw command)

Notice: independent vertices get grouped into primitives (dependency!)

Clipping



- May generate new vertices/primitives, or eliminate vertices/primitives
- Data-dependent computation
  - variable amount of work per primitive
  - variable control flow per primitive

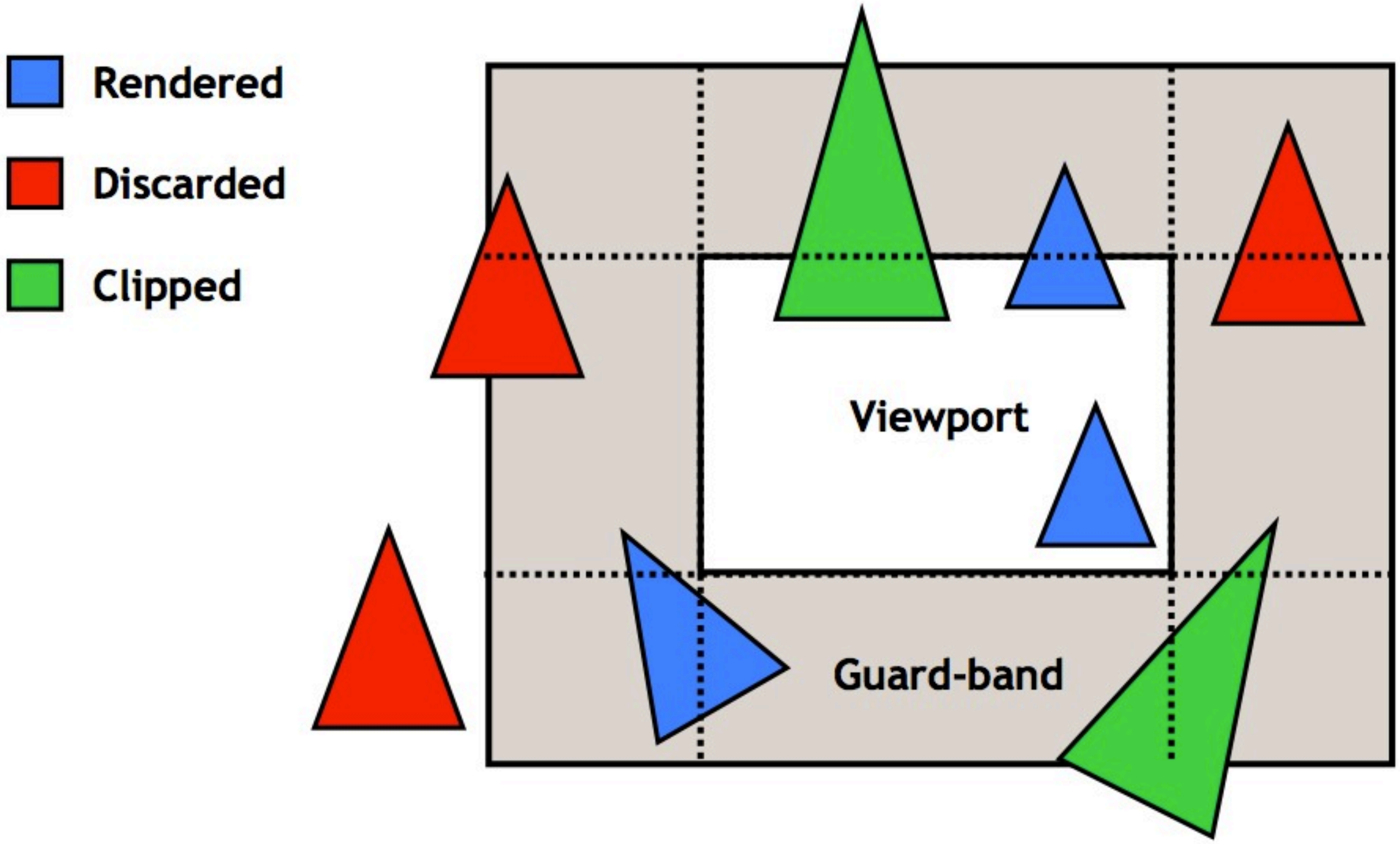
Why clipping?

- Avoid downstream processing that will not contribute to image (rasterization, fragment processing)
- Establish invariants for emitted primitives
  - Can safely divide by w after clipping
  - Bounds on vertex positions (can now choose precision of subsequent operations accordingly)

Guard-band clipping

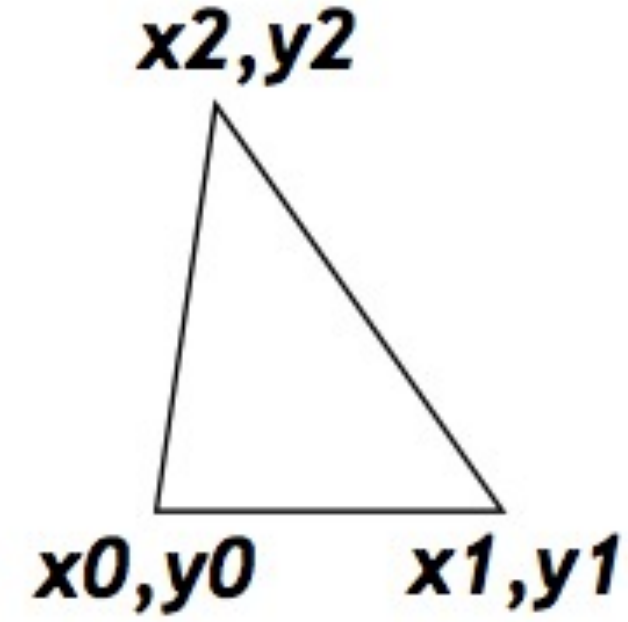
[RealityEngine, Akeley 93]

- Reduces variance in per-primitive clipping work
- Cost (conservative: primitives no longer guaranteed to be fully on screen)
  - Rasterizer must not generate off-screen fragments
  - Increased precision needed during rasterization



