Real-Time
Graphics Architecture

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http://www.graphics.stanford.edu/courses/cs448a-01-fall

Geometry

Outline

- Vertex and primitive operations
- System examples
  - emphasis on clipping
- Primitive generation
- OpenGL selection

Readings

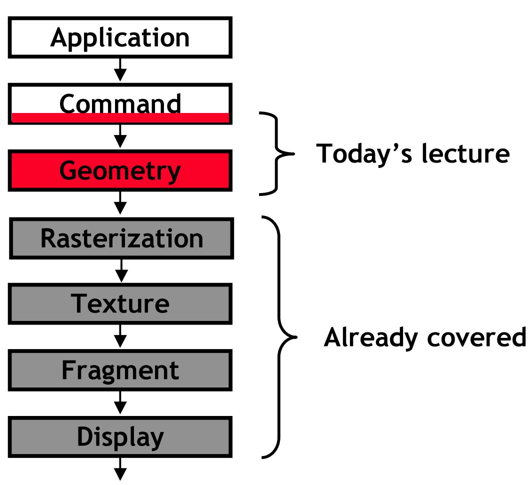
Required

- *High-Performance Polygon Rendering*, Akeley and Jermoluk, Proceedings of SIGGRAPH ’88.
- *RealityEngine Graphics*, Akeley, Proceedings of SIGGRAPH ‘93.
- *InfiniteReality: A Real-Time Graphics System*, Montrym, Baum, Dignam, and Migdal, Proceedings of SIGGRAPH ’97.

Recommended

- *Curved PN Triangles*, PDF to be on web site soon
- *OpenGL Specification*

Modern Graphics Pipeline



Geometry Processing

Two types of operations

- Vertex operations
  - Operate on individual vertexes
- Primitive operations
  - Operate on all the vertexes of a primitive

Vertex Operations

Transform coordinates and normal

- Model → world (not rigid)
- World → eye (rigid)

Normalize the length of the normal

Compute vertex lighting

Transform texture coordinates

- Generate if so specified

Transform coordinates to clip coordinates (projection)

Divide coordinates by w

Apply affine viewport transform (*x*, *y*, and *z*)

Coordinate Transformation

4x4 matrix, 4-component coordinate

Single-precision floating point is typical

Matrices can be composed

- By the application
- By the implementation
  - Be careful about invariance

$$\begin{pmatrix} x' \\ y' \\ z' \\ w' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{42} & m_{44} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix}$$

Normal Transformation

$(n_x' \; n_y' \; n_z') = (n_x \; n_y \; n_z) \, M_u^{-1}$ $\quad M_u$ = *upper-left 3x3 of M*

Approaches to acquiring M_u^{-1} include

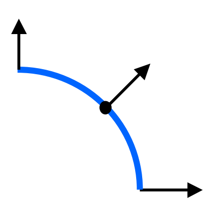
- Maintain separately, or
- Compute when coordinate matrix is changed, or
- Force specification by application

Why transform normals? (Can lighting be computed in model coords?)

- Model matrix may not be rigid
- But, recall quadrilateral decomp. problem

Why normalize normals to unit length

- Lighting equations require unit length
- Non-rigid model matrix distorts lengths
- Requires reciprocal square root operation



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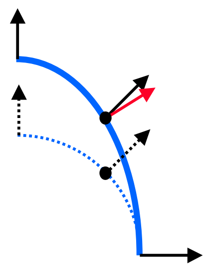


Lighting

Simple *n* dot *l* evaluation

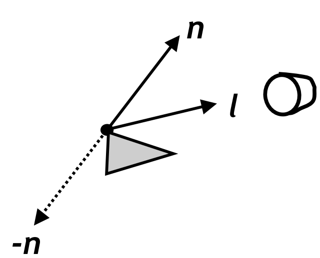
- Plus ambient and specular
- Multiple lights, …
- Remember, *n* is not a facet normal

Possibly two-sided

- Compute for *n* and -*n*
- Both results may be needed!
- Much arithmetic is shared

View-direction simplification

- Eye vector is [0,0,1]
- Saves arithmetic



There is no such thing as view direction!

