Characterization and Reverse-engineering Assignment - EEC 277

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1 Introduction

This report is divided into two parts; performance analysis of the graphics card and reverse engineering to charactrize undocumneted features of the GPU. In the first part, we are going to characterize the performance of the two GPU using `wesBench` benchmark. The target here is to find the crossover point between the geometry/vertex stage and fragment/rasterization stage for different scenarios. Broadly speaking, the graphics pipeline overall performance is a function of the slowest of these two stages. It is well known that the geometry stage favors large primitive triangles since the speed of this stage is dependent on the operations-per-vertex. In contrast, rasterization stage favors small primitive triangles since a large triangle would require more fill operations [1].

Second part is concerned with detecting the precision of the graphic card. We first characterize the error associated with primitives math operations OpenGL. Additioanlly, we use a simple shader program to ensure the compliance of our GPU with IEEE-754 standards and to detect the rounding algorithm implemented.

All the experiments presented in the report are done on NVIDIA GeForce GT 610 GPU on a Windows 7 machine with four-core Intel(R) Xeon(R) CPU of 3.7GHz and 32.0GB RAM.

2 Part A

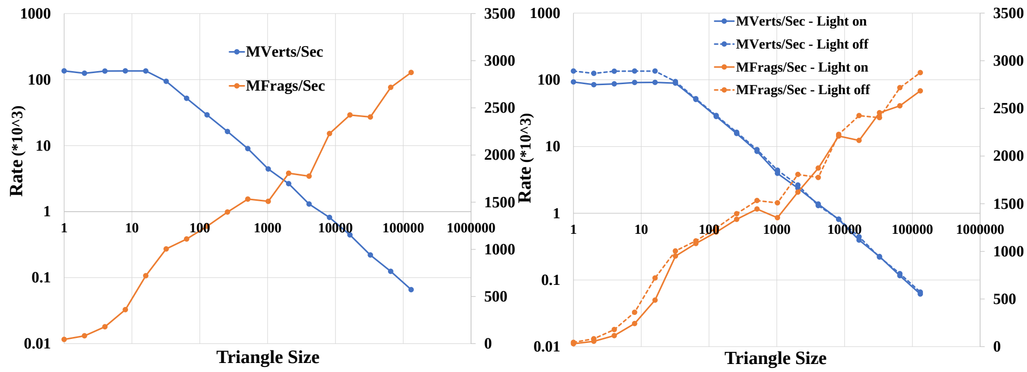
2.1 Geometry Rate Vs. Fill Rate:

The objective of first experiment is to find the crossover point for the unlit, untexture triangles between the fill rate and geometry rate in terms of triangle area in pixels. This is done by testing both rates for different triangle sizes. The results are shown in Figure 1(a) on a log-log scale, where the fill rate (MFrags/Sec) increases as expected for small triangles and geometry rate (MVerts/Sec) decreases. The crossover point is between triangle area between 2^{10} and 2^{11} pixels. We notice that for triangle of size between 2^1 to 2^4 pixels the geometry rate is almost constant. Even though the geometry rate is the highest but this could be due to more efficient use of caching. Since the triangles are of small size, and due to spatial locality, more triangle can be fetched and put into the cache.

On the other side, the rapid change on the fill rate starts to slow down at triangle size greater than 2^4 pixels. This is noticable since the fill rate curve can be approximated by a quadratic function for upto triangle size of 2^4. After that, the curve takes a linear trend which is slower than quadratic trend. This could be due to the fact that the geometry stage is not sending enough work to the rasterization stage. So even the overall fill rate increases as the triangle size increases, but the slope of the curve is not the same overall.