Back-face culling

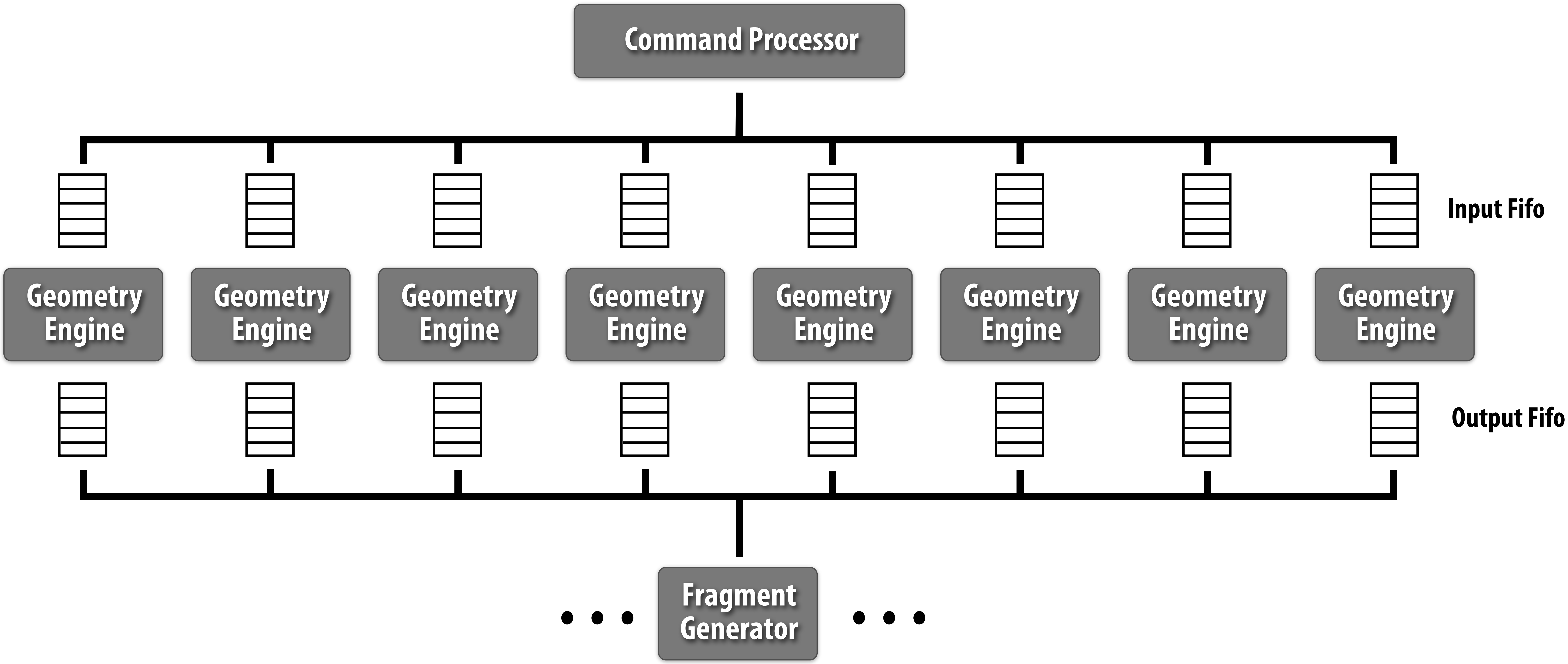
- Use sign of triangle area to determine if triangle is facing toward or away from camera
- May discard primitive as a result of this test
  - For closed meshes, eliminates ~ 1/2 of triangles (these triangles will be occluded anyway)



$$\text{Triangle area} = \frac{(x0y1 - x1y0) + (x1y2 - x2y1) + (x2y0 - x0y2)}{2}$$

SGI Reality Engine 1992

[Akeley 93]



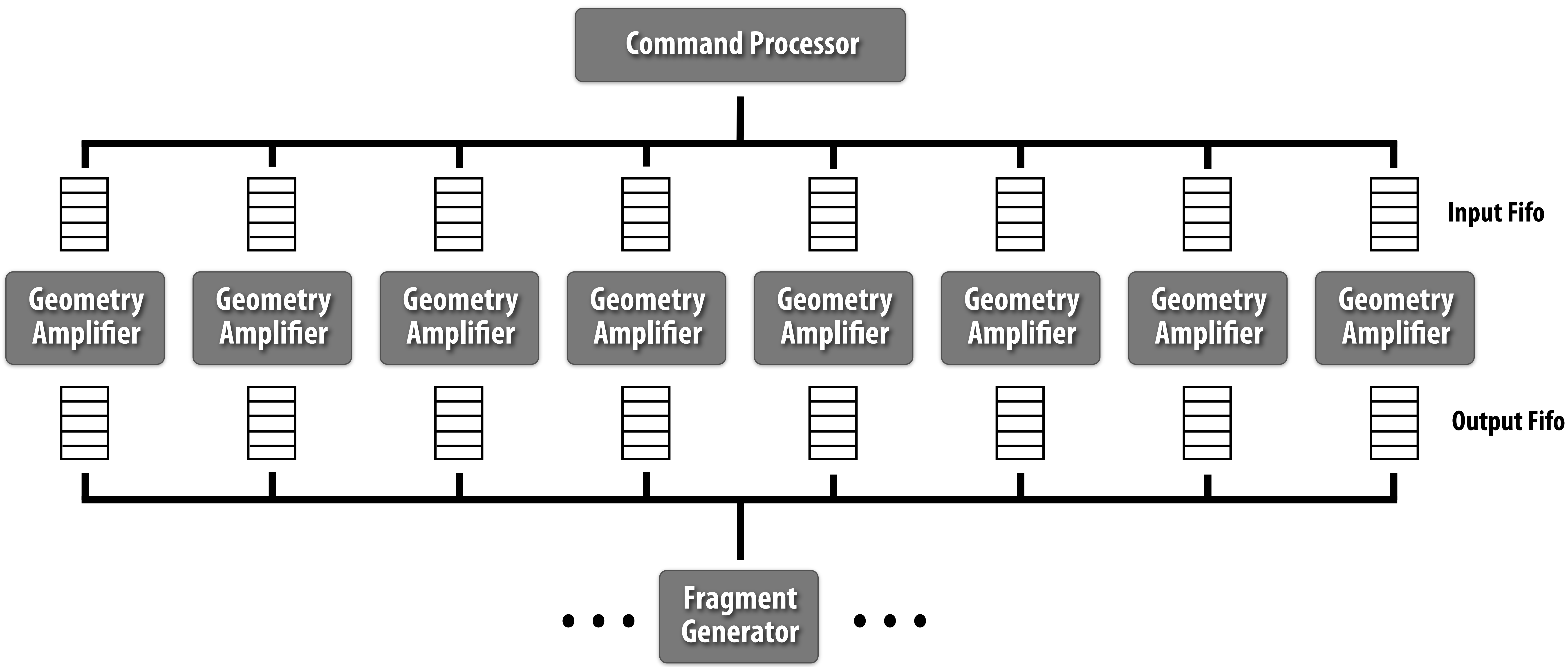
- Divide triangle strips from application into small strips, round robin to geometry engines
- Buffers absorb variance in amount of work per triangle

Programmable geometry amplification

- Amplification by "geometry shader" or tessellation functionality in a modern pipeline is far greater than that of clipping
- Geometry shader: output up to 1024 floats worth of vertices per input primitive
- Tessellation: thousands of vertices from a base primitive

Thought experiment

Assume maximum amplification factor is large (known statically)



Simple approach 1: make on-chip buffers as big as possible: run fast for low amplification

