PlayStation 2 Clipping

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Standard graphics pipeline

- Vertices passed to T&L unit
- Transformed to clip space
- Hardware clips to viewport

- Programmer has no hassles.
  - Not the case with PS2

Why no clipping

- Clipping in hardware is very expensive.
  - At least one FP divider and vector multiplier required
  - Up to 3 for full pipelined hardware
    - relying on symmetry to clip +&- together
  - This hardware lies idle for a great deal of the time
    - PS2 designed to maximize use of hardware
      - Have software handle infrequent cases

PS2 Hardware

PS2 Overview

- MIPs CPU core
  - 128 bit register set, multimedia extensions
- Vector Units
  - SIMD FP processors, operate on 4xSP
  - Individual data & code memory
    - Can run independently of core cpu
  - VU0 closely tied to core
  - VU1 closely tied to GS

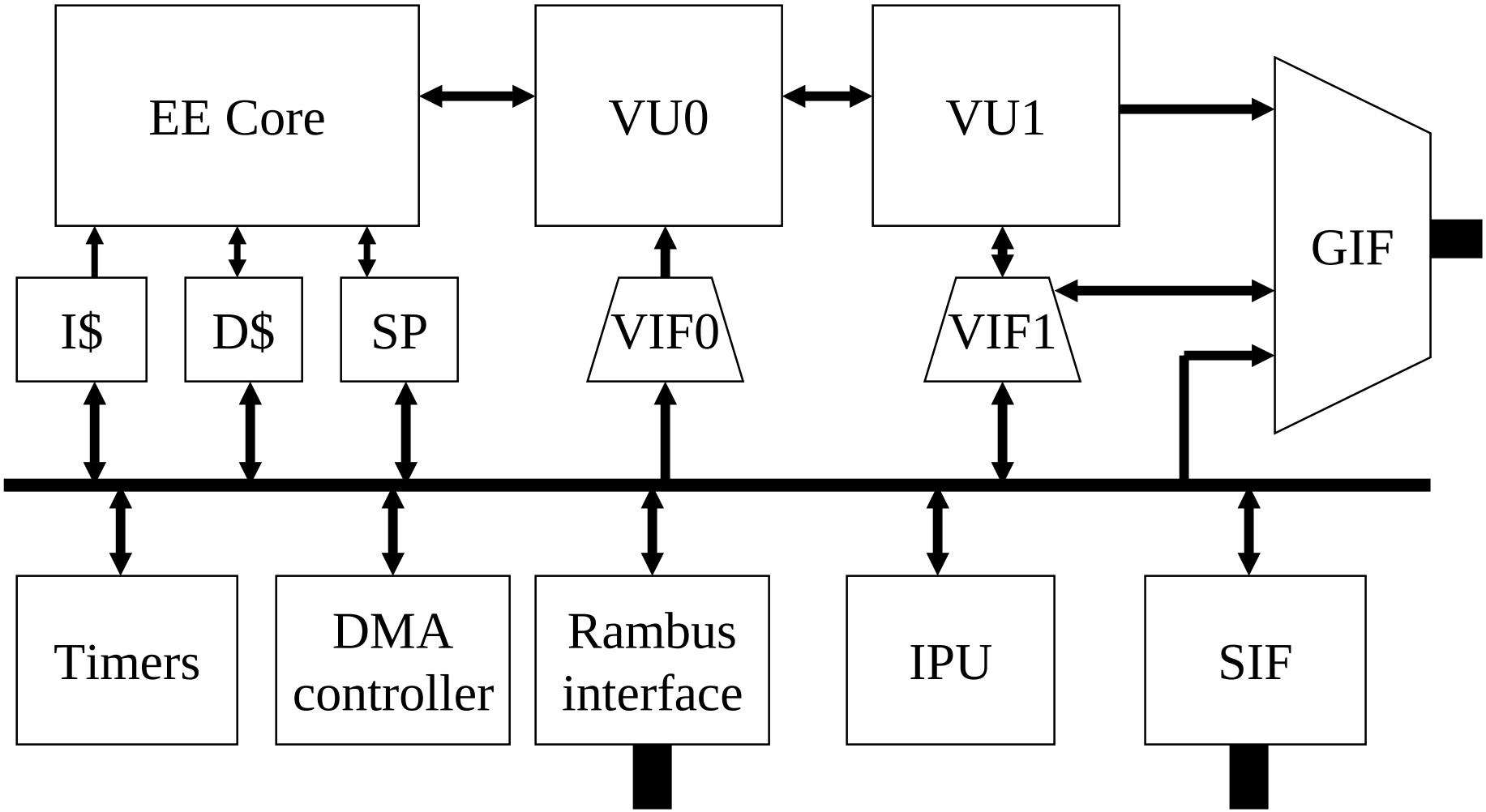
PS2 Overview

- Graphics Synthesisor
  - Rasteriser with 4MB embedded memory
  - Optimised for high fill rate

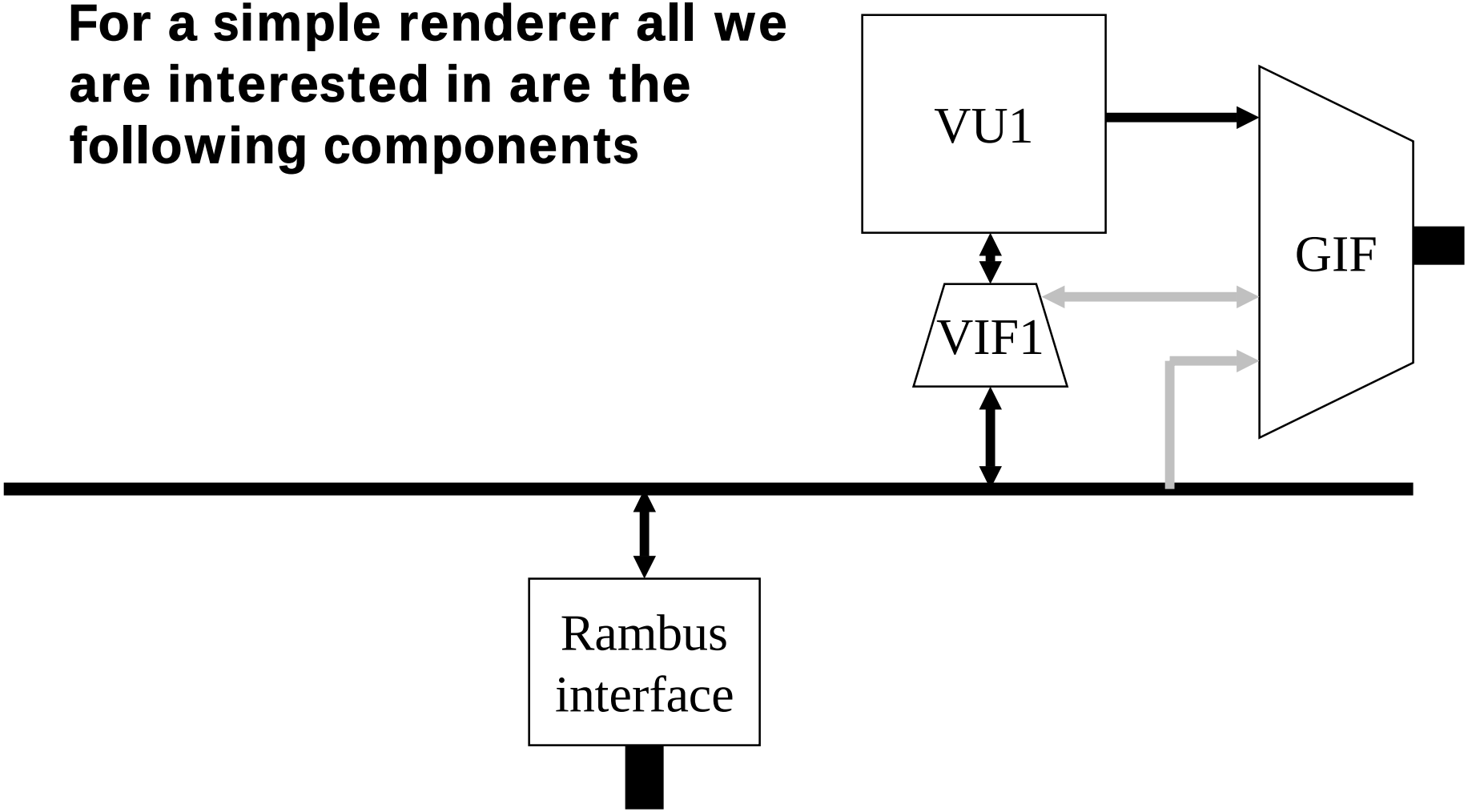
  - Very simple.
  - No processing of vertex data
    - Only 2D scissoring supported

    - This means work for the programmer!!

