國立交通大學

資訊科學與工程研究所

碩士論文

細線化前之區塊深度值測試與其對系統設計之影響

Pre-rasterization blocked-Z test and its impact on system design

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摘　　要

本論文提出一個區塊式深度值測試方法來有效的減少在細線化之前的資料量。在繪圖管線中，不管是否存在其他深度值測試方法，區塊式深度值測試都可以和既有的繪圖管線完美的結合，而且區塊式深度值測試的效果比起以物件為單位的深度值測試好許多。在本論文中，會在細線化前將物件切分成許多適當大小的區塊且透過區塊式深度值的測試來過濾掉大部分被擋住的區塊，以此來減少繪圖管線後續的工作量和儲存空間。有主要兩個優點:一來是可以透過單次的深度值測試過濾掉許多網格(一個區塊內的所有網格);二來是可以減少細線化不必要的運算量。而為了實現本論文，需要額外的一塊區塊深度值儲存器和切分區塊及區塊深度測試的電路。

雖然本論文會加深整個繪圖管線的深度，但不會影響整體繪圖管線的總處理量，甚至可能提高。其原因是對網格作運算是整體繪圖管線的瓶頸處，而本論文可以有效得減輕這些瓶頸處。

Pre-rasterization blocked-Z test and how it impacts system design

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Abstract

We propose a blocked-Z test to effectively eliminate unnecessary data traffic between triangle setup and rasterization. This method works seamlessly with the existing rendering pipeline, with or without those existing fragment-based hierarchical Z/early Z/Z tests. And it performs much better than primitive-based Z test, in terms of data structuring and coverage. In this method, primitives are blocked into proper sizes and blocked-Z tested to filter out the most of hidden blocks, easing the storage and workloads of subsequent rendering tasks. Advantage of this method comes from two features: the blocked test, in which only one test may be sufficient to filter out a group (of the block size) of fragments; and the place of the test saving even unnecessary rasterization. Block sizes are determined statically without hardware nor runtime overhead, and an additional blocked-Z buffer, of the size of [Z buffer/(# fragments in block)], plus blocking and Z-test circuitry, are required. This design lengthens the rendering pipeline, but will not affect the throughput; in fact, it may even increase throughput, since a common wisdom is that the fragment-based pipeline stages are graphics rendering bottlenecks, and our proposal effectively relieves these bottlenecks. Experimental results using Doom3 and Quake4 with various screen sizes show that the rasterization and Z test workloads can be saved by 70%.

誌謝

這兩年來的碩士研究生涯中，首先，我要感謝我的指導教授 鍾崇斌老師。感謝他嚴謹與耐心的指導，使我在我的碩士研究中，獲得許多寶貴的建議與方向，並且學習到如何以不同的角度去看待研究事物，並對各種可能性加以討論並提出質疑，而得以完成此碩士論文及順利通過畢業口試。此外，感謝我的畢業口試委員 單智君教授、謝萬雲教授、謝錫堃教授，由於他們的建議，使得此論文研究更加完整。

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此外，感謝我的家人在背後默默的支持我，即使你們對於研究上沒辦法給予我太多意見，但有你們在一旁關心我，也讓我能更堅定與堅毅地繼續我的研究之路。最後，女友妤珍在背後的支持更是我前進的動力，沒有妤珍的體諒、包容，相信這兩年的生活將是很不一樣的光景。

陳浤偉 2009.9

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Chapter 1 Introduction

Nowadays, 3-D scenes have greatly number of objects and high depth complexity due to emphasizing more and more visual realism. When three-dimensional (3-D) computer graphics process such these scenes, the workloads of each unit are extremely high, especially the pixel shader. It is because the pixel shader needs to process texture mapping, shadow, or some complex computation to get final color for every fragment. For example, the complex scenes may have several hundred thousand objects in one frame and may generate several hundred million fragments to be processed in pixel shader.

In order to reduce the workload of pixel shader, 3-D computer graphics do the per-fragment early-Z test before pixel shader to filter out some invisible fragments. It can alleviate the workload of pixel shader significantly. However, the per-fragment early-Z test has large workload since it has to test the Z value for every fragment. So there is another approach, generally called primitive-level early-Z test, to reduce the workload of per-fragment early-Z test. Primitive-level early-Z test processes the Z test based on primitive before rasterization, opposed to the fragment, it can filter out many invisible fragments which compose of primitive in one time. It even can reduce the workload of rasterization. But the effect of primitive-level early-Z test cannot guarantee since the primitive can be filter out when the primitive is totally occluded by another primitives.

In this thesis, we are going to design a low computation early-Z test before rasterization to reduce the workloads of per-fragment early-Z test and rasterization. And it can perform better than primitive-level early-Z test, in terms of data structuring and coverage.

1.1 Motivation

As we can know, the per-fragment early-Z test has the highest filtering ratio. It can filter out the most occluded fragments than other coarse early-Z test since fragment is the smallest granularity in rendering pipeline. However, per-fragment early-Z test has serious workloads. It needs to perform the depth test for all fragments in one frame, and the fragment count in one frame is very high.

Primitive-level early-Z test can alleviate the workload of per-fragment early-Z test since it would filter out some totally occluded primitives before rasterization. However, primitive-level early-Z test only can filter out totally occluded primitives. The partial occluded primitives would still perform the subsequent rendering stage. It may cause some redundant operation.

1.2 Objective

We are going to propose a low computation early-Z test before rasterization for achieving the high filtering ratio as possible. It can filter out the partial occluded primitives before rasterization. Hence, the proposed method can reduce more workloads of rasterization and per-fragment early-Z test.

1.3 Organization about this thesis

The origination of follow sections in this thesis is: Chapter 2 introduces background of programmable GPU pipeline, two well-known early-Z test approaches and related works. Chapter 3 introduces our proposed method, blocked-Z test. We will introduce how to generate blocks, how to perform depth test based on block, and how to perform rasterization for blocks. Experiment results are shown in chapter 4. Conclusion is made in chapter 5.

Chapter 2 Background and related works

In section 2.1, we will give a brief concept of programmable rendering pipeline in Graphic Processing Unit (GPU). In section 2.2, we will introduce the per-fragment early-Z test briefly. In section 2.3, we will introduce the Hierarchical Z test which is one of well-known primitive-level early-Z test. Finally, some related works will be study.

2.1 Programmable GPU pipeline

Graphic processing unit (GPU) is a kind of application specific processor. It targets on graphics rendering, which display the two-dimensional image (2D) of three-dimensional (3D) space. The modern GPU become more and more complex due to the demand for 3D scene visual realism are increasing.

Nowadays, programmable GPU pipeline is the popular solution for the requirement of performance and flexibility in computer graphics. Different from the fixed function GPU pipeline, programmable GPU pipeline has two new units: vertex shader and pixel shader. These two new units can provide the flexibility to deal with any kind of operation requirement, like the 3D games, virtual realities …etc.

The programmable GPU pipeline is shown in Figure 2-1-1. There are several stages in this pipeline, which are vertex shader, triangle setup, rasterization, early-Z/HZ test, pixel shader, and depth processing.

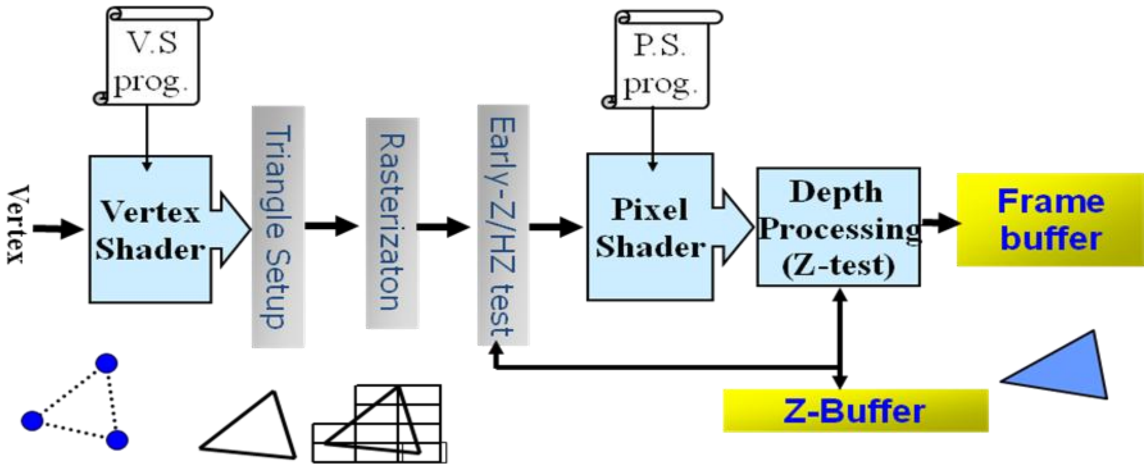


Figure 2-1-1 Programmable GPU pipeline

The first stage, vertex shader, majorly performs vertex's coordinate translations. It also can perform some complex mathematics operations on the vertex data by vertex shader program. The translations are a serial of coordinate translations from vertex's local coordinate to world space coordinate and finally translate to screen coordinate. After coordinate translations, vertex shader performs the Clipping to clip some objects which are not in the view volume.

After vertex processing, it sends the translated vertex data to triangle setup stage. Triangle setup is responsible for assembling the primitive according to their screen coordinate. It is finding three vertices which are belong to the same primitive and assemble these three vertices into primitive. Moreover, triangle setup calculates the edge slope and some primitive information after assembling the primitive. Based on the primitive information and edge slope, the later stage, rasterization, performs the interpolation of primitive. On the other words, rasterization interpolates each primitive into many fragments. The difference between fragment and pixel is that fragment has the depth information. When the fragments output to the frame buffer, it will call the pixel. The well-known approach is according to the each horizontal scan line on the primitive to generate fragments, which is shown in Figure 2-1-2.

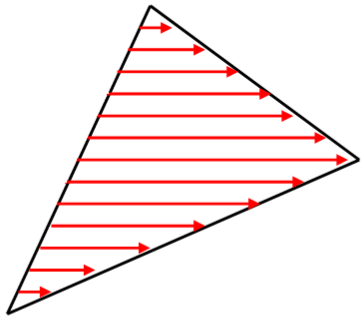


Figure 2-1-2 Horizontal scan line on the primitive

After rasterization, early-Z test performs the depth test to filter out some invisible fragments. The brief concept and operation will be introduced in later section. The passing early-Z test fragments will be sent to pixel shader. The major work of pixel shader is coloring the fragments. It may directly perform some computation to get the color or perform the texture mapping to get the color. It also can perform some complex computation to get the special effect like multi-texturing by pixel shader program. After pixel shader, the fragment with final color will be sent to depth processing stage.

Since there are many fragments located on the same screen coordinate, it needs to perform the depth test to find out which fragments will display on the screen and filter out those invisible fragments. The invisible fragments mean that they are occluded by the smallest depth value of fragment. The main operation is that depth processing compares the Z value of the executing fragment with the corresponding Z value on the Z buffer. If Z value of the executing fragment is smaller, then write this fragment to the frame buffer and update the Z buffer. Otherwise, filter out this fragment. Finally, having the smallest Z value’s fragments will on the frame buffer for displaying on the screen.

