PowerVR GLSL optimization

Low level

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1. Introduction

This document describes ways to optimize GLSL code for PowerVR Series 6 architecture. The optimizations are low level in their nature, and therefore they can be used to get the last 10% of performance boost out from the hardware. Prior to using these techniques it is essential to make sure that the most optimal algorithms are used and that the GPU is well utilized.

Your mileage may wary depending on the exact compiler architecture used. Always check if your optimizations resulted in a performance improvement on the target platform.

Throughout the document you may find the USC instructions the GLSL code compiles to.

Based on:

http://www.humus.name/Articles/Persson_LowLevelThinking.pdf

http://www.humus.name/Articles/Persson_LowlevelShaderOptimization.pdf

2. Low level optimizations

2.1. PowerVR Series 6 USC diagram

Generally shader performance on PowerVR Series 6 architecture GPUs depends on the number of cycles it takes to execute a shader.

Depending on the configuration, PowerVR Series6 architecture delivers a variety of options for executing multiple instructions in the USC ALU pipeline within a single cycle.

It is possible to execute two F16 SOP instructions plus the F32 <-> F16 conversions plus the mov/output/pack instruction in one cycle.

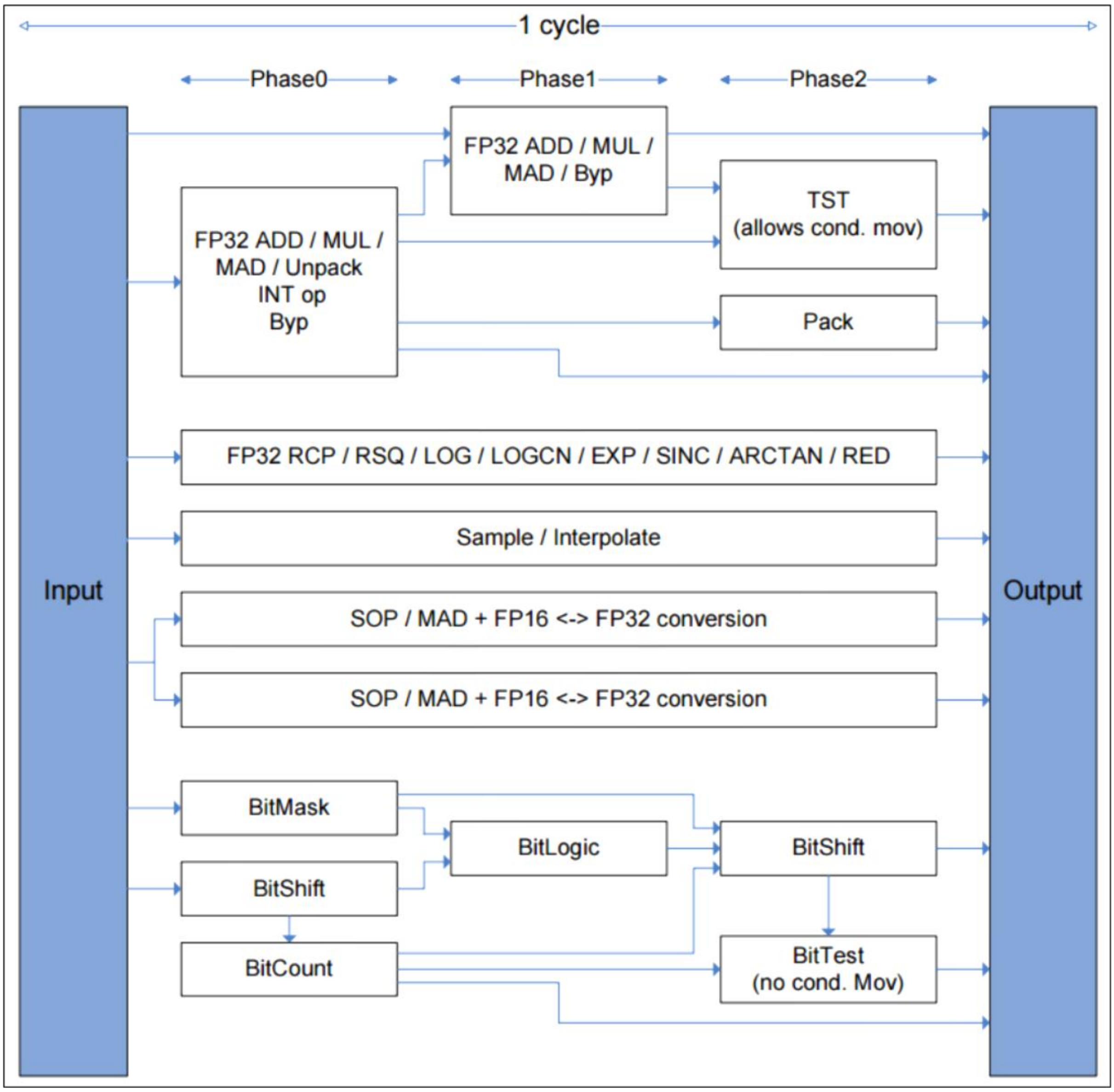
Alternatively, one could execute an FP32 MAD and an FP32/INT32 MAD/UNPACK instruction plus a test (conditional) instruction plus the mov/output/pack instruction in one cycle.