2.2 Geometry Rate Vs. Fill Rate on Lit Triangles:

The previous test was done on unlit, untexture triangles which is the default setting in `wesBench`. Now we turn on the light on the triangles and do the same test and compare the results with the unlit triangles. The results are shown in Figure 1(b) where the crossover point is almost the same (we only notice it moved a little closer to triangle of size 2^{11}). Additionally, we notice that the upper portion of the graph (towards triangle of size greater than 2^5 pixels) of the geometry rate curve is identical i.e., the dotted and the solid lines overlap. For the lower part of the graph, it is understood that the geometry rate should decrease since the lighting is being processed at this stage and thus more work need to done for computing each vertex, especially that more vertices are needed for such small triangles. This will directly affect the fill rate since less work is sent to the rasterization stage and thus



(a) Default

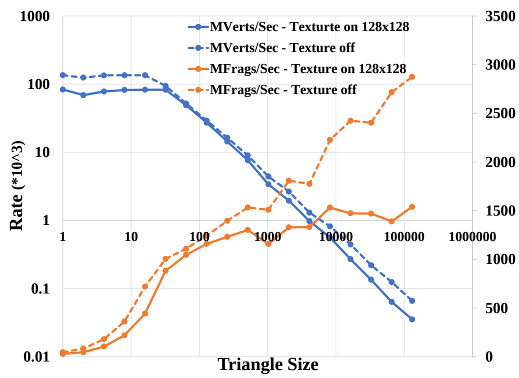
(b) Lit Triangles

Figure 1: Performance and crossover point of the default settings in `wes-Bench` (a) and the lit triangles Vs. the default (unlit) triangles (b) in millions of vertices per second and millions of fragments per second.

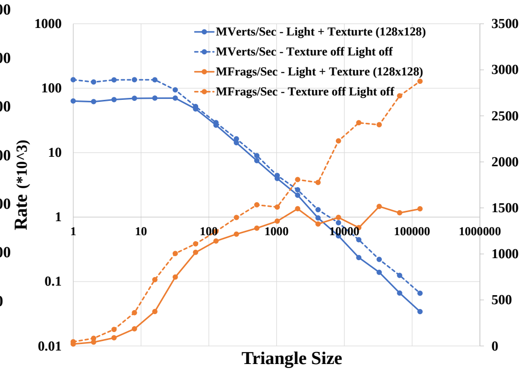
a decline in absolute fill rate. As the triangle size increases, less number of vertices need to be processed in the geometry stage. Thus, even though more work need to be done per vertex (compared with unlit triangles), we notice that the lit triangle rate is almost identical to the unlit ones. In contrast, the behavior of fill rate curve is not consistent and we do not see a certain trend. For example, triangle of size 2^{12} and 2^{15} pixels have a higher fill rate with lit triangles than with unlit ones. While for triangle of size 2^{14} and 2^{16}, it is the opposite. We would expect that for this upper portion to be identical with the unlit triangles, since the geometry stage is now able to send the same amount of work and there is no additional work required at the rasterization stage for lit triangles. Thus, We could not derive a conclusion for such behavior.

2.3 Geometry Rate Vs. Fill Rate on Textured Triangles:

Now we turn on testing the textured triangles. Following the same methodology as in Section 2.2, we add textures of size $2^7 \times 2^7$ to the triangles and vary the triangle size and record the fill and geometry rates. We tested first with texture of smaller size ($2^3 \times 2^3$), but the graph we got was identical to the untextured one, so we discarded. We assume that this happened due to



(a) Textured Triangles



(b) Lit, Textured Triangles

Figure 2: Performance of the textured triangle Vs. the default (untextured) triangles in `wesBench` (a) and lit, textured triangles Vs. the default (unlit, untextured) triangles (b) in millions of vertices per second and millions of fragments per second.

minimal workload required with small texture size.

Figure 2(a), compare the fill and geometry rate for textured and untextured triangles. The crossover point has shifted to be between triangle of size 2^{12} and 2^{13} pixels. The graph also shows a decline in the performance in the textured triangles for both the geometry and fill rate. For the geometry stage, the decline in the number of vertices processed per second is due to the necessary transformation done per vertex (applying the *projector function*[2]). The graph in Figure 1(b) and in Figure 2(a) suggest that per-vertex-operation for the lighting is similar to per-vertex-operation for texture which is indicated by the absolute value of geometry rate at a triangle size (for triangle size $\leq 2^5$ pixels). Additionally, the graph shows a divergence in the geometry rate between the textured and untextured curves. At first glance, this was surprising and we expected a similar behavior as in lit triangles (the curves overlap for large triangles). This stemmed from the fact that as the number of triangles decreased as the size increases, less number of vertices needed to be processed. However, we think that this divergence could be due to caching. Since we are using a relatively large texture ($2^7 \times 2^7$) and for a big triangles, it is required to fetch different parts of the texture image that may not be fetched all together into the cache (less spatial locality).