2.2 Per-fragment early-Z test

In the previous section mentions, the depth processing filters out all fragments which are occluded by previously drawn fragments according to a comparison of their depth value. The depth processing is performed after pixel shader. However, the pixel shader usually has the most complex computation in the rendering pipeline. Executing one fragment in pixel shader needs to spend much time. It might be inefficient to perform all fragments in pixel shader since many fragments will be filtered out afterwards.

In consequence, modern GPUs will perform depth test before pixel shader. Since the depth test is performed before pixel shader and based on the fragment, it is called the per-fragment early-Z test. Instead of traditional GPUs, only the passing per-fragment early-Z test fragments need to perform in pixel shader. The operation of per-fragment early-Z test is comparing the Z value of executing fragment with the corresponding Z value on the Z buffer or extra early-Z buffer. The extra early-Z buffer needs to be updated by the Z value on Z buffer. Since the order of fragment is not according to the depth order, the performance of this method depends on the executing order of fragments. The best case is where the primitives are fully sorted front-to-back, it almost can filter out all invisible fragments.

Although per-fragment early-Z test can filter out many invisible fragments to alleviate the workload of pixel shader, it has two problems. One is the workload of per-fragment early-Z test is serious. Since the fragment count in one frame is very enormous. For example, the fragment counts in high resolution screen even above hundred millions. Per-fragment early-Z test would compare the depth value hundred millions times. Another one is the data consistency problem. When the fragment which has the newest Z value passes the depth test, this fragment has to perform the pixel processing in pixel shader. After pixel processing, the newest Z value will update to the Z buffer. During this period, per-fragment early-Z test will not get the newest Z value even the fragment which has newest Z value passing the depth test. Therefore, it may miss some invisible fragments owing to data consistency problem.

2.3 Hierarchical Z test

In order to quickly filter out invisible primitives, some primitive-level early-Z test for filter out entire or part of primitives in front of rasterization are usually adopted. Hierarchical Z test is one of the famous approaches. Hierarchical Z test uses two level depth tests before pixel shader. One of the depth tests is between rasterization and pixel shader, the same place with per-fragment early-Z test. Another one is extra added before the rasterization. Figure 2-3-1 shows the rendering pipeline with hierarchical Z test. It can filter out the entire primitive in one depth comparison. So, hierarchical Z test can improve the utilization of rasterization and per-fragment early-Z test.

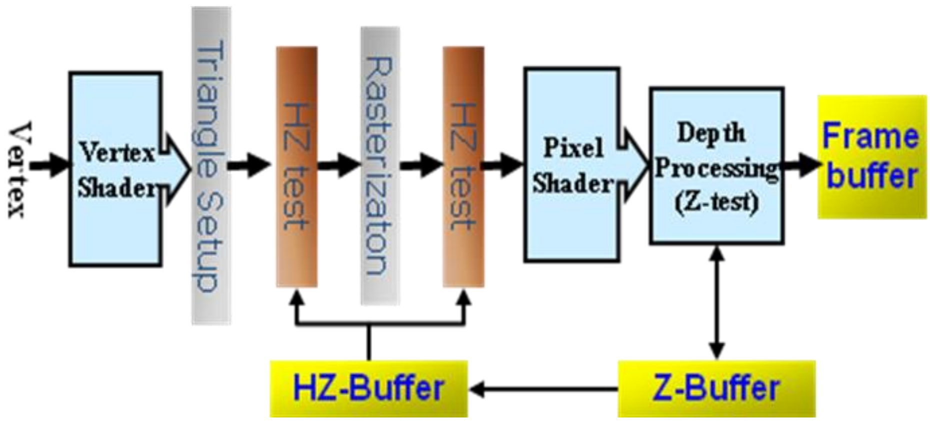


Figure 2-3-1 The rendering pipeline with Hierarchical Z test

Now we will introduce the detail operation of hierarchical Z test. Hierarchical Z test majorly uses the Z pyramid to perform depth test. The Z pyramid is shown as in Figure 2-3-2. The first level in the Z pyramid is the original Z buffer. And from first level Z buffer, it combines four Z values at each level into one Z value to the next upper level coarse Z buffer by choosing the farthest Z value. Each entry in the Z pyramid, except the first level Z buffer, represents the farthest Z value for a square area of the Z buffer. At the most upper level of the Z pyramid is a single Z value which is the farthest Z value in the whole frame. When every time the original Z buffer has the new Z value to be write in, it has to check if needing to update the upper level coarse Z buffer. If the Z values in the square area of original Z buffer all have the new Z value, it must to update the upper level coarse Z buffer.

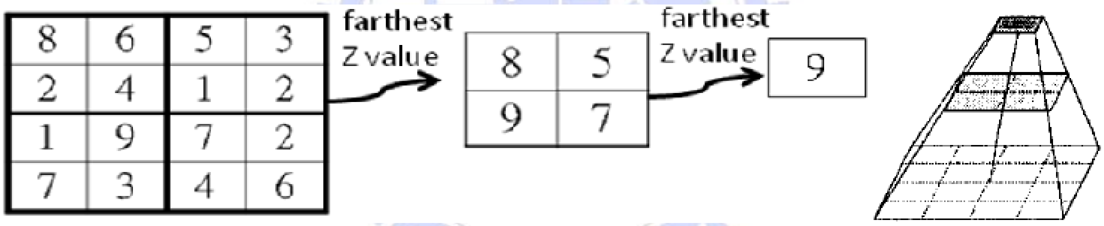


Figure 2-3-2 2x2 Hierarchical Z buffer Concept

In order to use the Z pyramid to perform the depth test for primitives, first it will find the most suitable level Z buffer which the corresponding area in the frame cover the bounding box of the primitive. If the nearest Z value of primitive is farther than choosing the most suitable level Z buffer, it represents this primitive is hidden by other primitives and can be filtered out. And the primitive which passing this stage depth test will perform depth test again after rasterization.

Although hierarchical Z test can filter out entire primitive to improve the utilization of rasterization and per-fragment early-Z test, it has two problems. The first is that updating the Z pyramid needs to take lots of times. And Z pyramid also has the data consistency problem, as same with per-fragment early-Z test. Another problem is the efficiency of hierarchical. We can know obviously that filtering out one primitive is harder than one fragment. If the primitive has large area in the screen, it is hard to be totally occluded by other primitives. Or the primitives intersect each other physically, we cannot decide which primitive can be filtered out. These two kinds of primitives would affect the performance of hierarchical Z test.

2.4 Related works

2.4.1 Tile-based early-Z test

Tile-based early-Z test [6] performs the early-Z test before rasterization. The main concept of tile-based early-Z test is that the primitives are divided into many tiles and perform the early-Z test based on the tile. Differently with hierarchical Z test, tile-based early-Z test can filter out entire or part of primitives. The problem which the primitives are partial covered by another primitives or intersect physically will improve.

Figure 2-4-1-1 shows the flow chart of tile-based early-Z test. First, the scene is segmented into plurality of tiles for performing a rendering with respect to a primitive. Select tile stage is finding the tiles which the primitive are covered and perform the depth test for every tiles. The tile Z value is the nearest Z value of primitive. If the tile Z value is larger than corresponding Z value on tile-Z buffer, this tile can be filtered out. Otherwise, this tile needs to update the tile Z buffer and performs the rendering.

The premise of updating the tile Z buffer is the tile which is completely included in the primitive. If the tile which is partially included in the primitive updates the tile Z buffer, another primitives which is not covered by this tile may be filter out. So only the tile which is completely included in the primitive has the authority to check if needing to update the tile Z buffer. The rule of updating the tile Z buffer is that the farthest tile Z value, which is represented by the farthest Z value of primitive, is smaller than corresponding Z value on tile Z buffer. Then using farthest Z value of primitive updates the tile Z buffer.

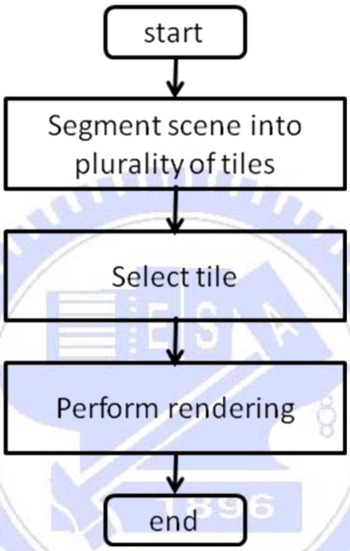


Figure 2-4-1-1 The flow chart of tile-based early-Z test

Since the tile-based early-Z test can filter out entire or part of invisible primitives before rasterization, the workload reduction of rasterization and per-fragment early-Z test will higher than hierarchical Z test. However, the tile Z value is representing the nearest Z value of primitive. It’s not a precise Z value for tiles. If we can calculate the more precise tile Z value, the performance will improve more.

2.4.2 Coarse Z filtering

Coarse Z filtering (CZF) [5] is a tile-level early-Z test between rasterization and per-fragment early-Z test. Figure 2-4-2-1 shows the rendering pipeline with coarse Z filtering. As we can see, coarse Z filtering performs the tile-level early-Z test prior to per-fragment early-Z test. It can reduce the workload of per-fragment early-Z test and reduce the memory bandwidth of Z buffer.

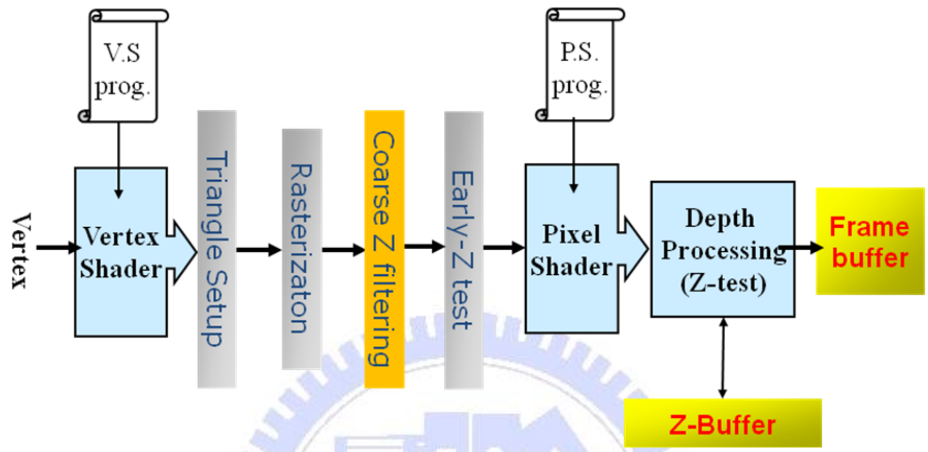
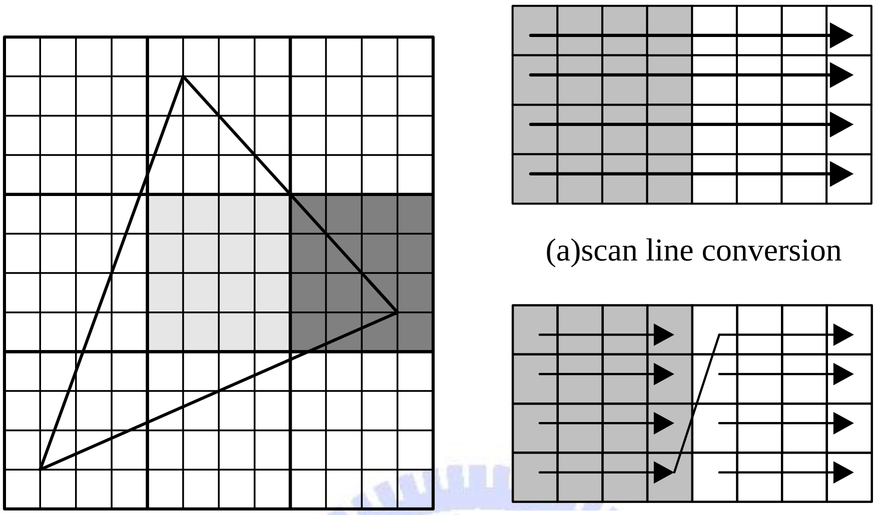


Figure 2-4-2-1 The rendering pipeline with coarse Z filtering

Coarse Z filtering segments the screen into tiles, and records each tile's data (tile mask and Z values) for tile-level depth test when performing the rasterization. In order to record each tile's data, the method of scan conversion in rasterization will follow the tile-based conversion, not scan line anymore. Figure 2-4-2-2(b) shows the tile-based scan conversion. The tile mask records which position in the tile having the fragment data. Figure 2-4-2-3 shows the example of the tile mask. And extra filtering buffer are needed to record the Z values in the tile.