If there are bitwise work to be done, it is possible to issue a bitwise SHIFT/COUNT, a bitwise logical operation, a bitwise shift, a test and the mov/output/pack instructions in one cycle.

It is also possible to execute a single complex operation (ie. rcp) and a mov/output/pack instruction in one cycle.

Lastly, one can execute an interpolate/sample instruction plus the usual mov/output/pack instruction in one cycle.

As you can see below, it is best to use all stages in one route in the pipeline below to fully utilize the ALU. Therefore it is advisable to arrange GLSL instructions that way.



2.2. Writing expressions in MAD form

In order to take advantage of the USC cores most effectively it is essential to always write math expressions in Multiply-Add form (MAD form).

For example changing the expression below to use the MAD form results in a 50% cycle cost reduction.

```
fragColor.x = (t.x + t.y) * (t.x - t.y); //2 cycles
{sop, sop, sopmov}
{sop, sop}
-->
fragColor.x = t.x * t.x + (-t.y * t.y); //1 cycle
{sop, sop}
```

2.3. Division

It is usually beneficial to write division math in reciprocal form.
To add finishing math expressions' simplification can yield additional performance gains.

```
fragColor.x = (t.x * t.y + t.z) / t.x; //3 cycles
{sop, sop, sopmov}
{frcp}
{sop, sop}
-->
fragColor.x = t.y + t.z * (1.0 / t.x); //2 cycles
{frcp}
{sop, sop}
```

2.4. Sign

Originally sign(x)'s result will be
-1 if x < 0,
1 if x > 0
and
0 if x == 0
However, if the last case is not needed it is better to use conditional form instead of sign().

```
fragColor.x = sign(t.x) * t.y; //3 cycles
{mov, pck, tstgez, mov}
{mov, pck, tstgez, mov}
{sop, sop}
-->
fragColor.x = (t.x >= 0.0 ? 1.0 : -1.0) * t.y; //2 cycles
{mov, pck, tstgez, mov}
{sop, sop}
```

2.5. Rcp/rsqrt/sqrt

On the PowerVR Series 6 architecture the reciprocal operation is directly supported by an instruction.

```
fragColor.x = 1.0 / t.x; //1 cycle
{frcp}
```

The same is true with the inversesqrt() function.

```
fragColor.x = inversesqrt(t.x); //1 cycle
{frsq}
```

Sqrt() on the other hand is implemented as: 1 / (1/sqrt(x))
Which results in a 2 cycle cost.

```
fragColor.x = sqrt(t.x); //2 cycles
{frsq}
{frcp}
```

A commonly used alternative: x * 1/sqrt(x) yields the same results

```
fragColor.x = t.x * inversesqrt(t.x); //2 cycles
{frsq}
{sop, sop}
```