For rasterization, the fill rate decline since the texture operation is more expensive on fragments. During the rasterization, the *corresponder function* (matrix transformation) is applied per fragment and texture value per fragment is interpolated [2]. Both could be the reason for the decline in the fill rate. We notice a similar divergence happens in fill rate. This is understandable since for large triangle more fragment are being processed per triangle (less parallelism can be extracted for big triangles).

2.4 Geometry Rate Vs. Fill Rate on Lit, Textured Triangles:

Here we use lit, textured triangles and compare the same performance metrics with the unlit, untextured triangles. Figure 2(b) shows that the crossover point did not change from the texture triangle case (Section 2.3) which might indicate that the graphics card used is optimized for this value. For large triangles (size $\geq 2^5$) the lighting does not have real impact on both the geometry or the fill rates, then the decline in the performance is purely due to the texture processing. For smaller triangle size, both lighting and texturing contribute in the performance decrease.

2.5 Geometry Rate Vs. Fill Rate for Strips Vs. Disjoint Triangles:

OpenGL offers to represent a set of triangle in form of a list allowing more efficient memory usage. The list (strip) offers substantial reduction in number of vertices needed to be processed. Instead of storing each triangle by its three vertices, strip stores a list of vertices such that each three vertices compose a triangle. Disjoint triangle store a triangle by its three vertices, thus almost all vertices are duplicated by the number of triangles a vertex is a member in.

We use `wesBench` to measure the relative performance of the fill rate and geometry rate using these two types of triangle. The results is show in Figure 6(a). First we notice that the triangle rate of strip triangle is almost identical to the vertex rate. Meanwhile for disjoint triangle, the vertex rate is three time higher than the triangle rate (at certain triangle size). The reason behind that is the triangle strip length is equal to number of vertices plus two, thus we notice for very large triangle the two curves (triangle and vertex rate) diverge.

An interesting observation is the vertex rate for triangle size $\geq 2^4$ for triangle strip is so close to this of disjoint triangle. This gives disjoint triangle higher performance in terms of vertex rate since the vertex rate is three time higher than the triangle rate. For smaller triangle size, strip triangle has higher triangle rate, but still vertex rate of disjoint triangle outperforms. This is because the triangle rate should be three times higher to start overcome the disjoint triangles. For fill rate, triangle strips outperforms the disjoint triangles. We assume that this is because both can feed the rasterization stage equally (similar triangle rate), but triangle strip exhibits better temporal and spatial locality which gives it an edge over disjoint triangle.

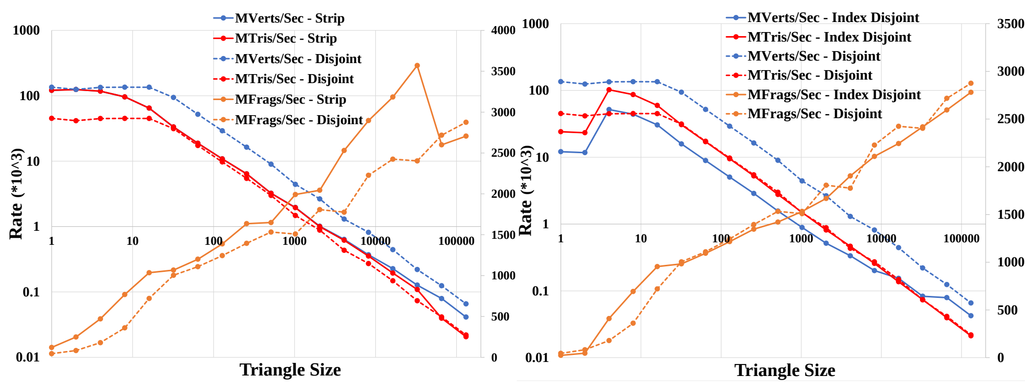
2.6 Geometry Rate Vs. Fill Rate for Indexed Disjoint Vs. Disjoint Triangles:

Here we try to evaluate the performance with two different type of triangles; disjoint and indexed disjoint triangles. With disjoint triangles, each triangle is specified by three vertices without reusing these vertices for a neighbor triangle. Indexed disjoint triangles reuse the vertices such that one vertex is shared among many triangles and thus no duplication is necessary. We will see later that the average number of triangles shared per vertex is approximately six triangles.

For indexed disjoint triangle, the total number of vertices is reduced by factor of three. Thus, we expect the geometry rate to be higher for the case of indexed disjoint triangles when compared with disjoint triangles. But actually this not the case as shown in Figure 6(b) where the disjoint triangles geometry rate outperforms the indexed variant. If we, instead, look at the triangle rate (MTris/Sex), we will find that the triangle rate is identical for triangle of size $\geq 2^5$. This means if the geometry stage is processing X triangles, then for the disjoint triangles case, $3 \times X$ vertex should be processed. But for the indexed disjoint case, less number of vertices will be processed. For triangle size $\geq 2^5$, by dividing the the geometry rate for the disjoint triangle by the geometry rate for indexed disjoint triangles and taking the normalized average, the result would be the number of triangles shared per vertex in the indexed disjoint triangles. Rounding the result, we found that it is 6 triangles per vertex. In conclusion, this indicates that the graphic card must been optimized to handle both cases efficiently by fixing the number of triangles being processed regardless to the vertex rate (which sounds a complicated task to achieve!)

For fragment rate, since the geometry stage in both cases is able to send the same workload (in terms of triangle rate) for triangle of size $\geq 2^5$, we the fragment is almost identical for both cases with few wiggles that could be due to caching behavior in the disjoint case. Additionally, when the triangle rate increases for index disjoint triangles (triangle size $2^1 - 2^5$), we notice an equivalent improvement in fragment rate. The reason behind that is for such small triangles, the process is limited by geometry stage. If the geometry rate improves (able to send more work to rasterizer), then fill rate will improve too.

We conclude from this comparison that we should also investigate the triangle rate, along with the vertex rate and fill rate in order to fully characterize and understand the graphic card behavior.



(a) Strips Vs. Disjoint (b) Indexed Disjoint Vs. Disjoint

Figure 3: Performance of the strips triangles Vs. disjoint triangles (a) and indexed disjoint triangles Vs. disjoint triangles (b) in millions of vertices per second, millions of triangle per second, and millions of fragments per second.

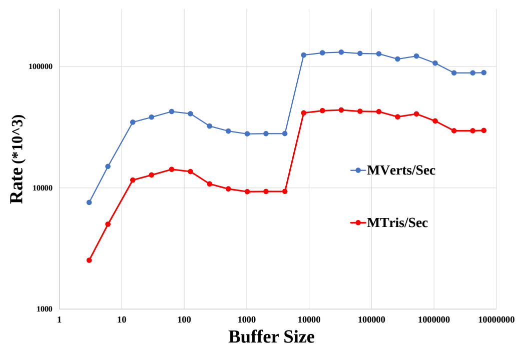
2.7 Geometry Rate Vs. Fill Rate for Varying Batch Size:

The objective of this experiment is to find the buffer size at which the system becomes GPU-limited not interface-limited. Using `wesBench`, we were able to test different buffer sizes with each `glDrawArrays` call and record the vertex and triangle rate of each buffer size as shown in Figure 4(a). We notice that the least performance corresponds to the smallest buffer size since the CPU is not able to send enough work to the GPU and thus the system is bandwidth-limited. With increasing the bucket size, the vertex and triangle rate improves up to buffer of size 2^4 where the system is GPU limited (limited by the geometry stage). The curve exhibits another jump in the performance with buffer of size 2^{12} where we have to decrease the triangle area to maintain a buffer of large size. After this second jump, the curve is almost the same which means that the process is still limited by the GPU.