After generating one tile data, coarse Z filtering performs the tile-level depth test. If the minimum Z value in the tile is larger than corresponding Z value in filtering buffer, this tile is occluded by another primitives and can filter out this tile. If the tile passes the coarse Z filtering, this tile has to check if needing to update the filtering buffer. The method of updating the filtering buffer is the similar with tile-based early-Z test [6]. Here will not introduce the method again. Figure 2-4-2-4 shows the pseudo code of coarse Z filtering.



(a)scan line conversion

(b)Tile-based scan conversion

Figure 2-4-2-2 Two different method of scan conversion

1	1	1	1
1	1	1	1
1	1	1	1
1	1	1	1

1	0	0	0
1	1	0	0
1	1	1	0
1	1	1	0

（a）TileMask=0xFFFF （b）TileMask=0x8DEE

Figure 2-4-2-3 The example of tile mask. (a) represents the tile which is totally included in primitive (b) represents the tile which is partially included in primitive

```
if (TileZmin >= FBZ)
{
        Filter out the tile;
        return;
}
if (TileMask == 0xffff)
&&(TileZmax < FBZ))
{
        FBZ = TileZmax;
}
Do per-fragment early-Z test;
return;


        *FBZ: Z value on filtering buffer
```

Figure 2-4-2-4 The pseudo code of coarse Z filtering

The coarse Z filtering has the more precise tile Z value than tile-based early-Z test [6], so it can filter out more invisible tiles. However, coarse Z filtering cannot reduce the workload of rasterization since coarse Z filtering perform depth test after the rasterization.

Chapter 3 Design

3.1 Design overview

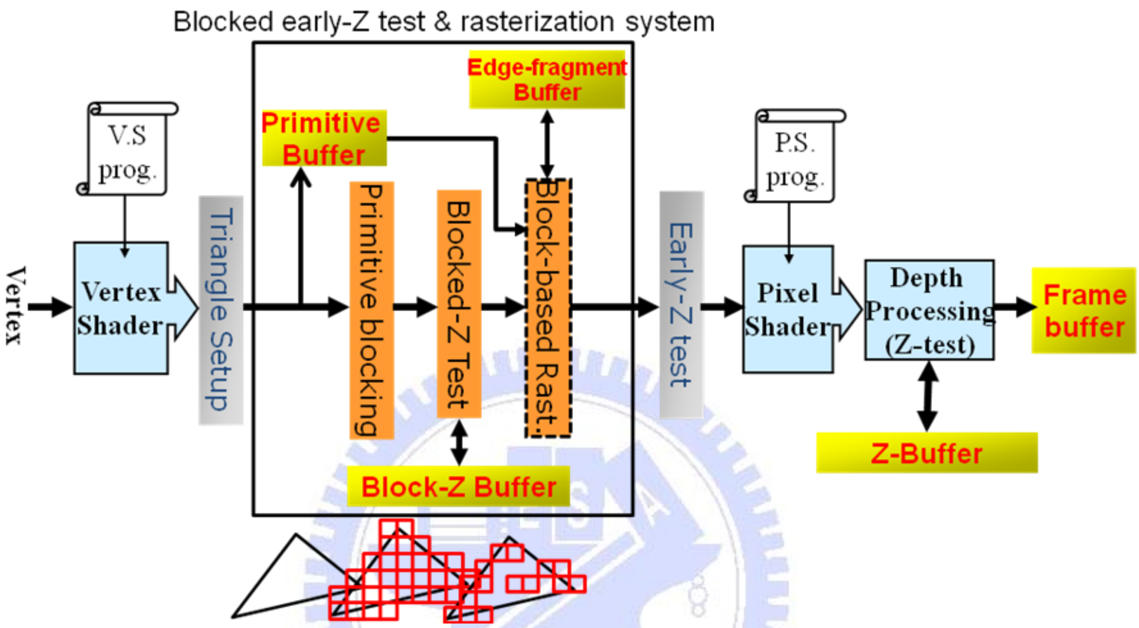


Figure 3-1-1 The rendering pipeline with proposed method, blocked-Z test, included. Note that rasterization is now replaced by block-based rasterization

Figure3-1-1 shows the rendering pipeline with the proposed method, blocked-Z test. The indicated range is the extra components that our method added. The original rasterization is now replaced by block-based rasterization. The main concept is processing early-Z test by using block, which has its own depth value, to be a test unit before rasterization. Blocked-Z test can filter entire or part of primitives. It can reduce the workloads of rasterization and per-fragment early-Z test since fragments within a block can be filtered in one operation. The data consistency problem can be solved by using extra blocked-Z buffer to record the newest depth value in time.

The following section will introduce the function of every extra added component. Primitive blocking stage calculates all the blocks which are covered by the primitive and calculates the nearest and farthest Z values of each block. The primitive buffer needs to store the current processing primitives for generating fragments in block-based rasterization. Blocked-Z test compares the nearest Z value of blocks with corresponding Z value in blocked-Z buffer to decide whether the blocks can be filtered or not. The blocked-Z buffer always has the newest depth value, not wait updating from Z buffer. Block-based rasterization interpolates fragments for blocks which pass the blocked-Z test, and then passes fragments to per-fragment early-Z test. The edge-fragment buffer stores the edge-fragments data in every block-row. It can reduce the redundant computation in block-based rasterization.

3.2 Primitive blocking

First of all, the screen will be blocked, like the Figure 3-2-1. Every grid is one block, and every block has its own block coordinate. The origin of the coordinates is the left-bottom block. For example, the top vertex of primitive locates on the (4,7) block coordinate. Since every block on the screen is a two-dimensional block, which we note this kind of block as block^2. Then primitive blocking calculates all blocks which are covered by the primitive. The blocks which generate from primitive blocking have Z values. They are three-dimensional blocks, which we note this kind of blocks as block^3. The shaded blocks in figure 3-2-1 all are block^{3}s.

The attributes of one block^3 are the following:

1. Block^3 coordinate: $(X, Y, Z_{nearest}, Z_{farthest})$

   The (X,Y) is the location of block coordinate on the screen. $Z_{nearest}$ is the nearest Z value in this block^3. It can decide whether this block^3 is completely occluded by other block^3 or not. $Z_{farthest}$ is the farthest Z value in this block^3. It can decide whether this block^3 completely occludes other block^3 or not.

2. Full or partial cover block^3

The full cover block^3 means that all fragments in this block^3 have primitive data. On the other word, full cover block^3 is the block which is totally in the primitive. Otherwise, this block^3 is partial cover block^3. In figure 3-2-1, the block A is a full cover block^3 and block B is a partial cover block^3.The purpose of discriminating full or partial cover block^3 is for updating the blocked-Z buffer. The operation of updating block-Z buffer will perform in later stage, blocked-Z test. Only the full cover block^3 have authority to check if needing to update the block-Z buffer. It is because only full cover block^3 can guarantee to completely occlude other block^3.

3. Primitive ID

When we perform the rasterization, it needs the primitive information to interpolate fragments. However, the block^3 don't have any primitive information, it cannot perform the block-based rasterization to interpolate fragments. So it needs to record the primitive ID which the block^3 originally belong to. When this block^3 has to perform block-based rasterization, it can get the primitive information to generate all fragments in this block^3.

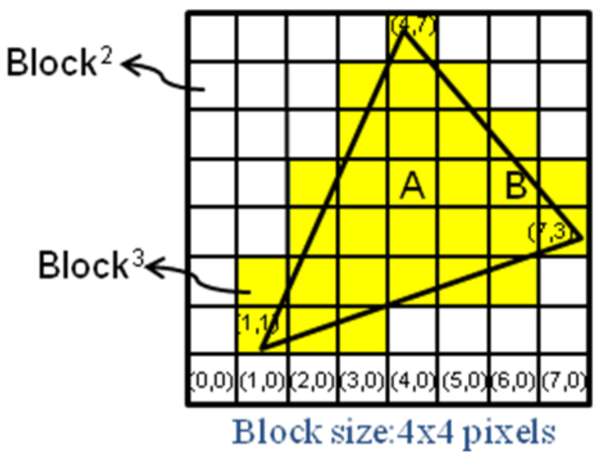


Figure 3-2-1 A sketch of primitive blocking. The yellow blocks are the blocks which are generated from one primitive by primitive blocking

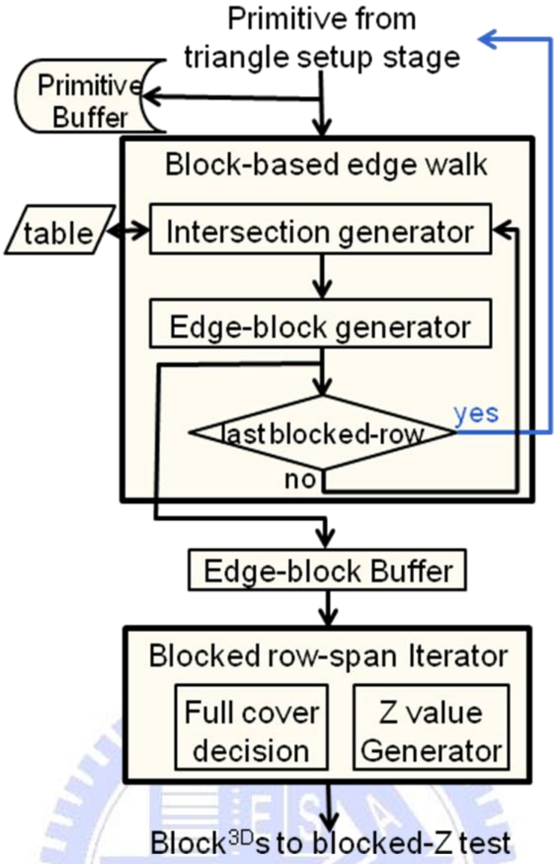


Figure 3-2-2 Flowchart of primitive blocking hardware

The primitive blocking contains two stages, block-based edge walk and blocked row-span iterator, as shown in Figure3-2-2. The block-based edge walk calculates two edge-blocks, Z strides, and full cover bound blocks for every blocked-row. Edge-block is the block[3] on the primitive edge. Full cover bound blocks can indicate which blocks in one blocked-row are full cover block[3]. The block row-span iterator generates all blocks between two edge-blocks in the same blocked-row. Since these two stages have different execution latency, we need to add an edge-block buffer to store edge-blocks, Z strides, and full cover bound blocks. Then, the two stages can parallel execute. If without the edge-block buffer, block-based edge walk may be stalled to wait blocked row-span iterator.