The only case when it is better to use the above alternative if the result is tested. In this case the test instructions can fit into the second instruction.

```
fragColor.x = sqrt(t.x) > 0.5 ? 0.5 : 1.0; //3 cycles
{frsq}
{frcp}
{mov, mov, pck, tstg, mov}
-->
fragColor.x = (t.x * inversesqrt(t.x)) > 0.5 ? 0.5 : 1.0; //2 cycles
{frsq}
{fmul, pck, tstg, mov}
```

2.6. Abs/Neg/Saturate

Modifiers such as abs(), neg() and clamp(…, 0.0, 1.0) (also known as saturate()) are free in certain cases on PowerVR architecture. It is essential to take advantage of this.

Abs() and neg() are free if they are used on an input to an operation, in which case they are indeed turned into a free modifier by the compiler.

Saturate on the other hand turns into a free modifier when used on the output of an operation.

Note that complex and sampling/interpolation instructions are exceptions to this rule (ie. saturate is not free when used on a texture sampling output, or on a complex instruction output).

When these functions are not used accordingly they may introduce additional mov instructions which may inflate the cycle count of the shaders.

It is also beneficial to use clamp(…, 0.0, 1.0) instead of min(…, 1.0) and max(…, 0.0). (changes test instruction to a saturate modifer)

```
fragColor.x = abs(t.x * t.y); //2 cycles
{sop, sop}
{mov, mov, mov}
-->
fragColor.x = abs(t.x) * abs(t.y); //1 cycle
{sop, sop}
```

```
fragColor.x = -dot(t.xyz, t.yzx); //3 cycles
{sop, sop, sopmov}
{sop, sop}
{mov, mov, mov}
-->
fragColor.x = dot(-t.xyz, t.yzx); //2 cycles
{sop, sop, sopmov}
{sop, sop}
```

```
fragColor.x = 1.0 - clamp(t.x, 0.0, 1.0); //2 cycles
{sop, sop, sopmov}
{sop, sop}
-->
fragColor.x = clamp(1.0 - t.x, 0.0, 1.0); //1 cycle
{sop, sop}
```

```
fragColor.x = min(dot(t, t), 1.0) > 0.5 ? t.x : t.y; //5 cycles
{sop, sop, sopmov}
{sop, sop}
{mov, fmad, tstg, mov}
{mov, mov, pck, tstg, mov}
{mov, mov, tstz, mov}
-->
fragColor.x = clamp(dot(t, t), 0.0, 1.0) > 0.5 ? t.x : t.y; //4 cycles
{sop, sop, sopmov}
{sop, sop}
{fmad, mov, pck, tstg, mov}
{mov, mov, tstz, mov}
```

However, watch out for complex functions, as they are translated into multiple operations and therefore in this case it matters where you put the modifiers.

For example, normalize() is decomposed into:

```
vec3 normalize( vec3 v )
{
  return v * inversqrt( dot( v, v ) );
}
```

As you can see, in this case it is best to negate one of the inputs of the final multiplication rather than the inputs in all cases (or create a temporary negated input):

```
fragColor.xyz = -normalize(t.xyz); //6 cycles
{fmul, mov}
{fmad, mov}
{fmad, mov}
{frsq}
{fmul, fmul, mov, mov}
{fmul, mov}
-->
fragColor.xyz = normalize(-t.xyz); //7 cycles
{mov, mov, mov}
{fmul, mov}
{fmad, mov}
{fmad, mov}
{frsq}
{fmul, fmul, mov, mov}
{fmul, mov}
```

3. Transcendental functions

3.1. Exp/Log

On the PowerVR Series 6 architecture the 2^n operation is directly supported by an instruction.

```
fragColor.x = exp2(t.x); //1 cycle
{fexp}
```

The same is true with the log2() function.

```
fragColor.x = log2(t.x); //1 cycle
{flog}
```