No Interdependencies

Vertex operations apply to vertexes independently

Transform coordinates and normal
- Model → world
- World → eye

Normalize the length of the normal

Compute vertex lighting

Transform texture coordinates

Transform to clip coordinates

Divide by w

Apply affine viewport transform

Primitive Operations

Primitive assembly

Clipping

Backface cull

Transform coordinates and normal
- Model → world
- World → eye

Normalize the length of the normal

Compute vertex lighting

Transform texture coordinates

Transform to clip coordinates

Assemble vertexes into primitives

Clip primitives against frustum

Divide by w

Apply affine viewport transform

Eliminate back-facing triangles

Primitive Assembly

Assemble based on application commands

- Independent or strip or mesh or ….

Decompose to triangles

- Prior to clipping to maintain invariance

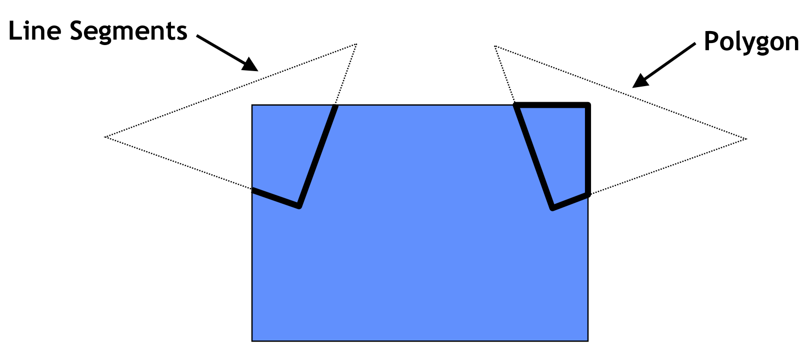
Algorithm properties

- Fixed execution time (good)
  - All vertex operations up to this point have this property
- Vertex interdependencies (bad)

Clipping

Two types

- Point, line: eliminates geometry
- Polygon: eliminates and introduces edges



Clipping

Two types

- Point, line: eliminates geometry
- Polygon: eliminates and introduces edges

Invariance requirements

- Pre-decomposition to triangles
- Care with edge arithmetic

Algorithm properties

- Vertex interdependencies (bad)
- Data-dependent execution (worse)
  - Variable execution time (substantially different)
  - Variable code paths

Backface Cull

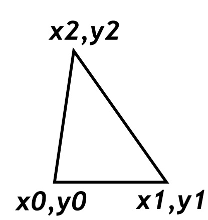
Facet facing toward or away from viewpoint?

- No facet normal (other APIs?)
- Use sign of primitive's window coordinate "area"
  - Remember, only triangles are planar

Use facing direction to

- Select lighting result (for *n* or *-n*)
- Potentially discard the primitive

Advance in sequence to improve efficiency?



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

Some Examples

Systems

- Clark Geometry Engine (1983)
- Silicon Graphics GTX (1988)
- Silicon Graphics RealityEngine (1992)
- Silicon Graphics InfiniteReality (1996)
- Modern GPU (2001)

What we'll look at

- Organization of the geometry system
- Distribution of vertex and primitive operations
- How clipping affects the implementation

Clark Geometry Engine (1983)

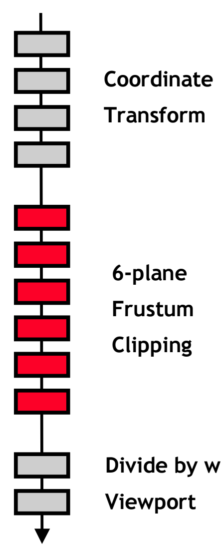
1st generation capability

Simple, fixed-function pipeline

- Twelve identical engines
- Soft-configured at start-up

Clipping allocated ½ of total 'power'

- Performance invariant (good)
- Typically idle (bad)



GTX Geometry Engine (1988)

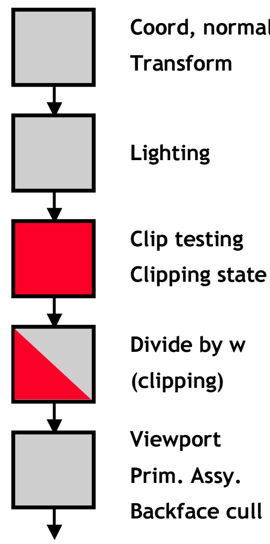
2nd generation capability

Variable functionality pipeline

- 5 identical engines
- Modes alter some functions
  - Load balancing is difficult

Clipping allocated 1/5 of 'power'