3.2.1 Block-based edge walk

In this section, we will introduce how to calculate the edge-blocks, Z strides, and full cover bound blocks.

3.2.1.1 Intersection generator

The purpose of the first stage of block-based edge walk, intersection generator, is to find the two edge-blocks for every blocked-row. Since the edge-block in one primitive edge may not be only one, we have to find the most outside edge-block in blocked-row. In figure 3-2-1-1-1, edge-block A and edge-block B both are edge-block. In this case, we must choose the edge-block A since that cannot miss some blocks to rendering.

In order to find the most outside edge-block, we will find the correct intersections to indicate which edge-block is the most outside edge-block. There are two kind of intersections, ceiling or floor intersection. The intersection means the intersection of primitive and ceiling or floor scan-line of one blocked-row. In figure 3-2-1-1-1, the four points on primitive edge are ceiling or floor intersections.

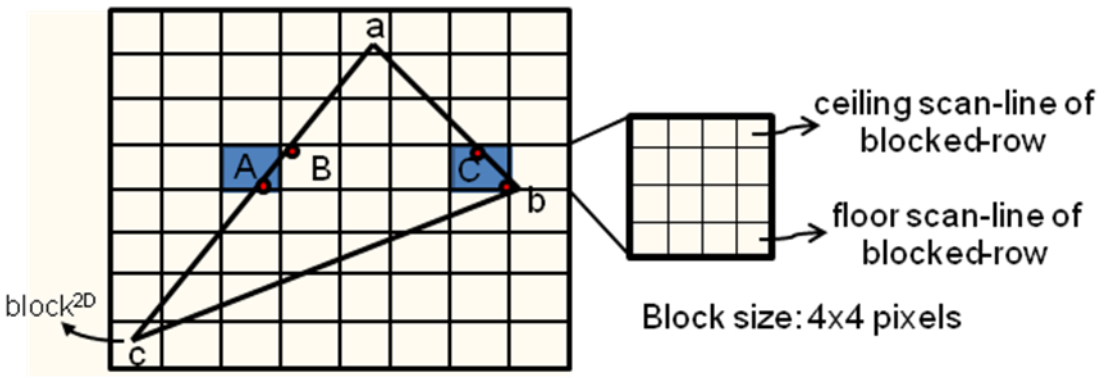


Figure3-2-1-1-1 Example of primitive blocking

For finding the correct ceiling or floor intersection, first we use table lookup to decide the direction of Y coordinate of intersection. The direction table is shown in Table 3-2-1-1-1. In the beginning, we have to know the primitive is major left or major right primitive. Major edge is the edge which has maximum y value vertex and minimum y value vertex, like the edge $\overline{ac}$ in Figure3-2-1-1-1. We can see edge $\overline{ac}$ is on the left of this primitive, so this primitive is a major left primitive. And the information of major edge can be known in triangle setup stage, so we don't have to spend extra computation to get this information. When deciding what kind of primitive, we use the slopes of major and minor edge to look up table to get the direction of Y coordinate of intersection in blocked-row. The direction of Y coordinate may be floor or ceiling in blocked-row. After looking up table, we can know the Y coordinate value of intersection. Then using edge function and Y coordinate value of intersection can get the X coordinate value of intersection. After these steps, we can know the correct intersection is ceiling intersection or floor intersection.

For example, we know the slope of edge $\overline{ac}$ is positive in figure 3-2-1-1-1. After looking up table, the Y coordinate of representative point has take the floor direction of blocked-row. And using Y coordinate vale and edge function can get the red point in block A. This red point is the representative point of block A. If we take ceiling minus direction on major edge in indicated block-scan line, it would find the green point in block B. It will miss block A.

We perform the same process on minor edge, then we can calculate two representative point of edge-block in every blocked-row. Figure 3-2-1-1-2 shows the configuration of how to take the Y coordinate of edge-block with floor or ceiling minus direction. Actully it is very simple. If the direction is floor, we use zero to replace last few bits. If direction is ceiling minus, we use one to replace last few bits. And how many bits need to be replaced, it depends on block height.

Table 3-2-1-1-1 Direction table for determining edge-block

major left primitive	major right primitive	Block selection
sign of major edge slope / sign of minor edge slope	sign of major edge slope / sign of minor edge slope	(major , minor)
+ / +	- / -	(floor , ceiling)
+ / -	- / +	(floor , floor)
- / -	+ / +	(ceiling , floor)
- / +	+ / -	(ceiling , ceiling)

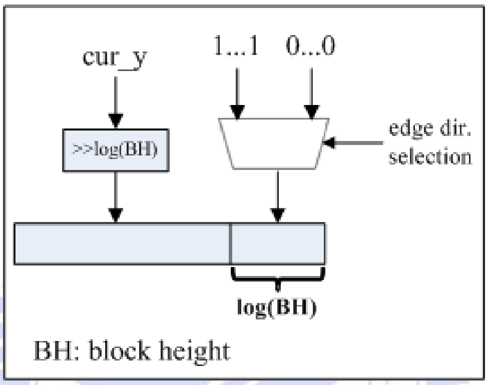


Figure 3-2-1-1-2 Generation of Y value representing a given blocked-row

3.2.1.2 Edge-block generator

After finding the representative points of edge-block, edge-block genereator can translate repredentative points of edge-block to block coordinate of edge-block by using equation (1). Equation (1) means that block coordinate of edge-block can generate by ignoring last few bits of representative point because block width and height are both 2 to the power of N.

R.P. of edge-block(X,Y) → block coordinate of edge-block($\left\lfloor \frac{X}{BW} \right\rfloor$, $\left\lfloor \frac{Y}{BH} \right\rfloor$) -----Equation (1)

BW: block width, BH: block height

There is an example in figure 3-2-1-2-1. The red point is the representative point of edge-block A. It locates on screen coordinate (11,16). Since the block width and height both are four pixels, we can use equation (1) to get the block coordinate of edge-block A, (3, 4). In the hardware design, it is easy to implement. It just ignores the last few bits of screen coordinate of representative points. And how many last few bits we need to ignore, it depends on the block width and block height.

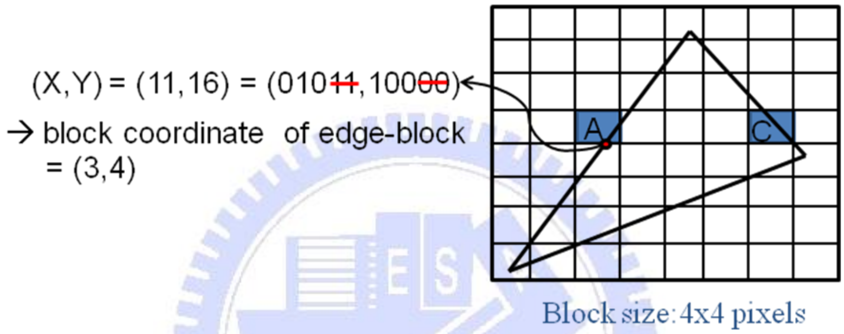


Figure 3-2-1-2-1 The example of edge-block generator

3.2.1.3 Z strides and full cover bound blocks

In previous section, we calculate two edge-blocks in every blocked-row for generating all block^{3}s' block coordinate between two edge-blocks in later stage, blocked row-span iterator. Moreover, we also need to calculate the nearest and farthest Z value of block^3 and decide the full cover bit of block^3. For this reason, we have to calculate Z strides and full cover bound blocks in every blocked-row.

In every blocked-row, we have to calculate two Z strides. One is the Z stride of bottom scan-line and another one is the Z stride of top scan-line, as shown in figure 3-2-1-3-1. First we find the edge-points (X_LT, X_RT, X_LB, and X_RB) on the top and bottom scan-line by using edge function and y coordinate values of top and bottom scan-line. Then we calculate the Z values of these four edge-points by using three vertices' Z values. Finally, using each two edge-points which are on the same scan-line and their Z value calculate Z strides of top and bottom scan-line. For example, the Z stride of top scan-line can be known by the following formula:

Z stride of top scan-line = (Z value of X_LT – Z value of X_RT) / (X_LT – X_RT)

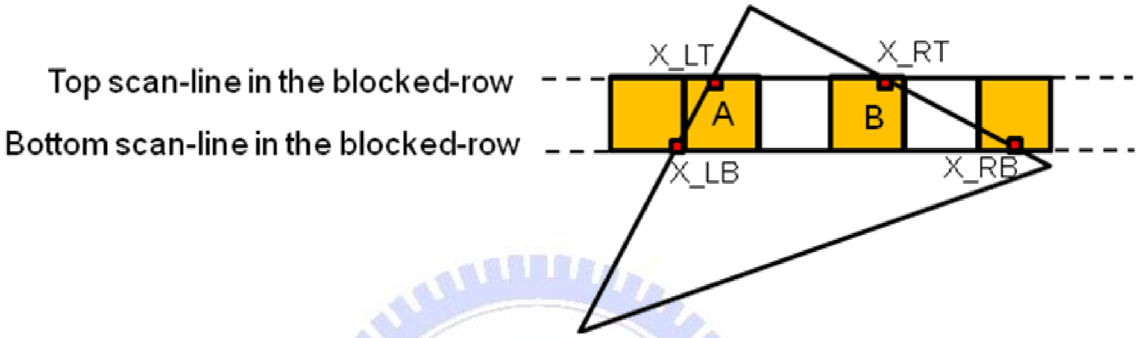


Figure 3-2-1-3-1The sketch of calculating Z strides and full cover bound blocks

The full cover bound blocks can indicate which block[3]s in one blocked-row are full cover. How do we find the full cover bound blocks? First we need to find the block[2]s, which the edge-points of top and bottom scan-line in blocked-row, are belonged to. In figure 3-2-1-3-1, we will find the four colored blocks. Then we compare these blocks and find the two inside blocks. The two inside blocks are the full cover bound blocks. The block A and block B in figure 3-2-1-3-1 are the full cover bound blocks. And the blocks only between the full cover bound blocks will be full cover block[3].

3.2.2 Blocked row-span iterator

In blocked row-span iterator, it will calculate all block[3]s between two edge-blocks in the same blocked-row. There are three major works. First, we need to find the block coordinate which the block^3 is belonged to. Since all block^{3}s are in the same blocked-row, the Y block coordinate of all block^{3}s are the same. And since the block^{3}s are the consecutive block^{3}s, we can calculate X block coordinate by just plus one to X coordinate of previous block^3.

Second, we need to calculate nearest and farthest Z values of block^3. Since the block^3 is a 3-D plane, the nearest and farthest Z value must be on the vertices. We directly calculate the Z values of block's four vertices and compare these four Z values to get the nearest and farthest Z values. The full and partial cover block^3 both use this method to calculate nearest and farthest Z values. Although partial cover block^3's four vertices aren't all in the primitive, we also use four vertices' Z values to decide the nearest and farthest Z value. It can simplify the computation. Since the intersection points of primitive and block^3 may have many different conditions, it is time wasting to calculate all Z values of intersection points of primitive and block^3. And using four vertices' Z values to get the nearest and farthest Z value don't have a large error with the precise nearest and farthest Z values.