Exp is implemented as:

```
float exp2( float x )
{
  return exp2(x * 1.442695); //2 cycles
  {sop, sop}
  {fexp}
}
```

Log is implemented as:

```
float log2( float x )
{
  return log2(x * 0.693147); //2 cycles
  {sop, sop}
  {flog}
}
```

Pow(x, y) is implemented as:

```
float pow( float x, float y )
{
  return exp2(log2(x) * y); //3 cycles
  {flog}
  {sop, sop}
  {fexp}
}
```

3.2. Sin/Cos/Sinh/Cosh

Sin, Cos, Sinh and Cosh on PowerVR architecture has a reasonably low cost of 4 cycles.
(2 cycles of reduction + fsinc + 1 conditional)

```
fragColor.x = sin(t.x); //4 cycles
{fred}
{fred}
{fsinc}
{fmul, mov} //+conditional
```

```
fragColor.x = cos(t.x); //4 cycles
{fred}
{fred}
{fsinc}
{fmul, mov} //+conditional
```

```
fragColor.x = cosh(t.x); //3 cycles
{fmul, fmul, mov, mov}
{fexp}
{sop, sop}
```

```
fragColor.x = sinh(t.x); //3 cycles
{fmul, fmul, mov, mov}
{fexp}
{sop, sop}
```

3.3. Asin/Acos/Atan /Degrees/Radians

If one completes the math expressions' simplifications, then these functions are usually not needed. Therefore they don't map to the hardware exactly. This means that these functions have very high cost, and should be avoided at all times.

Asin() costs a massive 67 cycles.

```
fragColor.x = asin(t.x); //67 cycles
//USC code omitted due to length
```

Acos() costs a massive 79 cycles.

```
fragColor.x = acos(t.x); //79 cycles
//USC code omitted due to length
```

Atan is still costly, but it could be used if needed.

```
fragColor.x = atan(t.x); //12 cycles (lots of conditionals)
//USC code omitted due to length
```

While degrees and radians take only 1 cycle, they can be usually avoided if you only use radians

```
fragColor.x = degrees(t.x); //1 cycle
{sop, sop}
```

```
fragColor.x = radians(t.x); //1 cycle
{sop, sop}
```

4. Intrinsic functions

4.1. Vector*Matrix

The vector * matrix multiplication has quite a reasonable cost, despite the number of calculations that need to happen.

Optimizations such as taking advantage of knowing that w is 1 however don’t reduce the cost.

```
fragColor = t * m1; //4x4 matrix, 8 cycles
{mov}
{wdf}
{sop, sop, sopmov}
{sop, sop, sopmov}
{sop, sop}
{sop, sop, sopmov}
{sop, sop, sopmov}
{sop, sop}

fragColor.xyz = t.xyz * m2; //3x3 matrix, 4 cycles
{sop, sop, sopmov}
{sop, sop}
{sop, sop, sopmov}
{sop, sop}
```

4.2. Mixed Scalar/Vector math

Normalize/length/distance/reflect etc. functions usually contain a lot of function calls inside them such as dot(). One can take advantage of knowing how these functions are implemented.

For example, if we know that two operations have a shared subexpression, we can reduce the cycle count. However, that only happens if the input order allows it.

```
fragColor.x = length(t-v); //7 cycles
fragColor.y = distance(v, t);
{sopmad, sopmad, sopmad, sopmad}
{sop, sop, sopmov}
{sopmad, sopmad, sopmad, sopmad}
{sop, sop, sopmov}
{sop, sop}
{frsq}
{frcp}
-->
fragColor.x = length(t-v); //9 cycles
fragColor.y = distance(t, v);
{mov}
{wdf}
{sopmad, sopmad, sopmad, sopmad}
{sop, sop, sopmov}
{sop, sop, sopmov}
{sop, sop}
{frsq}
{frcp}
{mov}
```