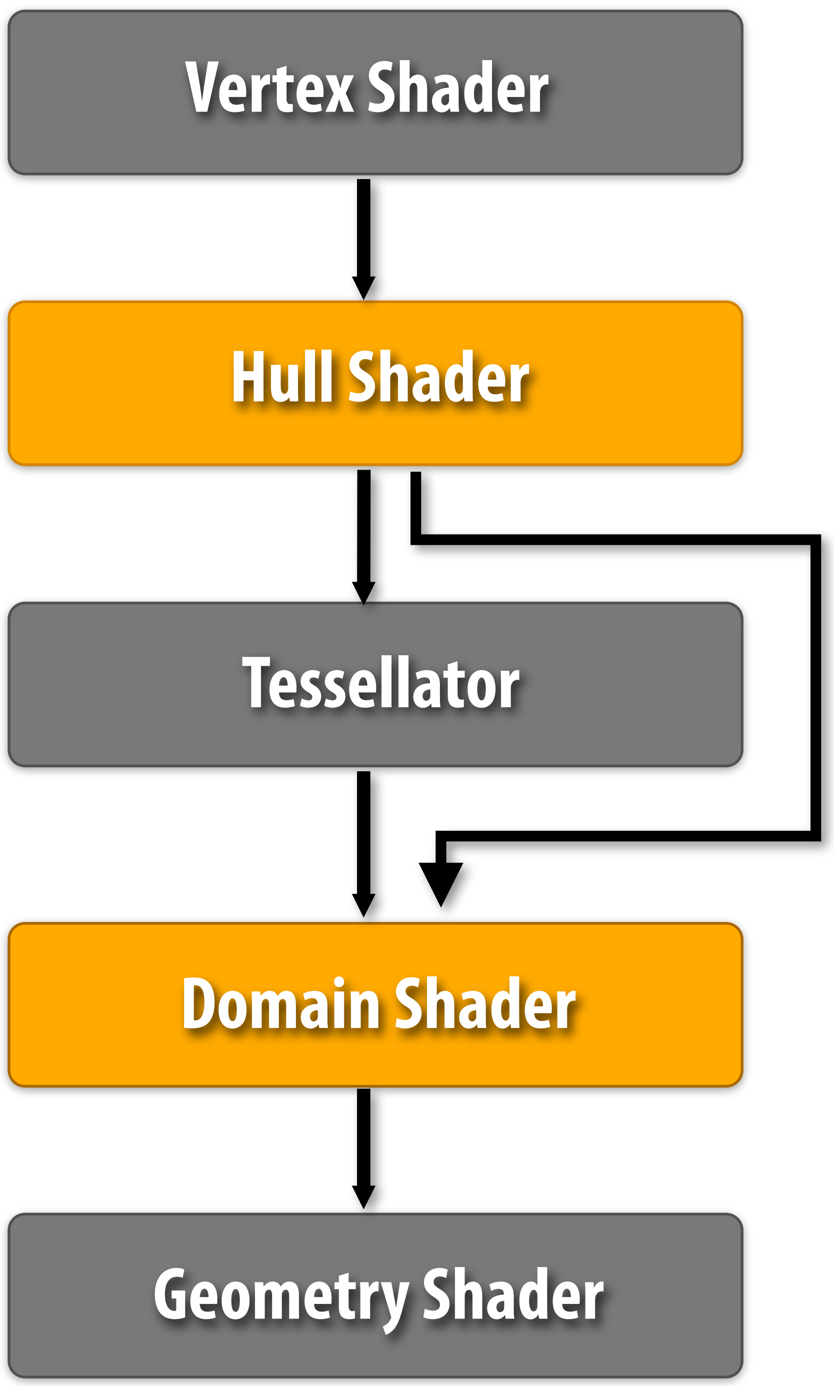
Simple approach 2: make huge FIFOs (store off-chip in memory)

Modern GPU tessellation [Moreton 01]

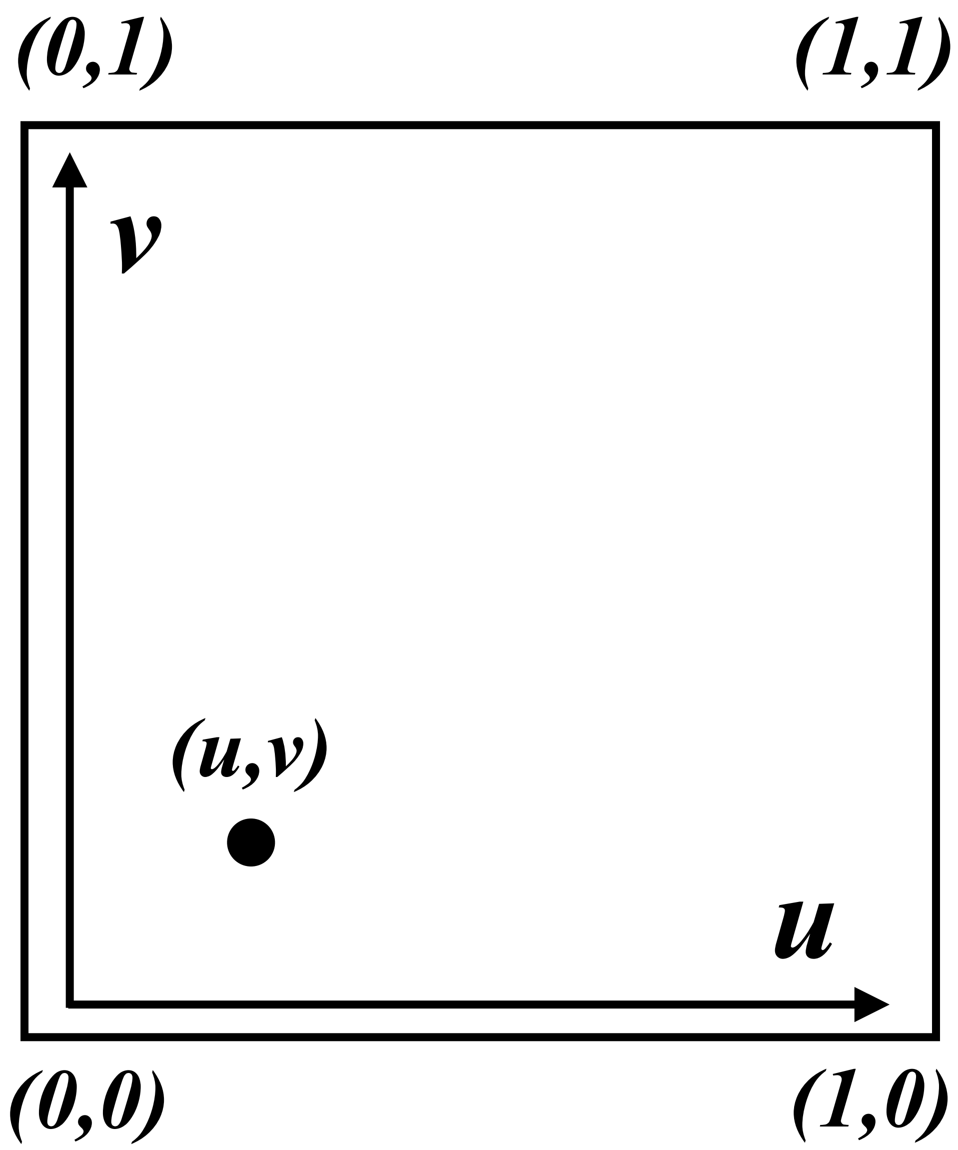
- Motivations:
  - Reduce CPU-GPU bandwidth
  - Animate/skin course resolution mesh, but render high resolution mesh