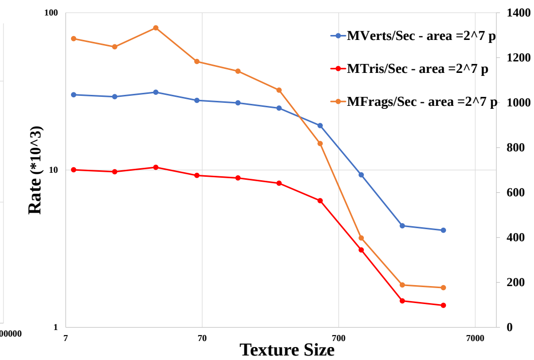
To calculate the bandwidth, we will have to multiply the number of vertices per batch (buffer size), but the content of these vertices. For our experiment, we used unlit, untextured triangles. Thus, the inofrmation hold by each vertex is the position (x,y,z,w) and its color (r,g,b). Each of these are 4 bytes which gives a total of 28 bytes per vertex. Thus, the bandwidth at the turnaround point 448 bytes/batch.

2.8 Geometry Rate Vs. Fill Rate for Varying Texture Size:

The final experiment was conduced to characterize the texture size and understand how it affects the performance. We used `wesBench` to vary the size of the texture image from $2^3 \times 2^3$ texels to $2^{12} \times 2^{12}$ texels and recorded the vertex, fill, and triangles rates as shown in Figure 4(b). We notice degradation in both the vertex rate and fill rate as the size of texture size increases. The decline in vertex rate (and triangle rate) is less dramatic than fill rate. For both vertex and fill rate, we assume the performance declines due to caching. For smaller texture size, the texture image can fit in the texture cache memory. Thus, the performance is limited by the operation itself. For larger texture size, the texture memory bandwidth is the bottleneck due to the repeated look-ups since the texture image could not be resident in the cache all the time. For fill rate, we would expect that the fill rate would remain constant for a range of texture size after which the fill rate would fall. Such a value would give an indication for the texture memory cache. But it looks like the cache is optimized (e.g. pre-fetching) such that the degradation in performance as the texture size increases is less dramatic.



(a) Varying buffer size



(b) Varying texture size

Figure 4: Performance of varying the texture size while fixing the triangle are to 2^7 pixels (a) and 2^{14} pixels (b) in millions of vertices per second, millions of triangle per second, and millions of fragments per second.

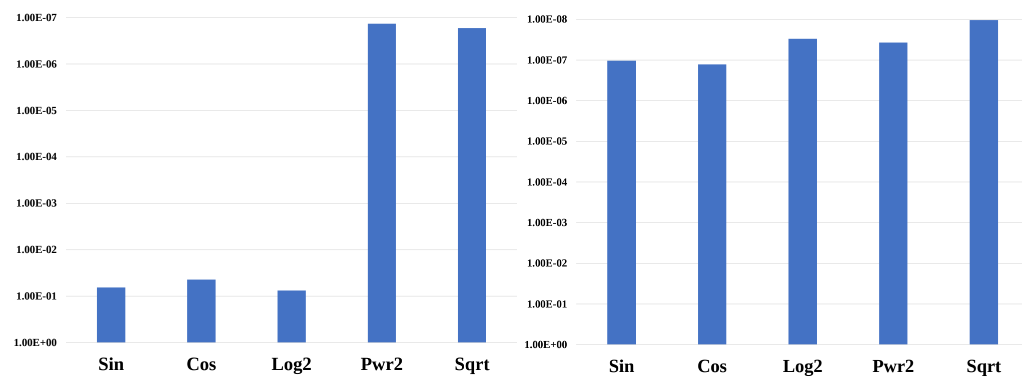
3 Part B

So far the characterization of the graphics card performance was in terms of the speed of operations. Now we turn to characterize the quality, specifically the precision of the native arithmetic operations. Precision is crucial because the speed render irrelevant if the results are not accurate. Even under the IEEE-754 Standards, identical operations could produce different results when executed on two different machines because of different hardware implementation and the peculiar nature of floating points operations (e.g. floating point addition is not associative).