Manually expanding these complex instructions can sometimes help the compiler optimize the code.

```
fragColor.xyz = normalize(t.xyz); //6 cycles
{fmul, mov}
{fmad, mov}
{fmad, mov}
{frsq}
{fmul, fmul, mov, mov}
{fmul, mov}
-->
fragColor.xyz = inversesqrt(dot(t.xyz, t.xyz)) * t.xyz; //5 cycles
{sop, sop, sopmov}
{sop, sop}
{frsq}
{sop, sop}
{sop, sop}
```

Also, in expanded form you can take advantage of grouping vector and scalar instructions together.

```
fragColor.xyz = 50.0 * normalize(t.xyz); //7 cycles
{fmul, mov}
{fmad, mov}
{fmad, mov}
{frsq}
{fmul, fmul, mov, mov}
{fmul, fmul, mov, mov}
{sop, sop}
-->
fragColor.xyz = (50.0 * inversesqrt(dot(t.xyz, t.xyz))) * t.xyz; //6 cycles
{sop, sop, sopmov}
{sop, sop}
{frsq}
{sop, sop, sopmov}
{sop, sop}
{sop, sop}
```

Below is listed what the complex instructions can be expanded to.

Cross() can be expanded to:

```
vec3 cross( vec3 a, vec3 b )
{
  return vec3( a.y * b.z - b.y * a.z,
               a.z * b.x - b.z * a.x,
               a.x * b.y - b.y * a.y );
}
```

Distance can be expanded to:

```
float distance( vec3 a, vec3 b )
{
  vec3 tmp = a – b;
  return sqrt(dot(tmp, tmp));
}
```

Dot can be expanded to:

```
float dot( vec3 a, vec3 b )
{
       return a.x * b.x + a.y * b.y + a.z * b.z;
}
```

Faceforward can be expanded to:

```
vec3 faceforward( vec3 n, vec3 I, vec3 Nref )
{
  if( dot(Nref, I) < 0 )
  {
    return n;
  }
  else
  {
    return -n:
  }
}
```

Length can be expanded to:

```
float length( vec3 v )
{
  return sqrt(dot(v, v));
}
```

Normalize can be expanded to:

```
vec3 normalize( vec3 v )
{
  return v / sqrt(dot(v, v));
}
```

Reflect can be expanded to:

```
vec3 reflect( vec3 N, vec3 I )
{
  return I - 2.0 * dot(N, I) * N;
}
```

Refract can be expanded to:

```
vec3 refract( vec3 n, vec3 I, float eta )
{
  float k = 1.0 - eta * eta * (1.0 - dot(N, I) * dot(N, I));
    if (k < 0.0)
      return 0.0;
    else
      return eta * I - (eta * dot(N, I) + sqrt(k)) * N;
}
```

4.3. Operation grouping

Generally it is beneficial to group scalar and vector operations separately. This way the compiler can pack more operations into a single cycle.

```
fragColor.xyz = t.xyz * t.x * t.y * t.wzx * t.z * t.w; //7 cycles
{sop, sop, sopmov}
{sop, sop, sopmov}
{sop, sop}
{sop, sop, sopmov}
{sop, sop}
{sop, sop, sopmov}
{sop, sop}
-->
fragColor.xyz = (t.x * t.y * t.z * t.w) * (t.xyz * t.wzx); //4 cycles
{sop, sop, sopmov}
{sop, sop, sopmov}
{sop, sop}
{sop, sop}
```

5. FP16 overview

5.1. FP16 precision and conversions

FP16 pipeline is works well when reduced precision is sufficient. However, it is advisable to always check whether the optimizations resulted in (precision) artefacts.

When 16 bit float precision hardware is available (and shaders use mediump), then 16<->32 bit conversion is free (using modifiers), because the USC ALU pipeline includes it.

However, when shaders don’t use the 16 bit instructions or the hardware does not contain a 16 bit float pipeline (early Series 6 hardware), then the instructions just run on the regular 32 bit pipeline (therefore no conversions happen).

5.2. FP16 SOP/MAD operation

The FP16 SOP/MAD pipeline is one of the strongest points of the PowerVR ALU pipeline.