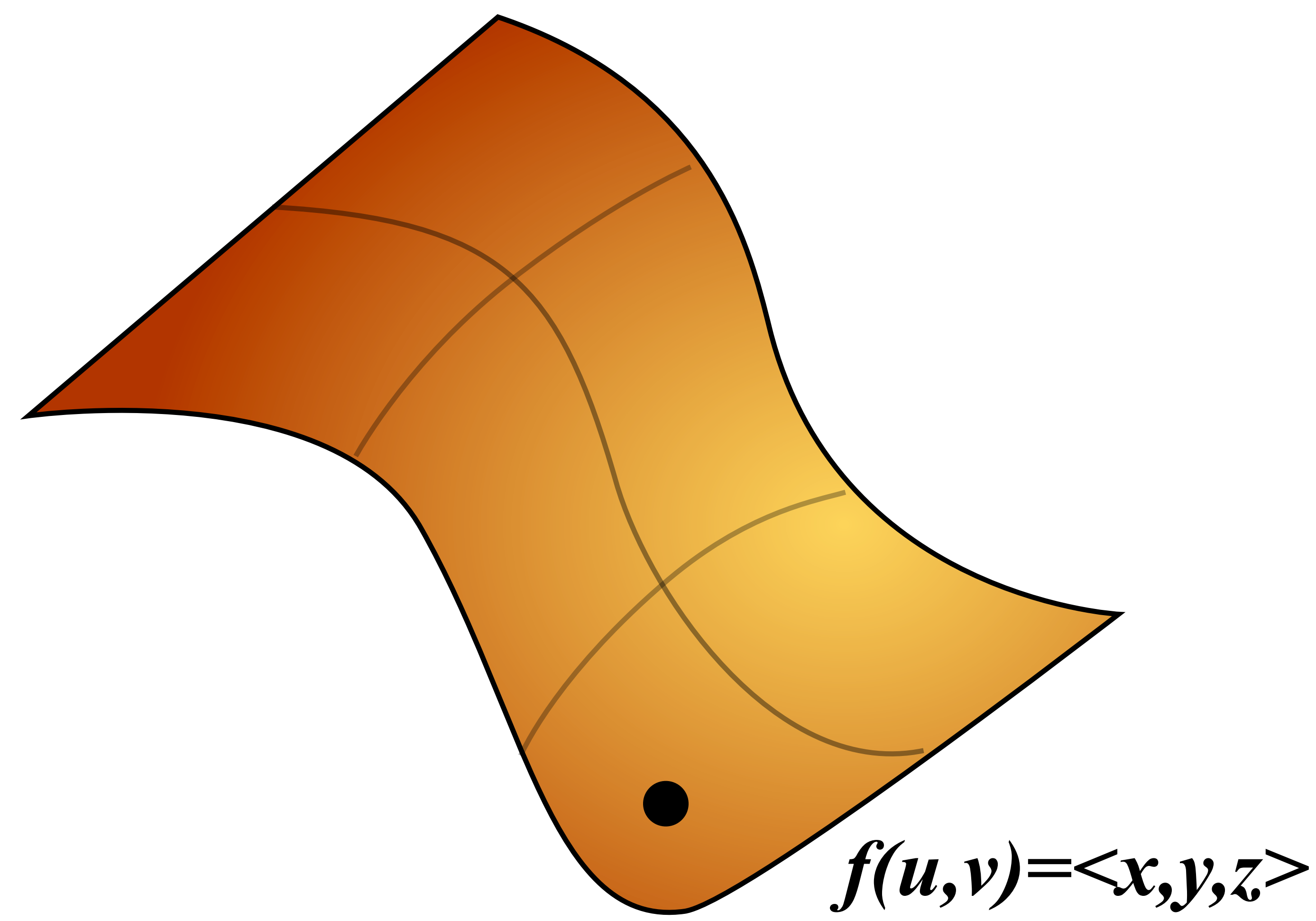
- Requires parametric surfaces (must support direct evaluation)

Note: D3D11 Stage Naming (not canonical stage names)



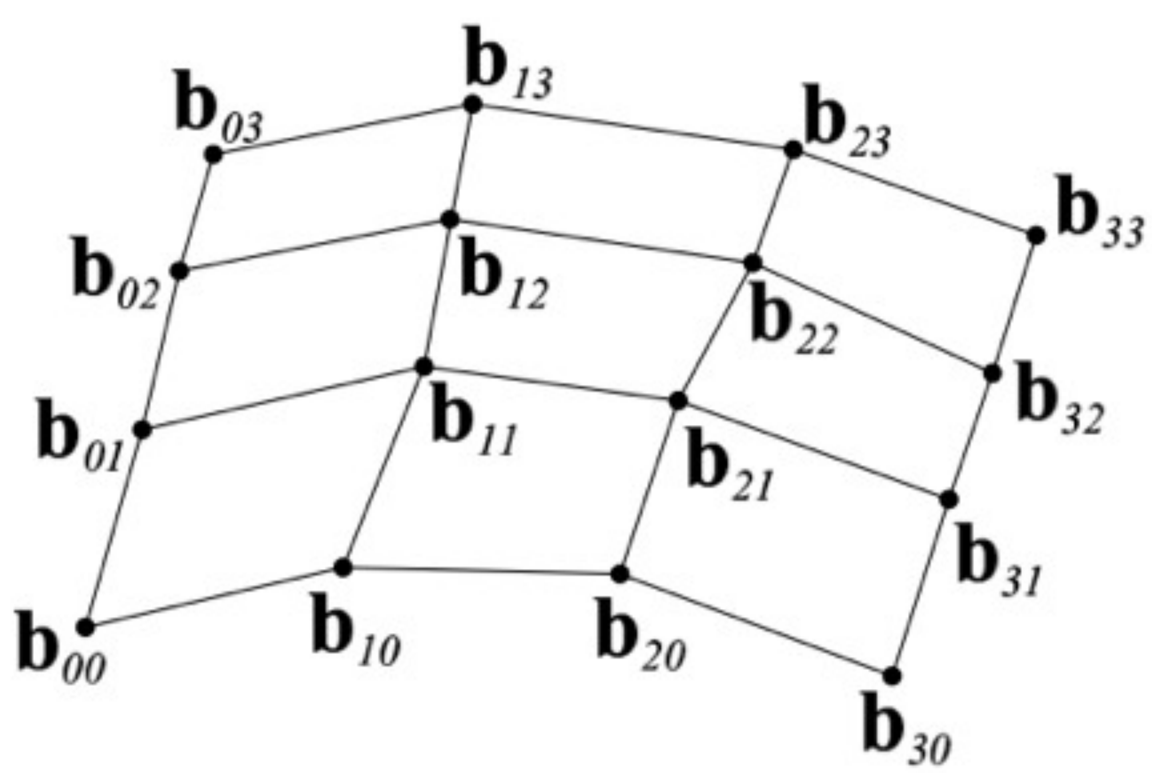
Parametric surface





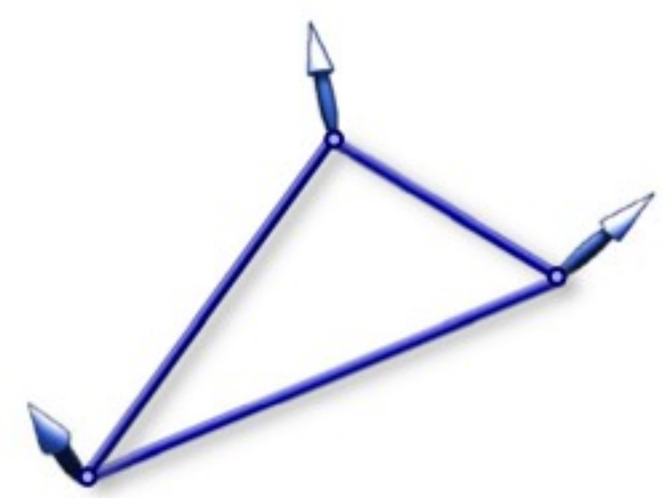
Parametric surfaces: common examples

Bicubic patch, 16 control points (quad domain)