In this section, we start by quantifying the error of the native arithmetic operations. We compare GPU's results with the CPU to measure the error. We also try to discover a precision-related undocumented features; how rounding is implemented in our graphic card.

3.1 Arithmetic Operations Accuracy:

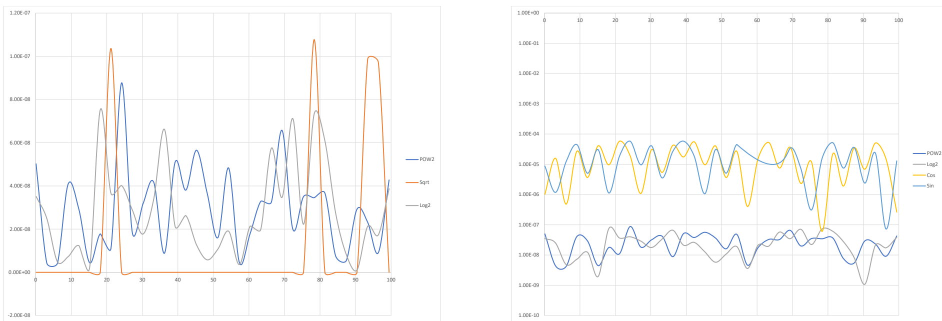
Here we test a range of basic float point arithmetic operation offered by the GPU. Taking the CPU results as our datum, the absolute relative error between the GPU's results and CPU's results represents the GPU errors. The rationale behind this method is that both CPU and GPU are compliant with IEEE-754 Standard. Our approach was to write an OpenGl code that utilizes fragment shaders to perform the arithmetic operations. Basically, we send floating point value to the GPU as a color component of pixels, then perform a basic operation on it, and finally we can read the pixel's final color component that we applied the shader to. Initially we wanted to use GLSL to write our fragment shader; however, we wanted to directly access the GPU hardware to eliminate any source of error that may stems from different software configurations or optimization. That's why we decided to use Shader Assembly Language ARB to impelment our fragment shader. That way we can guarantee that the GPU is only doing precisely what we ask it to do (eg: calculating the Sin of a number). Using ARB instructions, we were able to quantify the error in Sin, Cos, Power, Log, and Square root functions.



(a) Average Error (b) Maximum Error

Figure 5: Average and maximum relative error for few basic arithmetic operations.

We conduct the test for each of our functions by giving it a series of inputs starting from 0.1 and ending at 100 with an increment of 0.01 between each input values. Then we calculate how much the GPU results deviate form the CPU results and average that thoughout our iterations. Also we keep track of the maximum instance of error to give us an idea of how bad the worest case scenario can be. From figure 5 we can conclude that the sinusoidal fuction usually have higher error on our GPU. The average relative error for Sin was the highest among all fuctions also it had the worest case scenario ever. On the other hand the logarithmic function had the least error among all functions. However, the maximum value of the error of the log function was almost 1000 times as much as the average case. We can infer that the GPU implementation of the log is not as reliable as the other fuctions since some time its precision can vary dramatically.



(a) (b)

Figure 6: The error trend accross our testing space

Another important metric that we need to examine is how the precision of each of our operations get affected by increasing the value on the input. In other words, we need to figure our if there is a certain trend for the error in each our functions. Figure 6 shows samples of the relative error throughout our testing space.

3.2 Detect Precision via Shader Program

The purpose of this test is to first verify that our GPU is IEEE-754 compliant and second to identify the rounding algorithm implemented. For this test, we borrowed the fragment shader used in Russell's article [3] shown in Figure 7. In Russell's article, the shader was used to benchmark the accuracy of GPU floating point across different mobile GPUs.