Finally, we need to decide the block^3 is full or partial cover block^3. Since full cover bound blocks already know in previous stage, we only determine the block^3 if between the full cover bound blocks. If the block^3 is between full cover bound blocks, this block^3 is a full cover block^3. Otherwise, this block^3 is a partial cover block^3.

When one block^3 are generated, this block^3 will be transferred to blocked-Z test stage for testing the Z value. It can decide this block^3 are occluded or not.

3.3 Blocked-Z test

Blocked-Z test can filter out block^{3}s which are surely occluded by other block^3 since the occluded block^3 wouldn't display on the screen. It can reduce the workloads of later stages, like rasterization, per-fragment early-Z test. Because blocked-Z test is performed based on a block, as opposed to a fragment, it can filter out many fragments within a block in one compare operation. To achieve this goal, it needs to add a two-dimensional blocked-Z buffer to record the current nearest Z value of each block coordinate, as shown in figure 3-3-1. The width of block-Z buffer is that the width of screen coordinate divides block width. And height of block-Z buffer is that the height of screen coordinate divides block height. The size of each entry on block-Z buffer is 4 bytes, the common size of Z value.

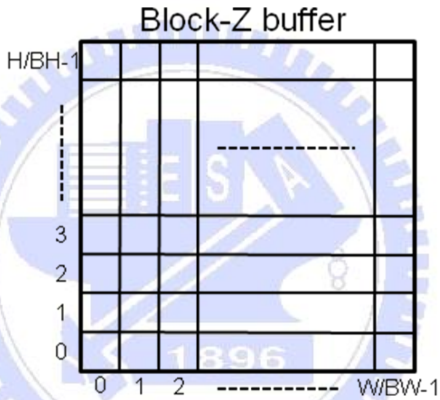


Figure 3-3-1 The configuration of block-Z buffer

Figure 3-3-2 shows the flow chart of blocked-Z test. After primitive blocking generate block^{3}s, using the nearest Z value of block^3 compares with corresponding block-Z value on blocked-Z buffer. If the nearest Z value of block^3 is larger than corresponding block-Z value, it can filter out this block^3. Otherwise, this block^3 will pass to the block-based rasterization. And when any block^3 passes the blocked-Z test, it has to check if needing to update the block-Z buffer. When the block^3 is full cover and the farthest Z value of block^3 is smaller than corresponding block-Z value on block-Z buffer, it must update the corresponding block-Z value with farthest Z value of block^3. Why only the full cover block^{3}s have the authority to check if needing to update block-Z buffer. It is because only the full cover block^{3}s can guarantee to occlude other block^{3}s when other block^{3}s are behind the full cover block^3. If updating the block-Z value with partial cover block^3, another block^{3}s may not be totally occluded by this partial cover block. It may filter out some block^{3}s which should display on the screen. So, only full cover block has authority to check if needing to update block-Z value.

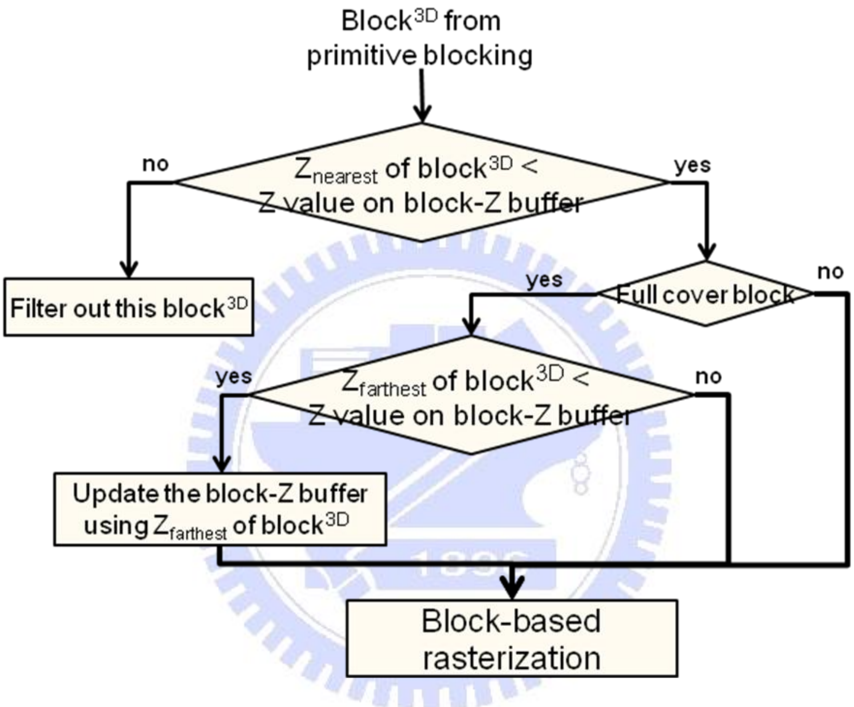


Figure 3-3-2 The flow chart of blocked-Z test

3.4 Block-based rasterization

Block-based rasterization generates fragments to those passing blocked-Z test block^{3}s. It can parallel processing with updating the block-Z buffer when the blocks pass blocked-Z test. Since the data of updating the block-Z buffer and block-based rasteriztion are different. To update the block-Z buffer needs the farthest Z value and full cover bit. And block-based rasterization needs the block coordinate of block^3 and primitive ID. Therefore, it can be parallel processing without any fault.

The operation of block-based rasterization is similar to general rasterization. The only difference is block-based rasterization needs to find the block^3 range and generates all fragments in the block^3. First, it needs to calculate two edge-fragments on primitive's edge in every scan-line of blocked-row. If block size is 8x8, like figure 3-4-1, we need to calculate these sixteen edge-fragments, the red squares, on primitive's edge. Then, using two edge-fragments on same scan-line calculates all attribute strides of every scan line, like RGBA, Z, texture coordinate. Finally, using attribute strides of every scan-line interpolates all fragments in block^3 range.

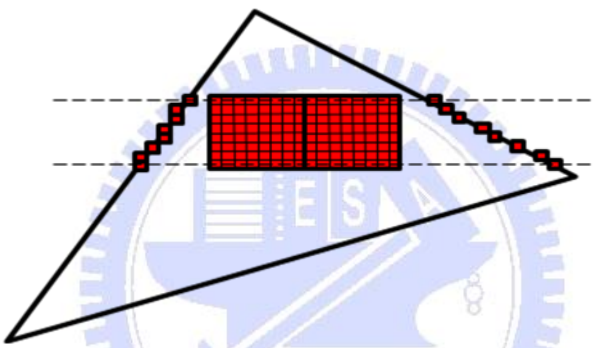


Figure 3-4-1 The sketch of block-based rasterization

Here is a problem that consecutive blocked-Z tested block^{3}s in same blocked-row like figure 3-4-1, it has to calculate the same edge-fragments on primitive edge and calculate the same attribute strides. So, we use an edge-fragment buffer to record edge-fragments which are on major edge and attribute strides in same blocked-row. Moreover, edge-fragment buffer must record primitive ID and row number to indicate which blocked-row's edge-fragment data is now on the edge-fragment buffer. Figure 3-4-2 shows the configuration of edge-fragment buffer. When passing blocked-Z test block^3 comes, it will check this block^3 whether is on the same blocked-row with the edge-fragment data on the edge-fragment buffer. If the primitive ID and row number on edge-fragment buffer is identical with current block^3, then we use edge-fragment data on edge-fragment buffer to generate fragments rather than calculate same edge-fragments and attribute strides again. Figure 3-4-3 shows the flow chart of block-based rasterization. The blocked-row number of Z-tested block^3 is the y coordinate value of Block^3. The block-ranged edge walk is to calculate the edge-fragments and Z strides in block height. Block range generator calculate which range in one scan-line needs to interpolate fragments. And the fragment generator is to interpolate all fragments in block range by using edge-fragments an attribute strides.

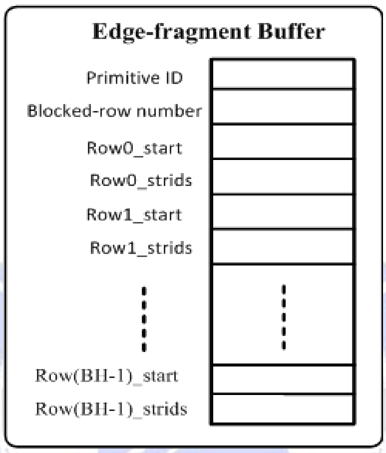


Figure 3-4-2 The edge-fragment buffer for a blocked-row

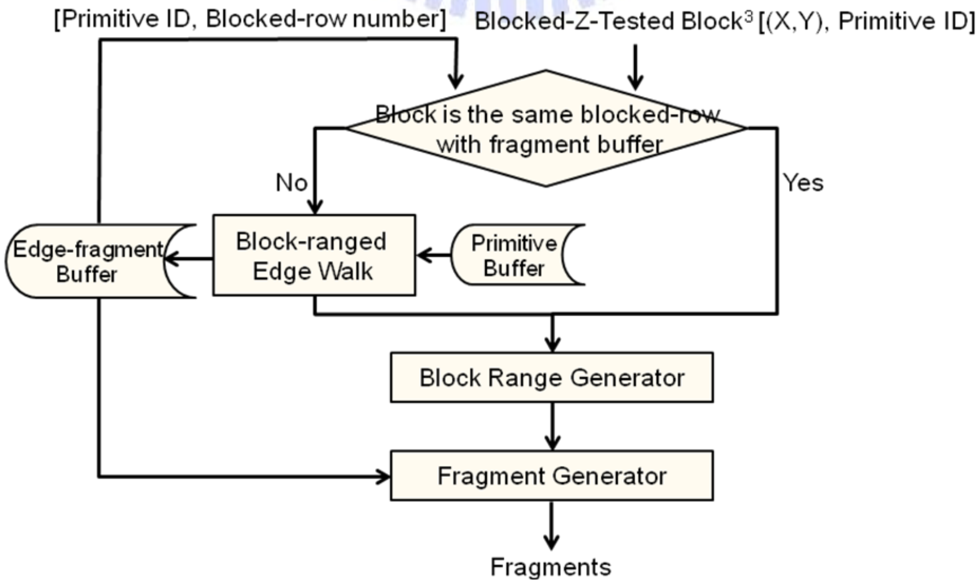


Figure 3-4-2 The flow chart of block-based rasterization

3.5 Data flow of our proposed method

In this section, we will briefly introduce the data flow of our proposed method, blocked-Z test. Figure 3-5-1 shows the data flow of our proposed method. The triangle setup will assemble the vertices into primitive and also calculate the edge slopes of three primitive edges. Then primitive blocking will generate all block^3 data and deliver block^3 data to blocked-Z test stage. After blocked-Z test, the $Z_{nearest}$, $Z_{farthest}$, and full cover flag wouldn't use anymore. Only the block coordinate and primitive ID of block^3 will deliver to block-based rasterization. After block-based rasterization, it will become fragment data and deliver these fragment data to per-fragment early-Z test.