See "Approximating Catmull-Clark Subdivision Surfaces With Bicubic Patches", Loop et al. 2008

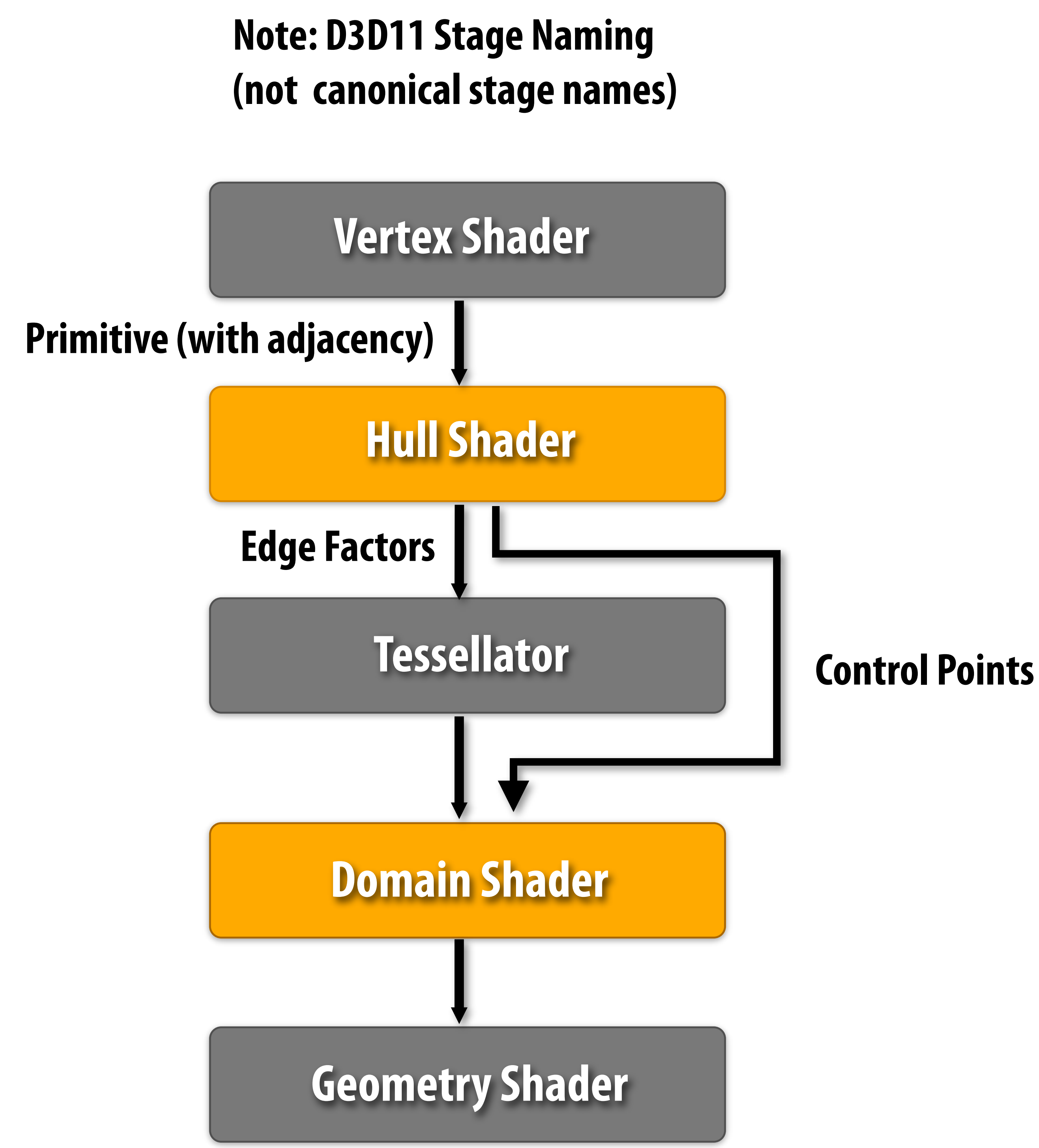
PN Triangles, 3 vertices + 3 normals (defines bezier patch on triangular domain)



See "Curves PN Triangles", Vlachos et al. 2008

Modern GPU tessellation

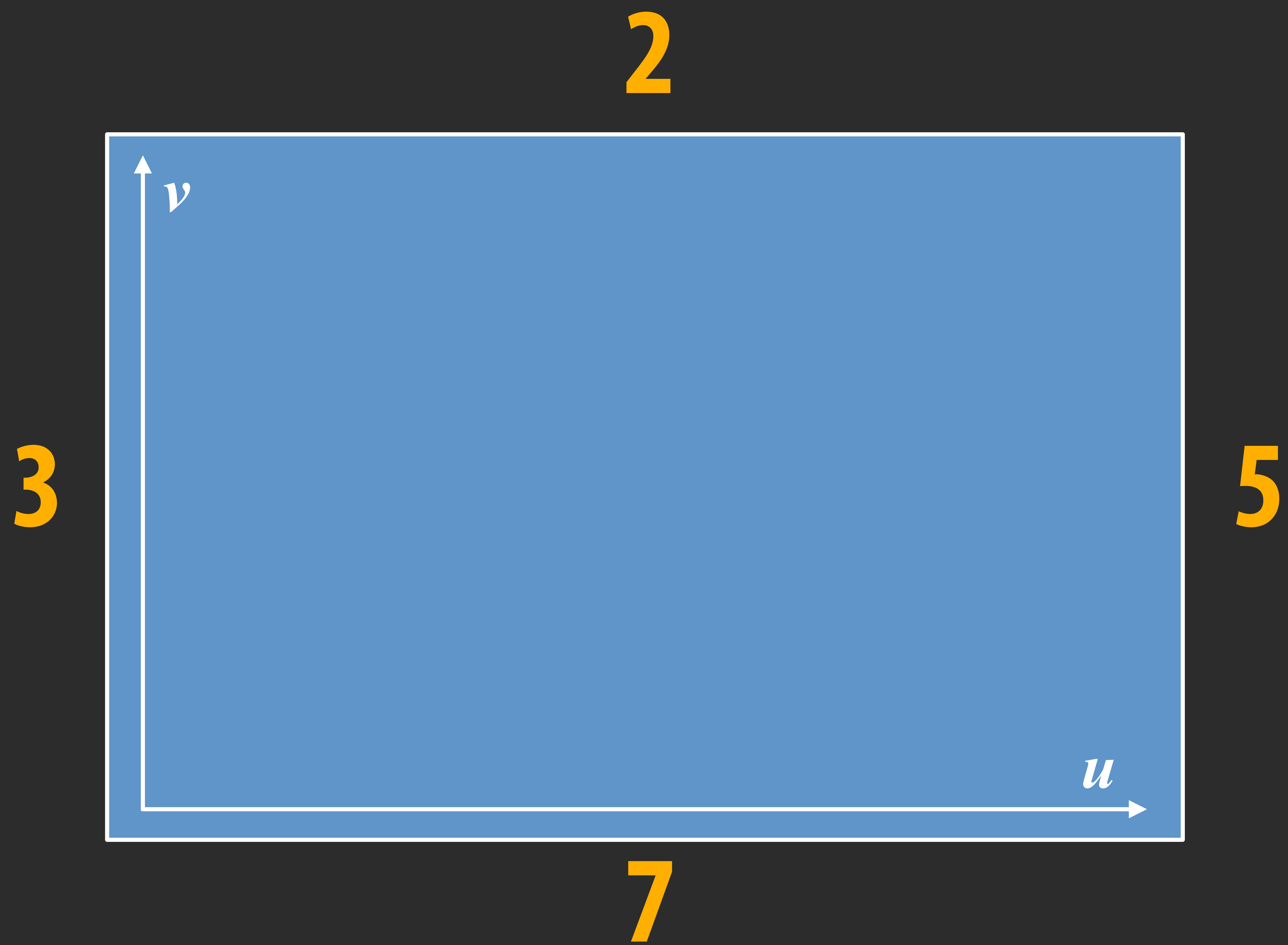
- Hull shader
  - Accepts primitives after traditional vertex processing
  - Computes tessellation factor along each domain edge
  - Computes control points for parametric surface (from primitive vertices)