Internal datapaths



For a simple renderer all we are interested in are the following components



PS2 simple graphics pipeline

- Geometry sent to VU1 via DMA, along with all state information.
- VU1 applies all transform, lighting, and clipping.
  - Back to old days..
- Polys sent directly from VU1 to GS
  - Special internal link from VU1 memory to GIF.

Simple transform

- Without worrying about clipping transform is vector matrix operation followed by homogeneous divide

```
Mul ACC,vf31,vf1w
Madd ACC,vf30,vf1z
Madd ACC,vf29,vf1y
Madd vf2,vf28,vf1x
div Q,vf0w,vf2w        (vf0w = 1.0 )
Mul vf2,vf2,Q
```

How does this compare?

- 6 instructions
  - 5 multiples and one divide
- Compare to 4 for Vertex shader
  - no divide as DX transforms to clip space

- VU ops contain upper and lower instruction!!!
  - Mul is upper
  - Div (and integer / loadstore) are lower

Ground rules

- Only integer arithmetic and accumulator have 1/1 throughput/latency

- FP ops have 1/4
- Load/Store is 1/4
- Divide is 7/7 - This is the killer
  - Scalar divide unit only

Real VU code

```
NOP
NOP
NOP
MULAw ACC,vf31,vf0
MADDAz ACC,vf30,vf1
MADDAy ACC,vf29,vf1
MADDx vf2,vf28,vf1
NOP x 3
NOP
NOP x 6
MULQ vf2,vf2,Q
NOP x 3
FTOI4 vf2,vf2
NOP x 3
NOP
```

```
LQI vf1,(vi1++)
NOP
NOP
NOP
NOP
NOP
NOP
NOP
NOP x 3
DIV Q,vf0w,vf1w
NOP x 6
NOP
NOP x 3
NOP
NOP x 3
SQI vf2,(vi2++)
```

Real VU code

```
NOP
NOP
NOP
MULAw ACC,vf31,vf0
MADDAz ACC,vf30,vf1
MADDAy ACC,vf29,vf1
MADDx vf2,vf28,vf1
NOP x 3
NOP
NOP x 6
MULQ vf2,vf2,Q
NOP x 3
FTOI4 vf2,vf2
NOP x 3
NOP
```

```
LQI vf1,(vi1++)
NOP
NOP
NOP
NOP
NOP
NOP
NOP x 3
DIV Q,vf0w,vf1w
NOP x 6
NOP
NOP x 3
NOP
NOP x 3
SQI vf2,(vi2++)
```

26 Cycles!! Very Bad

Better code….

- Only 6 upper instructions and 3 lower instructions are doing anything
- Theoretical performance is determined by the DIV throughput

- Even with texture correction, 7 cycles can be achieved.
  - ST needs to be projected to STQ for GS
  - 7 upper, 5 lower

Optimised transform

```
ftoi4.xyz vf12,vf8
mulq.xyz vf14,vf13,Q
mulq.xyz vf9,vf9,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf8
madday.xyzw ACC,vf29,vf8
maddx.xyzw vf8,vf28,vf8
ftoi4.xyz vf12,vf9
mulq.xyz vf14,vf13,Q
mulq.xyz vf10,vf10,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf9
madday.xyzw ACC,vf29,vf9
maddx.xyzw vf9,vf28,vf9
ftoi4.xyz vf12,vf10
mulq.xyz vf14,vf13,Q
mulq.xyz vf11,vf11,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf10
madday.xyzw ACC,vf29,vf10
maddx.xyzw vf10,vf28,vf10
ftoi4.xyz vf12,vf11
mulq.xyz vf14,vf13,Q
mulq.xyz vf8,vf8,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf11
madday.xyzw ACC,vf29,vf11
maddx.xyzw vf11,vf28,vf11
```

```
lq.xyz vf8,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf11w
sq.xyzw vf12,2-3(vi1)
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf9,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf8w
sq.xyzw vf12,2-3(vi1)
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf10,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf9w
sq.xyzw vf12,2-3(vi1)
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf11,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf10w
sq.xyzw vf12,2-3(vi1)
ibne vi1,vi2,prelit_loop
sq.xyz vf14,0(vi1)
```