- Clip testing is the constant load
- Actual clipping
  - Slow pipeline execution (bad) out of balance
  - Typically isn't invoked (good)



RealityEngine Geometry (1992)

3rd generation capability

Variable-functionality MIMD organization

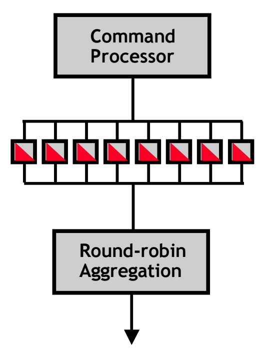
- Eight identical engines
- Round-robin work assignment
- Good 'static' load balancing

Command processor

- Splits large strips of primitives
- Shadows per-vertex state
- Broadcasts other state

Primitive assembly

- Complicates work distribution
- Reduces efficiency of strip processing



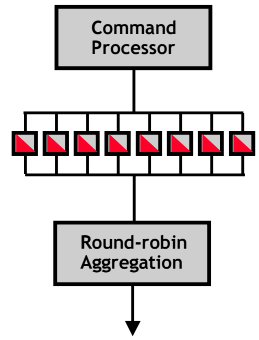
RealityEngine Clipping

Clipping introduces data-dependent (dynamic) load

- Cannot be predicted by CP

Dynamic load balance accomplished by:

- Round-robin assignment
- Large input and output FIFOs
  - For each geometry processor
  - Sized greater than (*n*) *long/typical*
- Large work load per processor
  - Minimize the *long/typical* ratio
  - Unlike pipeline processing



InfiniteReality Geometry (1996)

3rd generation capability

Variable-functionality MIMD organization

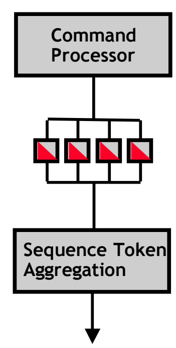
- Four identical (SIMD) engines
- Least-busy work assignment
- Good 'static' load balancing

Command processor

- Splits large strips of primitives
- Shadows per-vertex state
- Broadcasts other state

Primitive assembly

- Complicates work distribution
- Reduces efficiency of strip processing



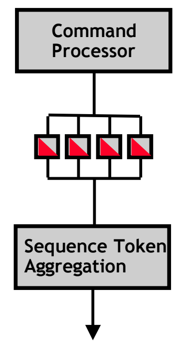
InfiniteReality Clipping

Dynamic load balance accomplished by:

- Least-busy assignment
- Even larger FIFOs
- Large work load per processor

Likelihood of clipping reduced by

- Guard-band clipping algorithm



Guard-Band Clipping

Expand clipping frustum beyond desired viewport

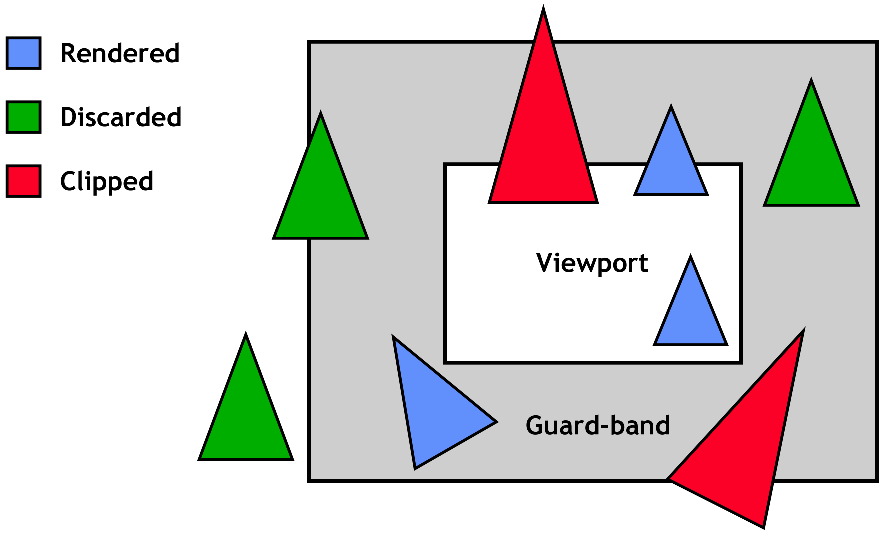
- Near and far clipping are unchanged
- Frustum clip only when necessary