Hull shader produces edge tessellation rates

Based on estimate of parametric surface position

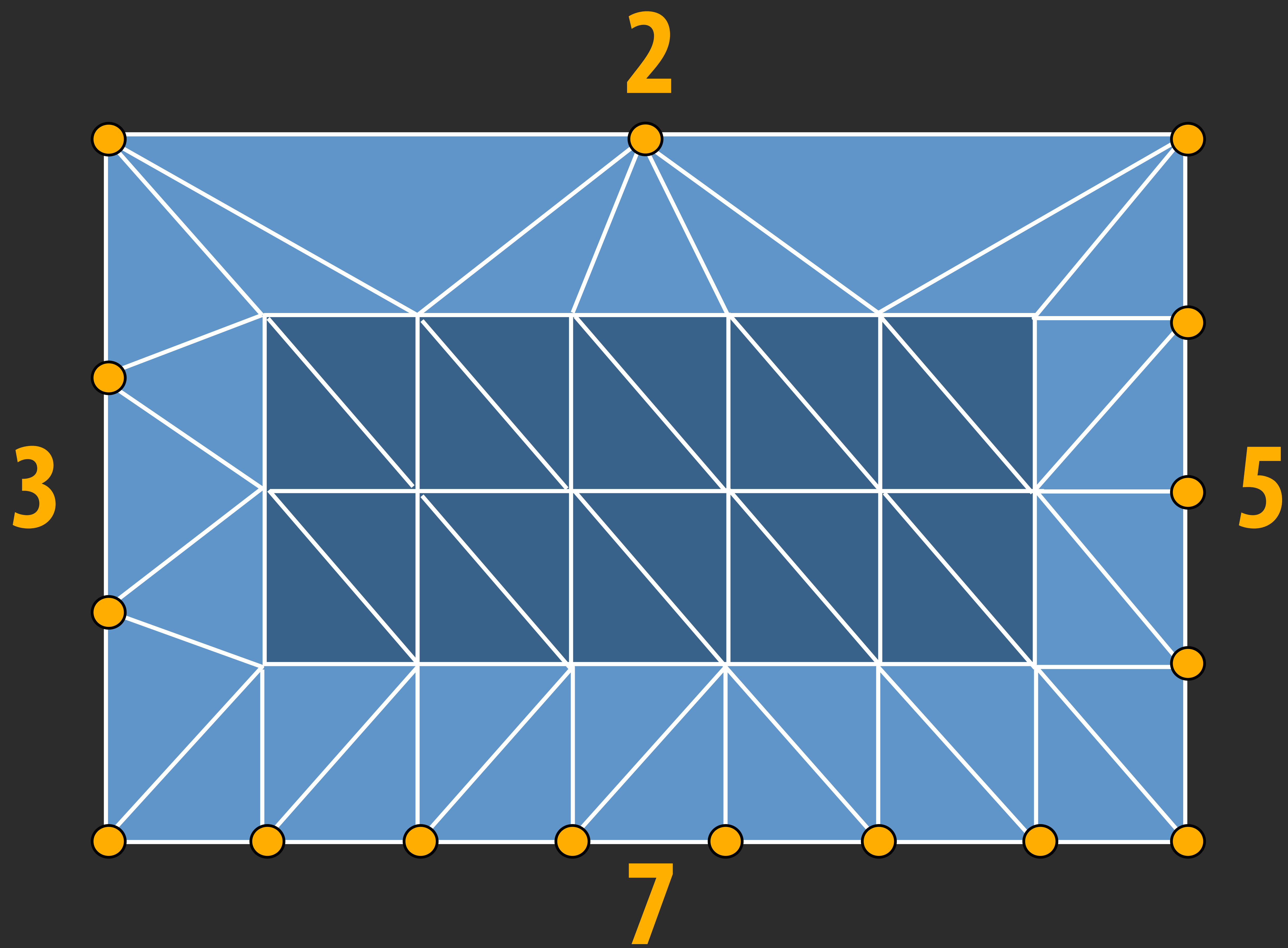
(Note: rates need not be integral)