3.2.1 Compliance with IEEE-754

The shader simply fills the screen with 26 bars. Given infinite precision, each bar should vary linearly from white (left) to black (right) as a function of X coordinate of the pixel. Note that the implementation calculates 1_X so we, instead, can consider $X = 0$ is to the left of the screen and $X = 1$ is

Listing 1: Fragment Shader.

```
void main(void) {
  float y = (gl_FragCoord.y / y_res) * 26.0
  float x = (1.0 -(gl_FragCoord.x / x_res))
  float yp = pow(2.0, floor(y))
  float fade = fract(yp + fract(x))
  if (fract(y) < 0.9)
     gl_FragColor = vec4(vec3(fade), 1.0)
  else
     gl_FragColor = vec4(0.0)
}
```

Figure 7: The fragment shader implementation for verify the floating-point representation compliance with IEEE-754 standards

to the right. The shader is written such that with each level/bar, one bit of the fraction (significand) is thrown away. For each level L, we add 2^L to the computed gray value (X coordinate of the pixel) and take the fraction of the result. The added integer (2^L) does not affect the value of the gray scale, but only its precision. For example, for the first bar, we add $2^L = (1)_{ten} = (1)_{two}$ which is represented by one bit. Thus, when added to $fract(x)$ and taking the $fract()$ of the result, we only loss one bit of the gray scale value's precision. For the next level, we add $2^L = (4)_{ten} = (10)_{two}$, which is represented by two bits and thus two bits loss in precision. This goes up till we end up with zero precision in the fraction part and thus the image turns to black. Figure 8 shows the result of running the shader on our graphic card. We can see that even though we are trying to draw 26 bars, only 23 bars are shown and the rest are black. This verifies that the fraction part (significand) of float point numbers in our graphic card is represented by 23 bits which matches exactly what IEEE-754 requirements.

3.2.2 Rounding Algorithm

We notice on the Figure 8 that for the last few upper bars that the linearly-varying gray scale is a little edgy. We believe that this is due to rounding. Next we explain why we believe so and we use this to investigate the type