Ideal triangle cases:

- Discard if outside viewport, else
- Render without clipping if inside frustum, else
  - Rasterizer must scissor well for this to be efficient
- Clip triangles
  - That cross both viewport and frustum boundaries
  - That cross the near or far clip-planes

Operation is imperfect, but conservative

Guard-Band Clipping Example



Modern Geometry Engine (2001)

Utilizes homogeneous rasterization algorithm

- No clipping required
- Hence no primitive assembly prior to rasterization
  - Push backface cull to rasterization setup
  - This is where triangle area is computed anyway

All geometry engine calculations are

- On independent vertexes - easy work distribution
- Not data dependent - minimal code branching

Allows efficient, SIMD geometry engine implementation

Programmability?

Primitive Generation

Why do this?

Some important reasons:

- Match application semantics
- Move computation from CPU to GPU
- Reduce storage requirements
- Perverse desire to complicate the GPU design ;-)

Highest-priority reason:

- Reduce CPU to GPU data rate!

Basic Idea

Introduce new pipeline stage

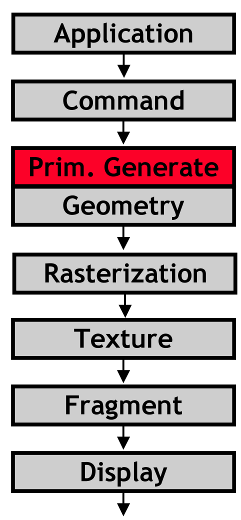
- We'll treat as part of geometry

Two-step application

- Specify generation function
  - Modes
  - Data values (potentially large)
- Execute generation function
  - Block-mode commands, and/or
  - Vertex-like commands

Generated geometry

- Is treated as if app-specified



Problems with Primitive Generation

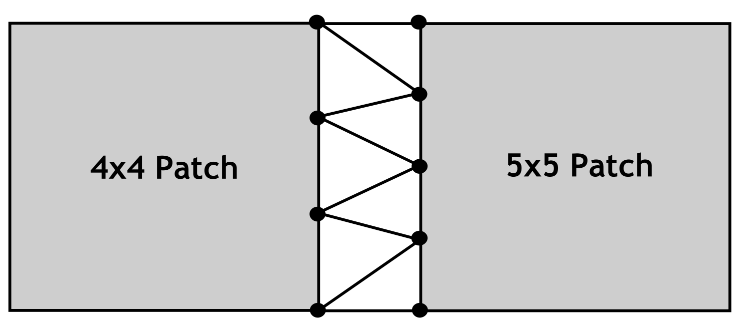
Specification may be complex

- E.g. 4th order 2D OpenGL Evaluation mesh
- May be more data than generated triangles!
- Specification/execution may be sequential
  - Require double buffer, separate execution engines

Cracks and T-vertexes

- Different surfaces must abut
  - But arithmetic is of finite precision
- Generally requires "stitching"
  - OpenGL accommodates this with mixed evaluation and vertex specification

Stitching Patches Together



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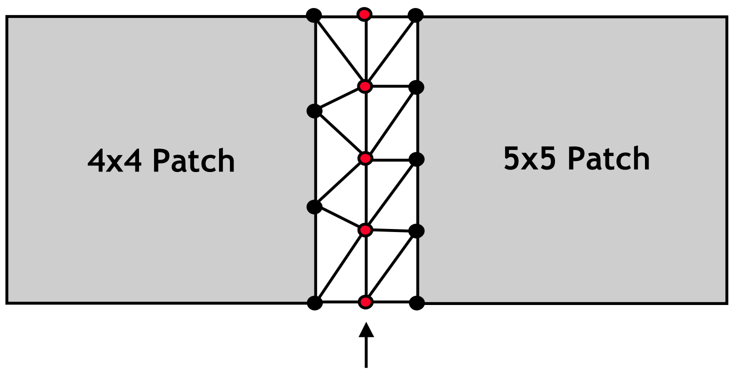


Stitching vertexes introduced

Problems with Primitive Generation

Implementation may be complex

- E.g. Trimmed NURBS
  - Limit tesselation to curve-specified region of 2D domain
- Algorithm doesn't "fit" GPU architecture
  - Don't redesign a general-purpose MP system

Semantics may not match application's

- E.g. Trimmed NURBS
- Getting this right is extremely difficult
  - Don't trespass on application's "secret sauce"

Where should primitive generation be done? ….