Fixed-function tessellation stage

Input: edge tessellation constraints for a patch

Output: (almost) uniform mesh topology meeting constraints

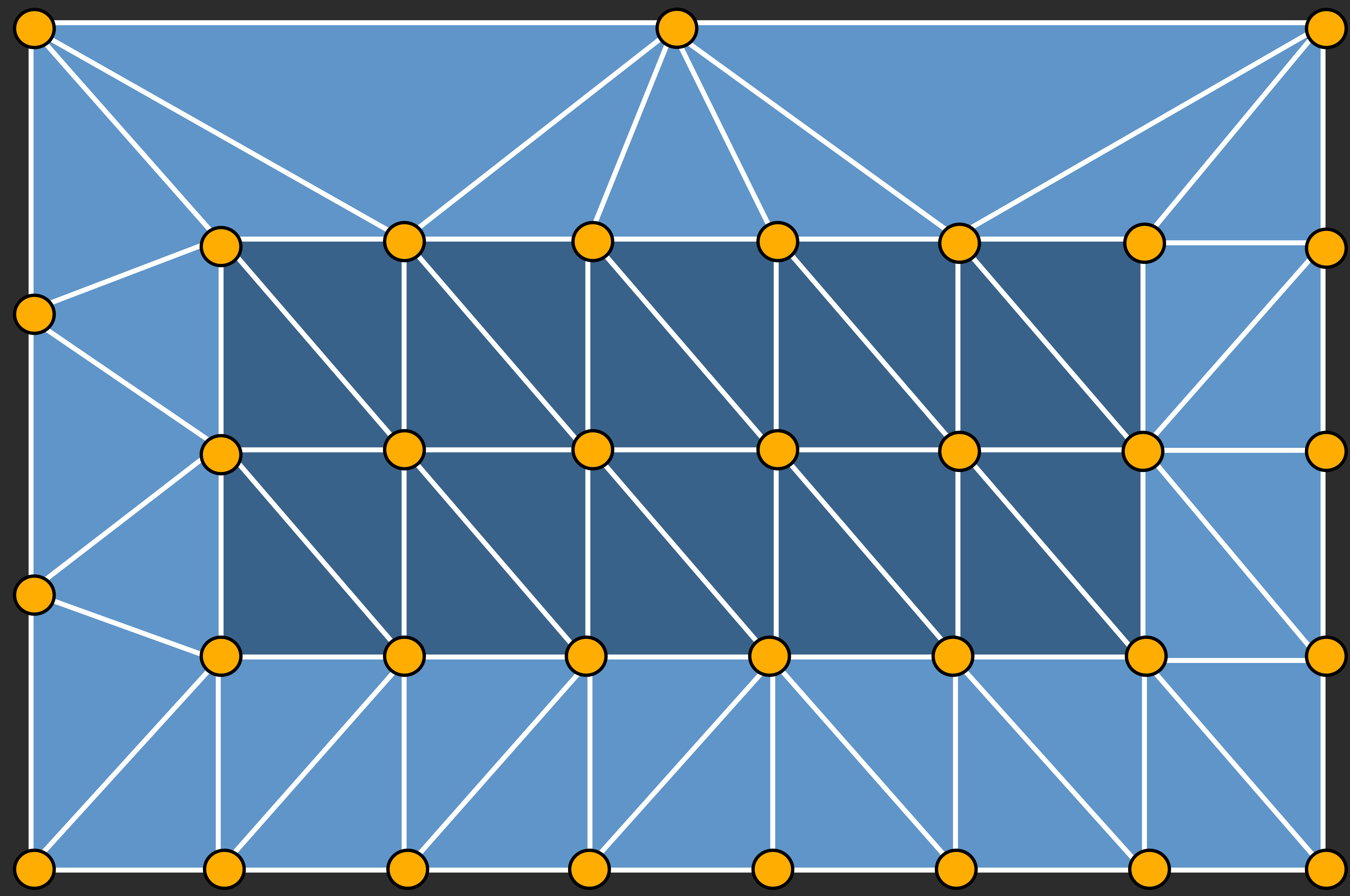


[Moreton 01]

Domain shader stage

Input: control points (from hull shader) and stream of parametric vertex locations (u,v) from tessellator

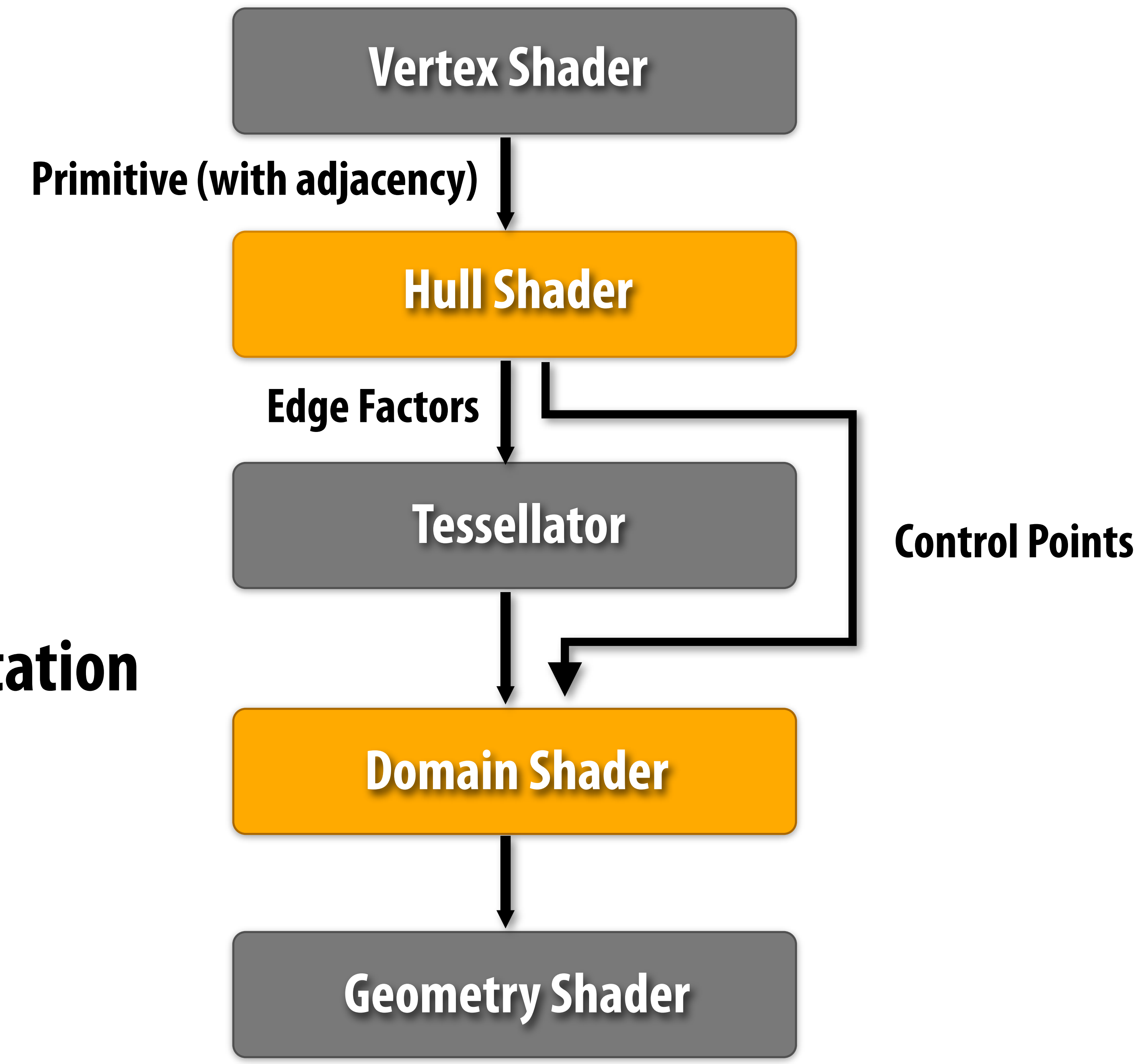
Output: position of vertex at parametric coordinate: $f(u,v)$