If used correctly, it enables developers to pack more operations into a single cycle. This may result in increased performance and reduced power consumption.

The single cycle FP16 SOP/MAD operation can be described by the following pseudo code:

```
//Inputs:
a, b, c, d = any of {S0, S1, S2, S3, S4, S5}.

z = min(s1, 1 - s0)

e, f, g, h = any of {S0, S1, S2, S3, S4, S5} or z.

//Inputs only for the MAD pipeline:
v, w, x, y = any of {S0, S1, S2, S3, S4, S5}.

//Operations to be performed
jop = any of {add, sub, min, max, rsub, mad}
kop = any of {add, sub, min, max, rsub}

//either use the MAD or the SOP pipeline
if (jop == mad)
{
  //two mad operations performed in parallel
  W0.e0 = a*e+v
  W1.e0 = b*f+x
  W0.e1 = c*g+w
  W1.e1 = d*h+y
}
else
{
  //multiply the SOP inputs and perform the desired operation on the result
  //performed in parallel
  j = (a * e) jop (b * f)
  k = (c * g) kop (d * h)

  //convert result to FP32
  //or keep the results as is
  if (rfmt(1) = 1)
  {
        w1 = toF32([k)
        w0 = toF32([j)
  }
  else if (rfmt(0) = 1) then
  {
        w0[31:16] = one of {j, a, b}
        w0[15:0]  = one of {k, c, d}
  }
  else
  {
        w0[31:16] = one of {k, c, d}
        w0[15:0]  = one of {j, a, b}
  }
}
```

It is also possible to apply various modifiers (abs, negate, clamp, oneminus) to the inputs and clamp to the outputs. See the next section for how to fully exploit the FP16 SOP/MAD pipeline.

5.3. Exploiting the SOP/MAD FP16 pipeline

The PowerVR Series 6 architecture has a powerful FP16 pipeline optimized for common graphics operations. This section describes how to take advantage of this.

It is important to note that converting the inputs to FP16 and then converting the output to FP32 is free.

With SOP/MAD you have a number of options:

In one cycle, you can execute 2 SOPs or 2 MADs or 1 MAD + 1 SOP. Alternatively, you can execute 4 FP16 MADs in one cycle.

Executing 4 MADs in one cycle.

```
fragColor.x = t.x * t.y + t.z;
fragColor.y = t.y * t.z + t.w;
fragColor.z = t.z * t.w + t.x;
fragColor.w = t.w * t.x + t.y;
{sopmad, sopmad, sopmad, sopmad}
```

SOP means Sum of Products with a choice of an operation between the result of the multiplies:

```
fragColor.z = t.y * t.z OP t.w * t.x;
fragColor.w = t.x * t.y OP t.z * t.w;
```

where OP can be either an addition, a subtraction, a min or a max:

```
fragColor.z = t.y * t.z + t.w * t.x;
fragColor.z = t.y * t.z - t.w * t.x;
fragColor.z = min(t.y * t.z, t.w * t.x);
fragColor.z = max(t.y * t.z, t.w * t.x);
```

You can also apply either a negate an abs() or a clamp (saturate) to all the inputs.

```
fragColor.z = -t.y * abs(t.z) + clamp(t.w, 0.0, 1.0) * -t.x;
```

Finally, you can also apply a clamp (saturate) to the end result:

```
fragColor.z = clamp(t.y * t.z OP t.w * t.x, 0.0, 1.0);
fragColor.z = clamp(t.y * t.z + t.w, 0.0, 1.0);
```

After applying all this knowledge, we can show off the power of this pipeline by using everything in one cycle:

```
//1 cycle
mediump vec4 fp16 = t;
highp vec4 res;
res.x = clamp(min(-fp16.y * abs(fp16.z), clamp(fp16.w, 0.0, 1.0) * abs(fp16.x)), 0.0, 1.0);
res.y = clamp(abs(fp16.w) * -fp16.z + clamp(fp16.x, 0.0, 1.0), 0.0, 1.0);
fragColor = res;
{sop, sop}
```