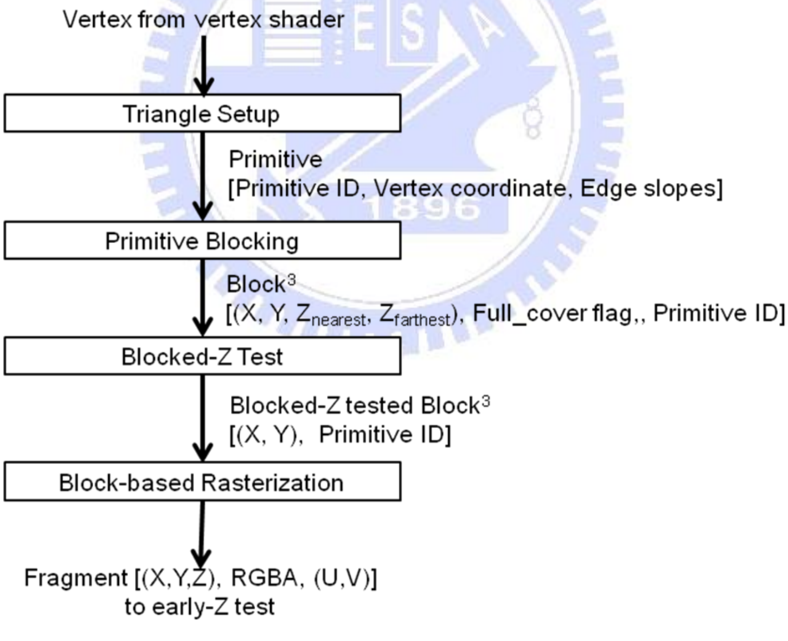


Figure 3-5-1 the data flow of our proposed method, blocked-Z test

3.6 The rendering pipeline with blocked-Z test

In this section, we explain how the pipeline operates smoothly. When the primitive deliver from triangle setup to primitive blocking, the primitive blocking divides the primitive into block^{3}s and triangle setup can generate another primitive. The block^{3}s will deliver to blocked-Z test unit as soon as the primitive blocking generates one block^3. Primitive blocking doesn't wait all block^{3}s in one primitive be generated and then deliver all block^{3}s to blocked-Z test unit. If do so, the blocked-Z test unit will often be idle by waiting the primitive blocking. In the same principle, the block-based rasterization can get the block^3 data immediately when the block^3 passes blocked-Z test. Since the block-based rasterization has longer processing time than blocked-Z test, it would always stay in busy time, wouldn't in idle time. So, the extra added pipeline components of our proposed method can operate smoothly.

Moreover, the rendering pipeline with blocked-Z test becomes deeper than general graphic pipeline since we add two new pipeline units, primitive blocking and blocked-Z test. The computation time may become longer and may not render thirty frames in one second. However, since it can parallel process different frames, only the first frame will take longer time to process. Figure 3-6-1 shows the pipeline operation of multiple frames. Although the pipeline stage becomes deeper, the total throughput can seem identical than traditional graphic pipeline, even increase throughput since our method can relieves some bottlenecks.

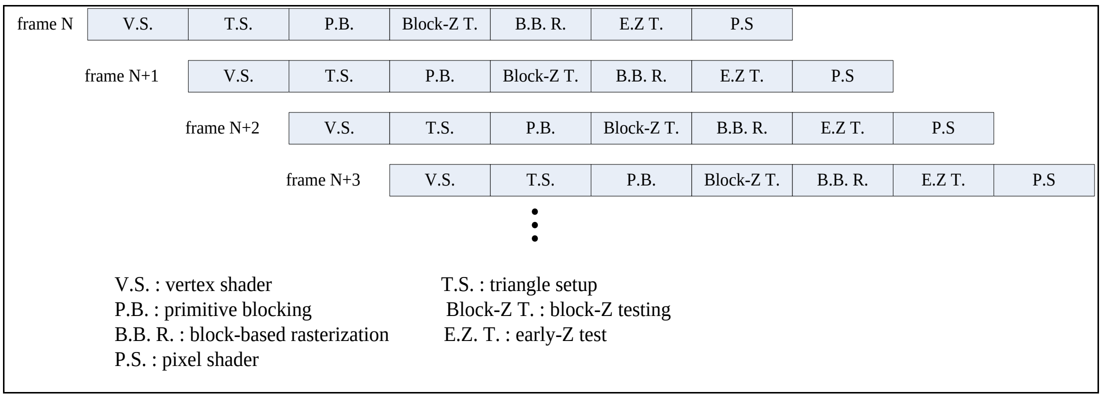


Figure3-6-1 The rendering pipeline with blocked-Z test

Chapter 4 Experiment and results

4.1 Experiment goal and environment

We are going to know how many percentages of occluded fragments can be filtered out in our blocked-Z test. And we also want to know how many extra workloads bring with the blocked-Z test. Finally, we will consider with the reduced workloads and extra workloads which produce from our blocked-Z test to evaluate how many total workloads blocked-Z test can reduce. Moreover, we will compare our blocked-Z test with the tile-based early-Z test [6] which the related work mentioned.

We trace the Atila simulator and dump the primitive data from Atila to be the input data for our experiment. The Atila simulator is proposed in [7]. The simulator architecture is based on the design of ATI GPU’s architecture and support OpenGL based benchmarks, like Doom3 [8], Quake4 [9], or the 3-D based computer games. The primitive data which we dump from Atila simulator are the benchmarks of Doom3 and Quake4 with 320*240, 640*480, 1280*1024, and 1600*1200 screen resolutions.

After we have the input data, we also implement the simulator of our blocked-Z test method. Then we can get the filtering ratio of blocked-Z test from the simulator which we implement. And we also can evaluate the workload reduction by the information from our blocked-Z test simulator. The filtering ratio means the percentage of fragments can be filtered out by any kind of early-Z test. The equation of filtering ratio is: filtering ratio = filtered out occluded fragments / original fragments generated by rasterization.

4.2 Experiment results

In section 4.2.1, we will show the filtering ratio of blocked-Z test with various block sizes, which are 4x4, 8x8, 16x16, 32x32, and 6x64 pixels. In section 4.2.2, we will show the extra overhead of blocked-Z test, included extra hardware requirements and extra workloads. And we will evaluate the workload reduction of rasterization and per-fragment early-Z test with our blocked-Z test.

4.2.1 Filtering ratio of blocked-Z test

The figure 4-2-1-1 and figure 4-2-1-2 show the filtering ratio of blocked-Z test with various block sizes. The filtering ratio of blocked-Z test means how many percentages of fragments can be filtered out in blocked-Z test. It can reflect the effect of blocked-Z test. The last bar chart of each set is the filtering ratio of per-fragment early-Z test. It can be a comparison with the blocked-Z test of various block sizes. Obviously, we can see that the filtering ratio is higher with the block size is smaller. And we can see that the filtering ratio with various block sizes in low screen resolution has larger variation. With the block size increase in low screen resolution, the filtering ratio decreases more than in high screen resolution. It is because the difference of block size in the low resolution has larger variation of covered range in the screen than in the high screen resolution. So, in the high screen resolution like 1600*1200, the filtering ratio with various block sizes has less variation. In figure 4-2-1-1, the average filtering ratio with various block sizes is about 80%. And In figure 4-2-1-2, the average filtering ratio with various block size is about 60%.

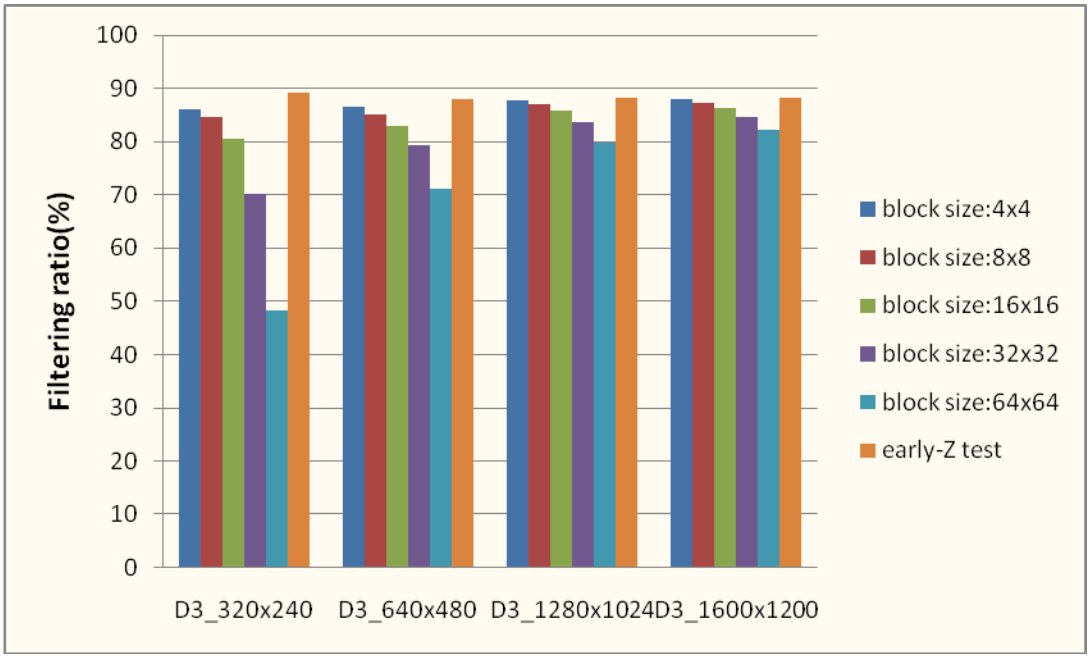


Figure 4-2-1-1 The filtering ratio of Doom3 with various block sizes

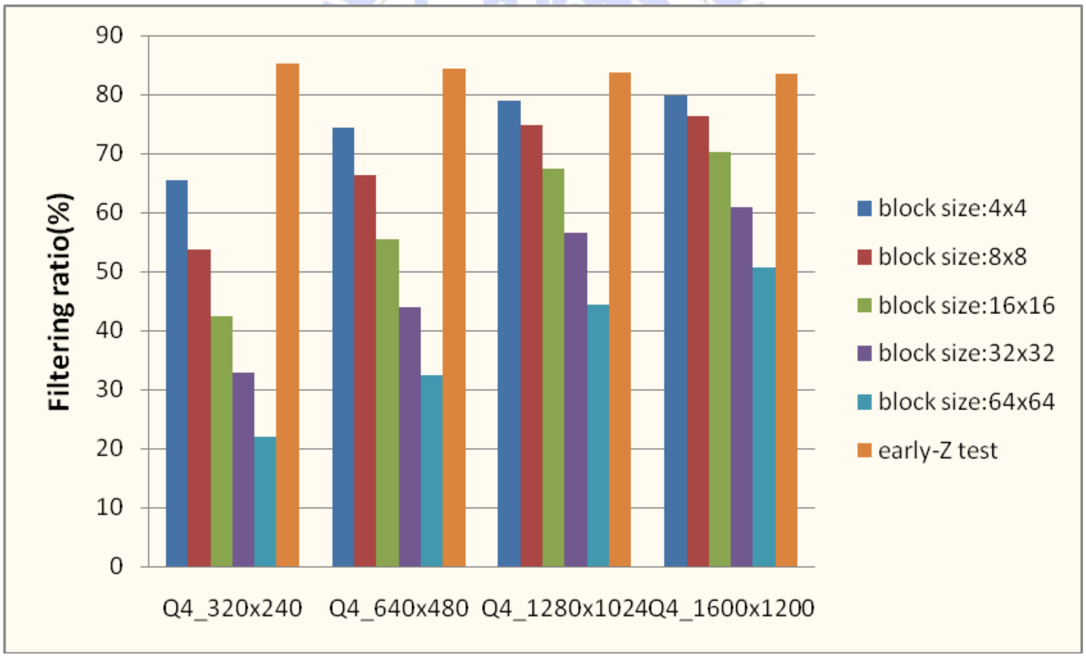


Figure 4-2-1-2 Filtering ratio of Qauke4 with various block sizes

4.2.2 Extra overhead of blocked-Z test

In this section, we will show the extra overhead which produce from blocked-Z test. In section 4.2.2.1, we show the extra workload of blocked-Z test. The extra workload is reflected by the block count. In section 4.2.2.2, we show the extra storage requirement and hardware that blocked-Z test need to use. With different block sizes, the storage requirement has a large variation.