Optimized transform

```
ftoi4.xyz vf12,vf8
mulq.xyz vf14,vf13,Q
mulq.xyz vf9,vf9,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf8
madday.xyzw ACC,vf29,vf8
maddx.xyzw vf8,vf28,vf8
ftoi4.xyz vf12,vf9
mulq.xyz vf14,vf13,Q
mul[illegible]xy[illegible]0[illegible]Q
mul[illegible]z[illegible]A[illegible]C[illegible]f3[illegible]vf0
[illegible]daz[illegible]w[illegible]C[illegible]f[illegible]vf9
madday.xyzw ACC,vf29,vf9
maddx.xyzw vf9,vf28,vf9
ftoi4.xyz vf12,vf10
mulq.xyz vf14,vf13,Q
mulq.xyz vf11,vf11,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf10
madday.xyzw ACC,vf29,vf10
maddx.xyzw vf10,vf28,vf10
ftoi4.xyz vf12,vf11
mulq.xyz vf14,vf13,Q
mulq.xyz vf8,vf8,Q
mulaw.xyzw ACC,vf31,vf0
maddaz.xyzw ACC,vf30,vf11
madday.xyzw ACC,vf29,vf11
maddx.xyzw vf11,vf28,vf11
```

Dont try to read this!!

```
lq.xyz vf8,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf11w
sq.xyzw vf12,2-3(vi1)
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf9,2+12(vi1)
lq.xy vf13,0+6(vi1)
i[illegible]1
[illegible]Q[illegible]
s[illegible]xy[illegible]1[illegible]v
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf10,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf9w
sq.xyzw vf12,2-3(vi1)
ibeq vi1,vi2,prelit_exit
sq.xyz vf14,0(vi1)
lq.xyz vf11,2+12(vi1)
lq.xy vf13,0+6(vi1)
iaddi vi1,vi1,3
div Q,vf0w,vf10w
sq.xyzw vf12,2-3(vi1)
ibne vi1,vi2,prelit_loop
sq.xyz vf14,0(vi1)
```

Clipping (Simple FOV)

- View frustum normally set up as

  -1 < X/Z < +1

  -1 < Y/Z < +1

  near < Z < far

- another form (as long as Z is valid)

  -Z < X < +Z

  -Z < Y < +Z

  near < Z < far

VU support

- VU contains special CLIP instruction
  - CLIP vfa.xyz,vfb.w
    - -|w| < x < +|w|
    - Same for y and z
      - Easy in HW: Implement single |xyz| > |w| with sign check
      - |w| also allows cc to be correct for negative w
  - Places 6 result bits in shift register
    - Holds up to 4 check results (24 bits)
  - Logical condition instructions can show result for triangle or quad

Setting up clipping

- $-|W| < X$ or $Y < +|W|$ is simple
- $near < W < far$ needs thinking about

$$n < w < f$$

$$1/f < 1/w < 1/n$$

$$0 < 1/w - 1/f < 1/n - 1/f$$

$$0 < (f-w)/wf < (f-n)/nf$$

Setting up clipping

$$0 < (f-w)/wf * nf/(f-n) < 1$$

$$0 < ((f-w)*n) / (w*(f-n)) < 1$$

$$0 < (2n *(f-w)) / (w*(f-n)) < 2$$

$$-1 < (2n*(f-w)/(w*(f-n)) - (w*(f-n))/(w*(f-n)) < +1$$

$$-1 < (2fn - 2wn -wf + wn)/(w*(f-n)) < +1$$

$$-1 < (2fn - w(n+f))/(w*(f-n)) < +1$$

$$-|w| < (2fn -w(n+f)) / (f-n) < +|w|$$

Homogeneous space

- X and Y checks have valid regions behind the camera (negative eyespace Z)
- However the near / far plane check only passes the region with positive w
- This means that the erroneous X/Y regions are not valid Z regions..
  - Z clipping must occur first!!!