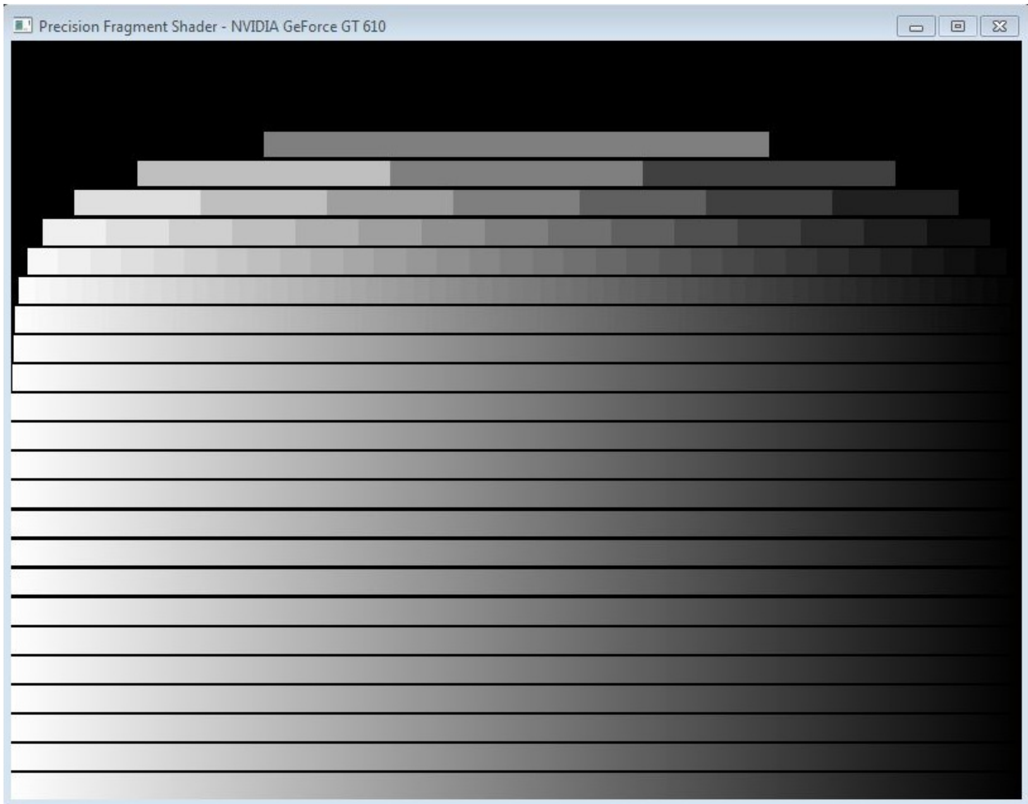


Figure 8: Results of applying shader in Figure 7.

of rounding algorithms that is used in our graphic card and compare it with an Intel-integrated graphic card.

Due to limited finite bits we have to store intermediate values during the calculation in with floating-point numbers, we must do rounding to these values. There are many modes of rounding available; rounding down (truncate), round up, and round to nearest even. Rounding up or down is straightforward and less complicated and thus it is more favorable for embedded system since more emphasis is on the speed than quality. The IEEE-754 requires the floating-point rounding to be nearest even. This requires storing few (three) extra bits to (guard, round and sticky bit) in order to keep track of the shifted bits [4]. This offers more accurate results such that the guard and round bits will, while shifting, keep track of the two most significant bits to be truncated. Sticky bit can be considered as logic bit that is set to 1 when there is nonzero bits after the round and guard bits.

Looking again at Figure 8, the last visible bar will have only one bit in the significand to represent it. The range of values we need to represent using this value is from 0.000 up 0.9999... in decimals. For the value between $0.00 - 0.25$, the guard bit is zero. Thus, regardless to the round and sticky bits, the number will be rounded down to 0. This simply means we do nothing or truncate. Since the most significant bit is zero, then we will end up with 0.0. This explains why the bar at the beginning is black. For values between $0.25 - 0.5$, the guard bit is now one and the result will depend on the round and sticky bit. Since the stick bit is set, then we will round up (add one to the most significant bit). This gives a value of $(0.5)_{ten} = (0.1)_{two}$ which is gray as the figure shows. Next for value between $0.5 - 0.75$, the guard bit is now zero again which means we round down (do nothing). Since the most significant bit is one, we will end up with 0.5. The range between $0.25 - 0.75$ will result in a most significant bit to be one which gives a gray color. For range between $0.75 - 0.99$, the guard and stick bit are not set and we will have to round up. Since now the most significant bit is one, adding one to it (rounding up) will result into moving to the next integer and zero in the most significant bit. This explains why the bar turns black at the end.

Appendix

We answer here few questions concerning the implementation of `wesBench`. This can be considered as the lessons we have learned after dealing with `wesBench` code.

Using glDrawArray or glDrawElement is faster and more efficient than using glBegin, glVertex, glEnd. Basically, using glDrawXXX allows us to use the notion of Vertex Buffer Object (VBO) which treats a set of vertices as one group as opposed to the direct mode of processing one vertex at a time. Using VBO shows improved performance when using large batches of vertices. Also using the VBO comes in handy with programmable shading. We can write a shader program to specify how our pipeline should manipulate the vertices attributes and that will apply to all elements in the VBO automatically. The old school, now deprecated, glBegin/glEnd approach relays on explicitly describing the attributes of each vertex. In `wesBench`, they use VBOs to send data to the GPU as a single array contains position data followed by color data, etc. This allows making one function call to draw the arrays rather than several calls. `wesBench` is actually drawing its geometry by constructing a $M \times M$ mesh of points that are positioned to fill one quarter of the screen resolution. The spacing between vertices in that mesh is specified by user inputted area of the triangles. This mesh is converted in the pipeline to fragments. `wesBench` makes sure that all the fragments should remain visible while rotating the mesh about the center of the screen for user-specified time duration.

References

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