4.2.2.1 Extra workload of blocked-Z test

Although blocked-Z test can reduce the workloads of the rasterization and per-fragment early-Z test, it has the extra workloads of the primitive blocking and blocked-Z test. In this section, we will discuss the extra workload of primitive blocking and blocked-Z test with various block sizes. Figure 4-2-2-1-1 and figure 4-2-2-1-2 shows the extra workload of primitive blocking and blocked-Z test with various block sizes in Doom3 and Quake4. We use the block count to evaluate the extra workload. The reason is primitive blocking needs to generate all blocks and blocked-Z test needs to perform depth test for every block. Obviously we can see, when the block size is smaller, the extra workload will higher. In these two figures, we can see that the workload will increase about three times when the block size grows four times.

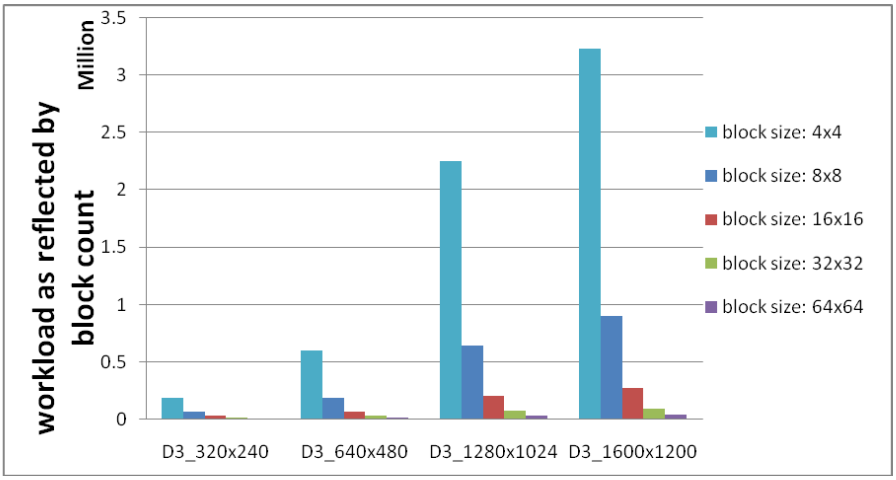


Figure 4-2-2-1-1 Extra workload of blocked-Z test with various block sizes

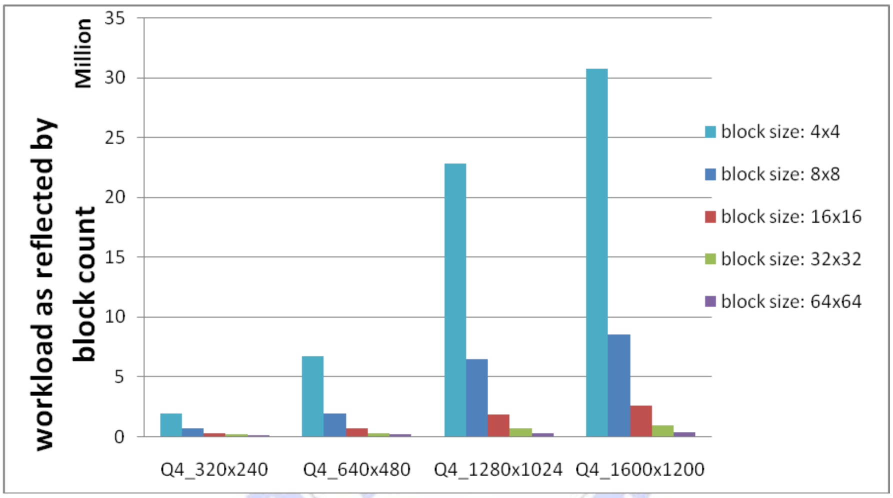


Figure 4-2-2-1-2 Extra workload of blocked-Z test with various block sizes

4.2.2.2 Extra storage requirement and hardware

In our method, we have three extra storage buffers, primitive buffer, edge-fragment buffer, and block-Z buffer. With the block size and screen resolution vary, the storage will have the different requirement. Table 4-2-2-2-1 shows the storage requirement in different block size and screen resolution. The major extra storage requirement is block-Z buffer since it needs to store all current nearest Z value for every block coordinate. The block-Z buffer size can calculate by (screen width * screen height / block size)*4 bytes. When the screen resolution is high and block size is small, the block-Z buffer size may greater than 100 Kbytes. We can see that when block size is 4x4 and screen resolution is 1600x1200, the block-Z buffer size is even above 400 Kbytes. The edge-fragment buffer size depends on the block size only. It needs to store the edge-fragment data two times of block height. The edge-fragment buffer size can calculate by (block height * 2)*20 bytes. And the primitive buffer size is a fixed size. It depends on how many primitives need to store in primitive buffer. In this table, we set the ten primitives needed to store in primitive buffer and each entry is 60 bytes. The maxumun of total extra storage is about 470 Kbytes. And the minimum of total extra storage is only aobut 2 Kbytes.

Table 4-2-2-2-1 Extra storage requirement with various block sizes and resolutions

	block size: 4x4				block size: 8x8				block size: 16x16				block size: 32x32				block size: 64x64			
screen resolution	320*240	640*480	1280*1024	1600*1200	320*240	640*480	1280*1024	1600*1200	320*240	640*480	1280*1024	1600*1200	320*240	640*480	1280*1024	1600*1200	320*240	640*480	1280*1024	1600*1200
bock-Z buffer size(KB)	18.75	75.00	320.00	468.75	4.69	18.75	80.00	117.19	1.17	4.69	20.00	29.30	0.29	1.17	5.00	7.32	0.07	0.29	1.25	1.83
Edge-fragment buffer size(KB)	0.16	0.16	0.16	0.16	0.31	0.31	0.31	0.31	0.63	0.63	0.63	0.63	1.25	1.25	1.25	1.25	2.50	2.50	2.50	2.50
primitive buffer size(KB)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
total extra buffer size(KB)	19.51	75.76	320.76	469.51	5.60	19.66	80.91	118.10	2.40	5.91	21.23	30.52	2.14	3.02	6.85	9.17	3.17	3.39	4.35	4.93

In our method, the primitive blocking and blocked-Z test unit is the extra hardware. Table 4-2-2-2-2 shows the extra hardware of primitive blocking and blocked-Z test unit.

Table 4-2-2-2-2 Extra hardware of primitive blocking and blocked-Z test

		primitive blocking	Blocked-Z test
Extra Hardware	multiplexer	8	0
	adder	14	0
	multiplier	3	0
	divider	4	0
	comparator	5	3

4.2.3 Total workload reduction with blocked-Z test

Although our method can reduce the workloads of rasterization and per-fragment early-Z test, the primitive blocking and blocked-Z test would produce the extra workloads. In this section, we evaluate the total workload reduction with considering the reduced and extra workloads.

The primitive blocking and rasterization are similar with their operation. Primitive blocking can consider a large granularity rasterization. It just spends much time to calculate the nearest and farthest Z value of block. And the blocked-Z test and per-fragment early-Z test both perform the depth test. The execution time of these two execution units can consider the same. Table 4-2-3-1 shows the time complexity of these four execution units, primitive blocking, general rasterization, blocked-Z test, and per-fragment early-Z test. The latency of each computation unit, like adder or multiplier, shows in the most left column. The cycle time of each computation unit is our hypothesis. And how many computation units that each execution unit is need to perform also show in the table. Then we can calculate each execution unit's latency by computation unit's latency multiply by the number of computation unit and it shows on last row in table 4-2-3-1.

Table 4-2-3-1 The time complexity of four execution units

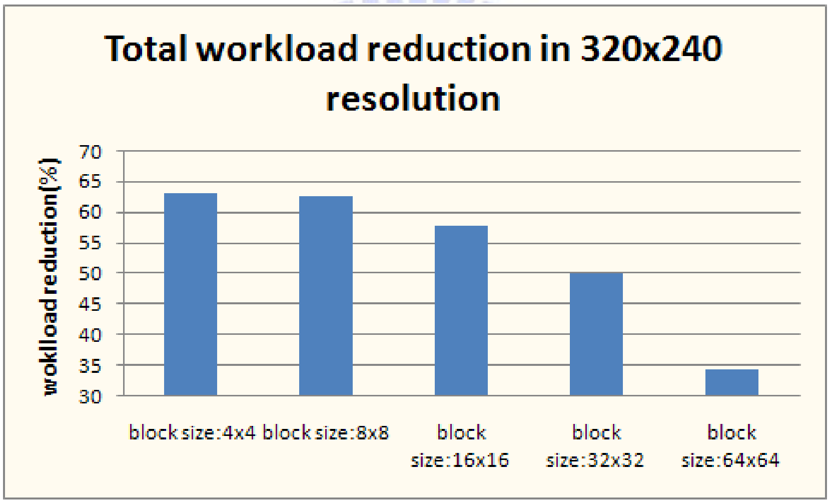
	primitive blocking	general rasterization	blocked-Z test	per-fragment early-Z test
multiplexer	2	2	0	0
Adder(1 cycle)	10	5	0	0
multiplier(10 cycles)	2	1	0	0
divider(10 cycles)	2	2	0	0
comparator(1 cycle)	2	0	1	1
latency	52 cycles	35 cycles	1 cycle	1 cycle

When we know the latency of these execution units, we can derive the equation (2) from these execution units' latency. The equation (2) can calculate the total change workload of our blocked-Z test method. It means that how many workload of rasterization and per-fragment early-Z test can be reduced.