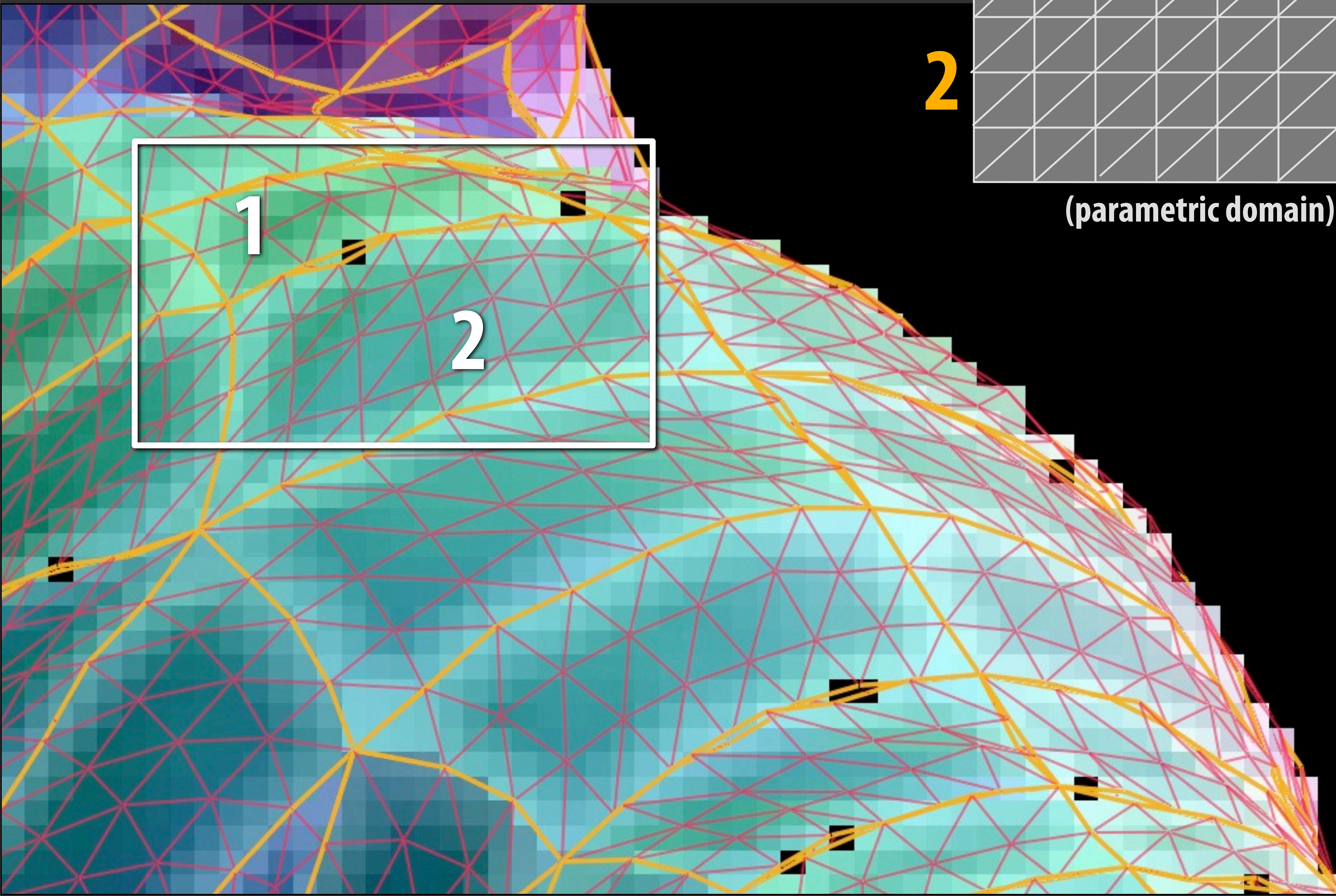
Modern GPU tessellation

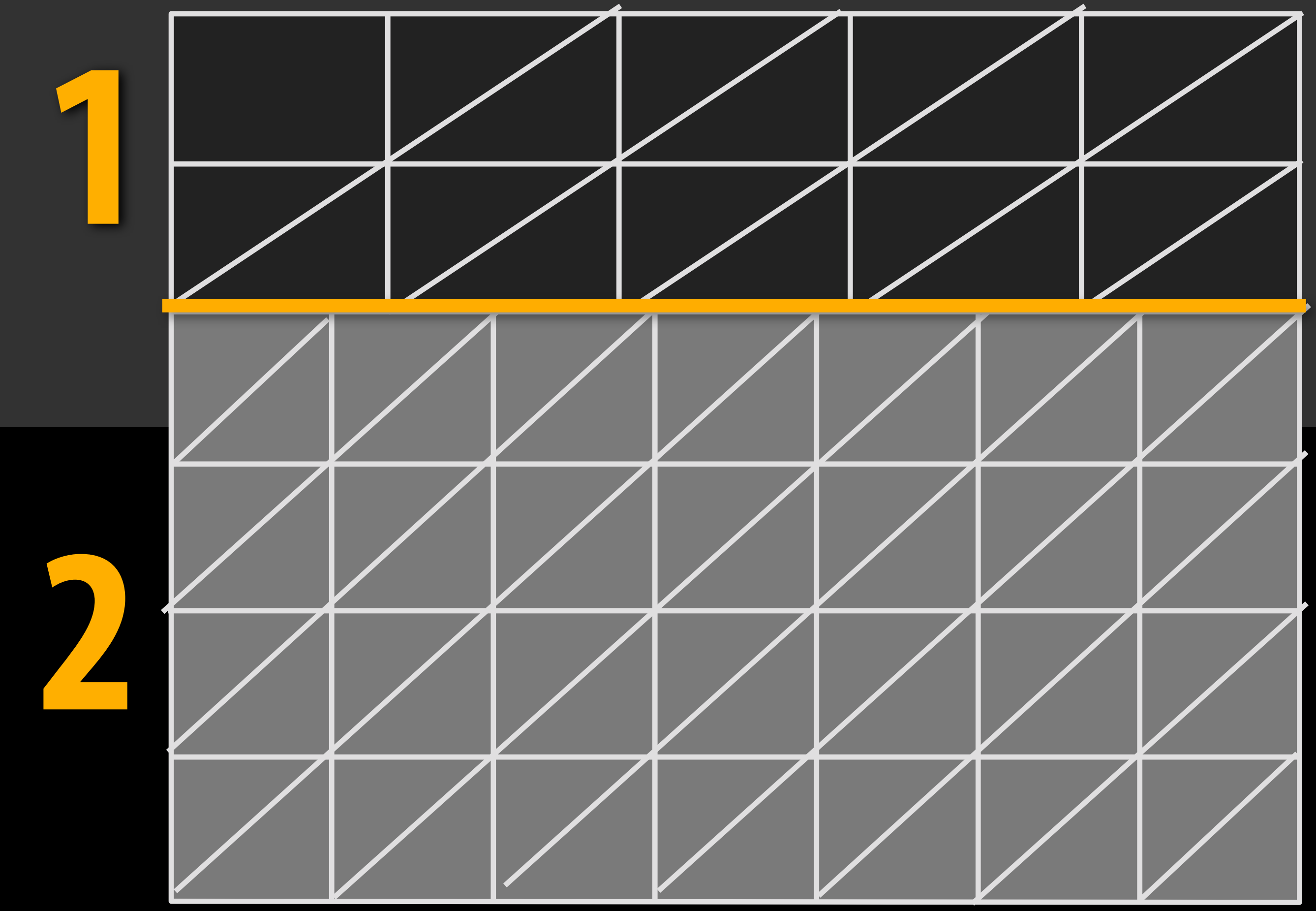
- Heterogeneous implementation
- Hull shader
  - Original primitive granularity
  - Data-parallel
  - Large working set (typically a primitive + one-ring)
- Tessellator
  - Surface agnostic, fixed-function hardware implementation
  - Irregular control flow
- Domain shader
  - Fine-mesh-vertex granularity
  - Data-parallel (preserves shader programming model)
  - Direct evaluation of surface (extra math, but data-parallel)

Note: D3D11 Stage Naming
(not canonical stage names)



Challenge: avoid cracks!





(parametric domain)

Modern GPU tessellation summary

- Heterogeneous, 3-stage implementation
  - Algorithms co-designed with pipeline abstractions and hardware

- Enables adaptive level-of-detail, high-resolution meshes in games

- Challenges
  - Application developer: avoiding cracks (requires consistent edge rate evaluation -- this is tricky in floating point math)
  - GPU implementor: managing large data amplification... while maintaining <u>parallelism</u>, <u>locality</u>, and <u>order</u>