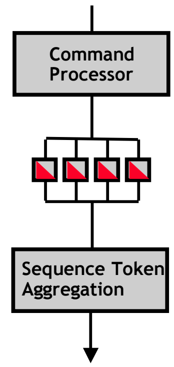
Where is Primitive Generation Done?

On geometry engines

- Reduces maximum vertex rate
  - Generation consumes GE cycles
- May serialize setup/execution
  - GEs not designed to double buffer
- Complicates load balancing
  - Command Processor distribution
- Complicates state handling
  - Command Processor managed this

OpenGL designed to accommodate this

- Awkward state semantics



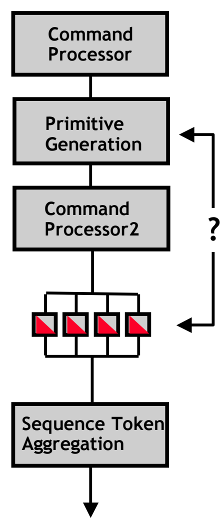
Where is Primitive Generation Done?

On an additional processor

- Requires fixed-function resources
  - Idle during normal operation
- May serialize setup/execution
  - If not designed to double buffer
- Simplifies
  - Geometry Engine load balancing
  - State management

Feels like a new pipeline stage

- Command processor functions split



Other Data Rate Reductions

Display lists

- Work well for client-server
- Allow bandwidth to be reassigned

Geometric decompression

- Strips and meshes
- Indexed triangle sets
- Geometry Compression (Deering ’95)
- Hypothetical backend for advanced compression format

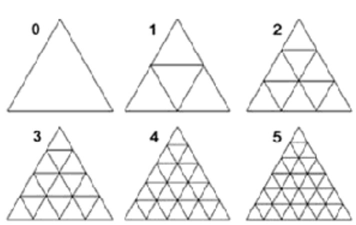
ATI PN Triangle technology …

ATI’s TRUFORM Technology

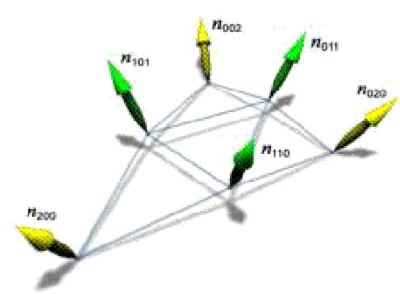
Requires minimal setup

- Single mode (triangle edge subdivision count)
- No geometric data

Operates on triangles as normally submitted



Edge Subdivison Count

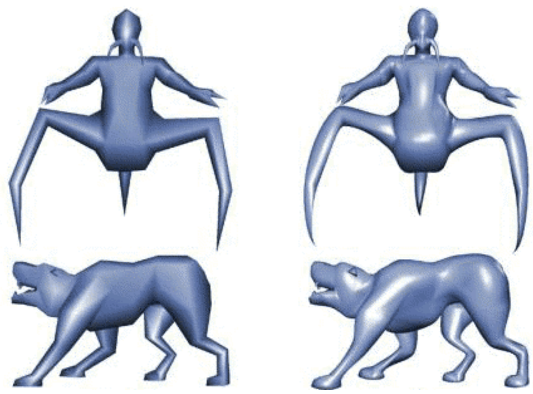


Normal-based surface extraction

ATI's TRUFORM Technology

Improves silhouettes

Improves lighting over per-vertex (per fragment?)



ATI's TRUFORM Technology

Limitations

- Constant subdivision per object
- Generally limited capability (e.g. continuity)

Strengths

- *Actually* reduces CPU to GPU data rate
- Requires minimal application recoding
- Easily avoids cracks and T-vertexes
- Is simple to understand, to implement, and to use

Leads toward a Reyes rendering approach

- Lots of small triangles
- Shading done in pre-projected coordinates
- Hardware trails software ….

OpenGL Selection

Light pen replacement mechanism

Light pen is a calligraphic device

- Focuses on screen
- Signals when stroke is drawn in focus region

Raster equivalent

- Point with a mouse
- Set "selection mode"
- Re-render entire scene
  - Clip frustum reduced to small region around pointer
  - Each object tagged (integer name)
- Return "hit" information

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