Implementing clipping

- PS2 renders strips
- Each new vertex is a new triangle
- If any vertex fails the cliptest the triangle needs clipping

- Note: Clipspace isn’t screen space
  - Scale and bias need to be added

VU clipspace renderer

```
mulaw ACC,vf31,vf0
maddaz ACC,vf30,vf1
madday ACC,vf29,vf1
maddax vf3,vf28,vf1
clipw.xyz vf3,vf3
mula ACC,vf3,vf27
maddw.xy vf4,vf26,vf3
nop
nop
mulq.xyz vf4,vf4,Q
mulq.xyz vf2,vf2,Q
ftoi4.xyz vf4,vf4
nop
nop
```

```
Lqi vf1,(vi2++)
lqi vf2,(vi2++)
nop
nop
div Q,vf0w,vf3w
fcand vi1,0777777
fcget vi5
iaddiu vi1,vi1,0x7fff
mfir vf4.w,vi1
mfir vf2.w,vi5
nop
nop
sqi vf2,(vi3++)
sqi vf4,(vi3++)
```

Clipspace renderer

- This code is 10 upper and 10 lower instructions
- All triangles are transformed, and any that need clipping (via the FCAND) are marked as non draw for the GS
- The calculated clipcodes are stored for later use in an unused field

Guard band clipping

- If our triangles are small, we don't really need to clip them.
- Just discarding the triangles outside the clip region is enough
- The GS 2D scissoring can clip efficiently for small triangles.
- All we need to do is to increase the size of the clip pyramid to allow a 'guard band'

Full clipping

- Full clipping is very slow
  - Sutherland Hodgman algorithm
  - Check against each plane
- We reuse the clipcodes generated in the previous code
- The OR of the vertex clip codes determines the planes to check against
  - Remember to clip against Z first!!

Per plane checks

- Line segment clip test.
- 4 cases for output
  - Both visible: Endpoint
  - None visible: No output
  - Leaving: Intersection
  - Entering: Intersection and endpoint
    - Intersection needs new clipcode generation
- Intersection calculation requires multiply and divide operations

Intersection for w

- Vf1 is p1, vf2 is p2, vf3 is w plane
  - sub vf4,vf2,vf1 — p2-p1
  - sub vf5,vf3,vf1 — w-p1
  - div Q,vf0w,vf4w — 1/(p2w-p1w)
  - mulw ACC,vf1,vf4w — p1.(p2w-p1w)
  - maddw vf6,vf4,vf5w — (w-p1w)(p2-p1)
  - waitq
  - mulq vf6,vf6,Q — Final result

Reuse of code

- Difficult to reuse code due to scalar component used in plane intersection

- One solution:
  - Rotate vector between checks
  - xyzw to yzwx
  - Clipping code always checks against W

- Or just three hardwired routines!!

Interpolation

- Only ST and XYZ are projected properly
- RBGA interpolation needs to be adjusted after projection to match GS

- This is only a problem for big triangles
  - Not GS friendly anyway

Clipper output

- The output from the clipper for one triangle is a n sided polygon
- This can be rendered as a fan or a strip
  - Fan: No need to reorder vertices
  - Strip: Can be stitched in with unclipped triangle strip to ensure no state change problems

Optimizations

- **Don’t clip degenerate triangles**
  - **They wont draw anyway, so cull them**
- **At the expense of much more unreadable code, the clipping operation can be folded into the strip rendering:**
    - **See the code for details**
- **For small triangles not all 6 clipplanes will intersect : Only 3 at most**

Optimizations

- Not all objects have to go through the clipper
- If the bounding volume for an object or a section of mesh is not clipped none of the triangles inside will be clipped
  - Use switchable VU code with two paths

Tearing

- Numerical inaccuracies can occur at the boundary of valid and clipped triangles
  - Sometimes this is caused by a different transform path in the renderer
    - Direct object to screen matrix for unclipped
    - Object to clip space / clip space to screen otherwise
- Only solution is to unify the maths!!

Thank you

- **Code and a more detailed document will be available at:**
  - **www.playstation2-linux.com**
  - **Also at GameDeveloper site**
- **You can email me at:**
  - **colin@users.playstation2-linux.com**