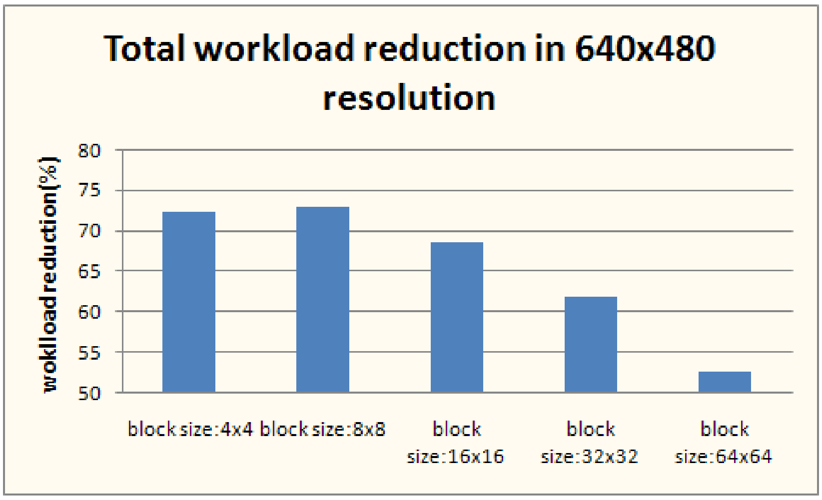
$$\text{Total\_change\_workload}(\%) = \frac{(35 \times \text{R.Rast} - 52 \times \text{P.B.}) + (\text{R.EZ.} - \text{B.Z})}{36 \times \text{O.F.C}} \quad ---\text{Equation}(2)$$

R.Rast.: reduced fragment count of rasterization
P.B.: block count of primitive blocking
B.Z.: block count of blocked-Z test
O.F.C.: original fragment count
R.EZ.: reduced fragment count of per-fragment early-Z test

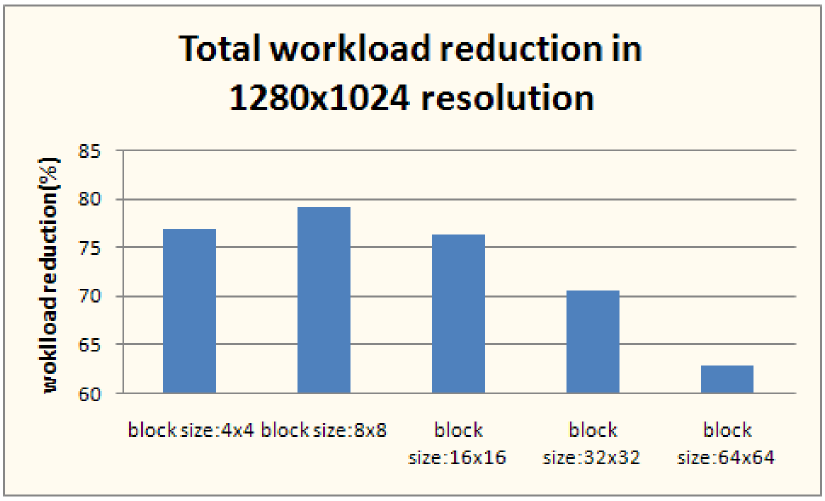
Using the equation (2), we can get the total reduced workload of blocked-Z test. Figure 4-2-3-1 shows the total reduced workload with various screen resolutions.



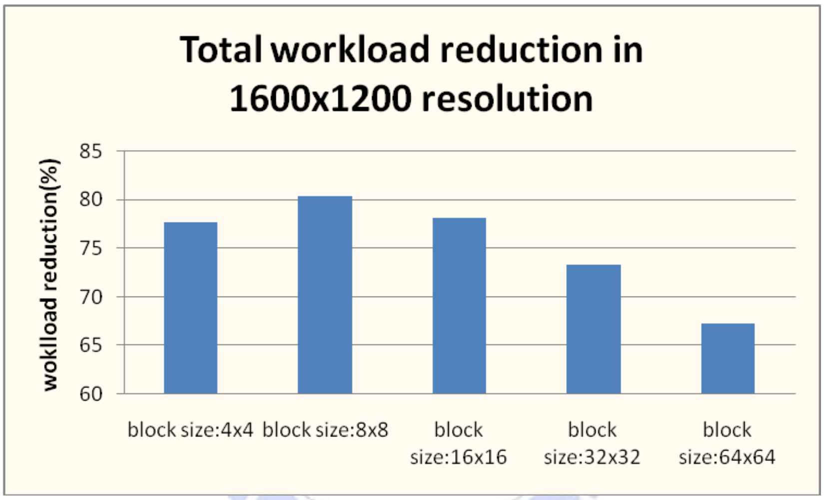
(a)



(b)



(c)



(d)

Figure 4-2-3-1 The total reduced workload of blocked-Z test with various screen resolutions. (a) 320x240 pixels (b) 640x480 pixels (c) 1280x1024 pixels (d) 1600x1200 pixels

We can see that 4x4 block size has the best performance only in 320x240 resolution. In the higher resolutions, 8x8 block size has the best performance. Although 4x4 block size has the highest filtering ratio than other block sizes, it has the more serious extra overhead than other block sizes, especially in the high screen resolution. So, in high resolution, 4x4 block size cannot get the highest workload reduction than other block size.

4.3 Performance compare with tile-based early-Z test [6]

Figure 4-3-1 and figure 4-3-2 show the filtering ratio of our proposed method and tile-based early-Z test [6] in Doom3 and Quake4. Each bar chart is the average value of filtering ratio in four screen resolution. In Doom3, our method can filter out more about 3% fragments averagely. It's about one million fragments. And in Quake4, our method can filter out more about 13% fragments averagely. It's about twenty-seven million fragments. Since Quake4 is higher complex scenes than Doom3, blocked-Z test has the better performance in Quake4.

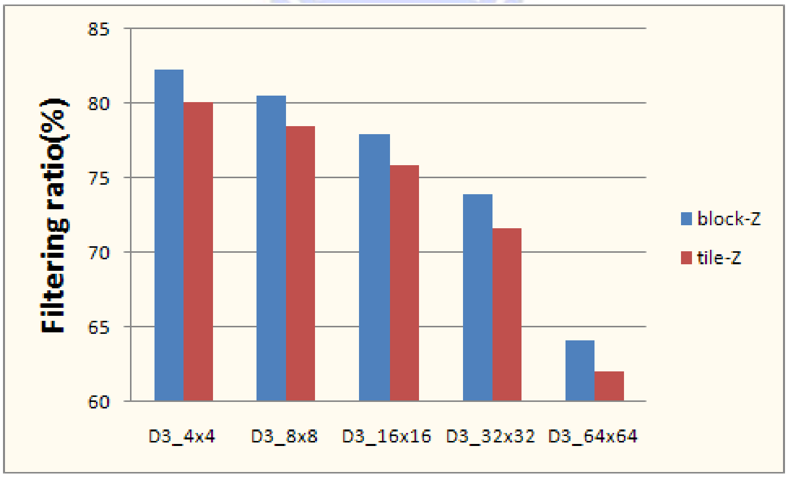


Figure 4-3-1 Filtering ratio of blocked-Z test versus tile-based early-Z test for Doom3

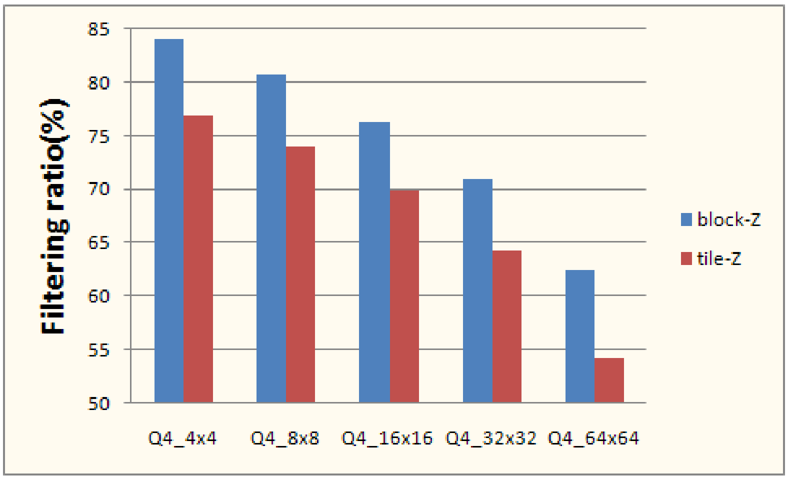


Figure 4-3-2 Filtering ratio of blocked-Z test versus tile-based early-Z test for Quake4

Since blocked-Z test has more precise depth value than tile-Z test, the filtering ratio of blocked-Z test is obviously better than tile-Z test. However, the computation of blocked-Z test is more complex than tile-Z test. We have to consider the extra overhead into evaluation. So we compare the total reduced workload with these two methods to see which method can get the better performance.

The total changed workload equation of blocked-Z test is already shown in section 4-2-3. The Equation (3) shows the total changed workload of tile-Z test. We can see that the latency of primitive tiling is shorter than primitive blocking in blocked-Z test method. It is because the computation of depth value in tile-Z test is simpler than blocked-Z test. Using equation (3), we can get the total reduced workload of tile-Z test. Figure 4-3-3 shows the total workload reduction of these two methods. Blocked-Z test averagely can reduce more about 5% total workload than tile-Z test.

$$\text{Total changed workload}(\%) = \frac{(35\times \text{R.Rast.} - 35\times \text{P.T.}) + (\text{R.EZ.} - \text{T.Z.})}{36\times \text{O.F.C}} --- \text{Equation}(3)$$

R.Rast.: reduced fragment count of rasterization
P.T.: tile count of primitive tiling
B.Z.: block count of tile-Z test
O.F.C.: original fragment count
R.EZ.: reduced fragment count of per-fragment early-Z test

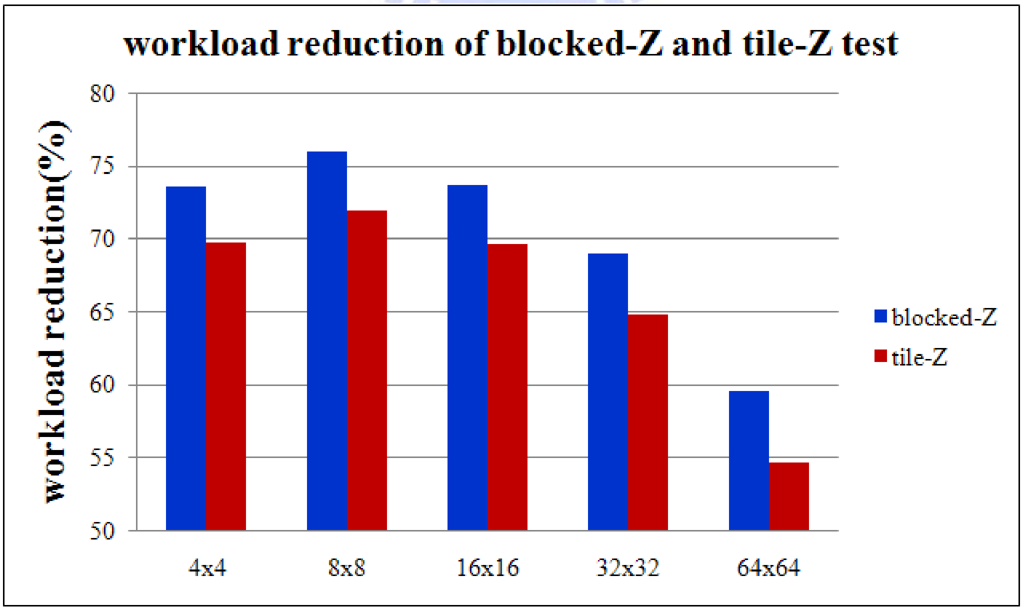


Figure 4-3-3 workload reduction of blocked-Z and tile-Z test

Chapter 5 Conclusion

As more complex models become commonplace in today's 3D computer graphics. How to reduce the unnecessary operations is the critical issue. In this paper, we proposed a low computational blocked-Z test to reduce workload of rasterization and per-fragment early-Z test. Blocked-Z test process the depth test by larger range, block, before rasterization and can achieve about 70% workload reduction. Moreover, when per-fragment early-Z test has less data to processing, it also can alleviate Z buffer access loading. Blocked-Z test can pay a little extra overhead to achieve a large amount of workload reduction. It can be a useful approach to reduce the workload in the 3D rendering pipeline.

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