國立交通大學

資訊科學與工程研究所

碩 士 論 文

繪圖處理器中順序獨立透明畫素片段儲存系統之設計

Transparent Fragment Storage System for Order-Independent Transparency in GPU

研 究 生：林慧榛

指導教授：單 智 君 教授

中 華 民 國 九 十 六 年 八 月

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Transparent Fragment Storage System for Order-Independent Transparency in GPU

合於碩士資格水準、業經本委員會評審認可。

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中 華 民 國 九十六 年 七 月 二十三 日

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摘　要

為了能正確且迅速繪製出場景透明度的效果，現今電腦圖學領域中提出了順序獨立透明計算之演算法，並配以額外透明畫素片段儲存系統之支援，以進一步降低演算法所需執行時間。然而，隨著現今對於高畫質場景的要求愈來愈高的情況下，場景中具透明度像素片段之數目亦日漸增加，其所需儲存空間亦日漸增大。如何能降低該儲存容量之需求，成為值得研究之議題。本論文針對順序獨立透明計算，提出一畫素片段儲存系統之設計：依畫素片段之螢幕座標位置，將畫素片段擺放至儲存系統中相對應的位址，並利用指標索引方式，將具相同螢幕座標之畫素片段串連起來，達到節省系統儲存空間、降低對儲存系統存取之次數、快速存取同螢幕座標畫素片段及之目的。

Transparent Fragment Storage System for Order-Independent Transparency in GPU

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Abstract

In order to correctly and fast render the transparent effect of a scene, some hardware oriented algorithms with additional transparent fragment storage supports for order-independent transparency are proposed in current computer graphics. However, as the scene complexity is constantly increasing, the number of transparent fragments and the size of transparent fragment storage support also increase significantly. To lower the demand for memory, in this thesis, we propose a transparent fragment storage system design for order-independent transparency. Within our fragment storage system, transparent fragments are stored in a corresponding location based on their x-y coordinate, and connected with the other fragments that has the same x-y coordinate by pointer indexing. The objective of our design is to reduce the memory requirement and the memory access frequency of the transparent fragment storage system.

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林慧榛 2007.8

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Chapter 1 Introduction

In order to support realistic scene in computer graphics, a special purpose processor, called **Graphics Processing Unit** or **GPU,** is required for high performance 3D graphics rendering. As the demand for high quality realistically rendering in computer graphics is continuously increasing, the support for transparent effect becomes more important for visual reality. Current GPUs provide the capability to generate the effect of transparency. The operation implemented in GPU to generate the transparent effect is called **alpha blending**: combining a translucent foreground with a background. Due to the alpha blending operation, rendering a scene with transparent objects realistic requires rendering in correct depth order—from back to front or front to back with respect to the viewpoint. It implies that the rendering order of transparent objects depends on their depth order with respect to the viewpoint, that is, order-dependent transparency. Traditionally, the transparent objects are sorted to get the correct depth order in the application level. However, it is difficult for software application developers to sort transparent objects since objects may intersect each other. In addition, as the number of transparent primitives increases rapidly, the application sorting becomes more and more complicated. Therefore, order-independent transparency, rendering transparent objects without application depth sorting, becomes an important issue for high performance rendering systems.

Order-independent transparency is a difficult architectural problem to solve and many researches have been investigated on it. There are several different kinds of order-independent transparency algorithms. Some algorithms model the alpha value as a probability measure such as alpha-dithering [Will]. Other multi-pass rendering algorithms [Ever01] pass fragments several times to blend them and produce the correct results. For the reason of fast rendering, most order-independent transparency algorithms modified the traditional GPU architecture with the additional hardware support for storing these transparent fragments. R-buffer(RB) proposal [Witt01] implements A-buffer [Carp84] software algorithm into hardware by adding an extra storage system to store transparent fragments in their arrival order. WF (Weight Factor) hardware oriented algorithm [Amor06] precomputes the contribution factor of each fragment to the final color of a pixel and sequentially stores transparent fragments based on their x-y coordinate into storage system.

As the scene complexity arises, the number of transparent fragments and the storage space for transparent fragments increase significantly. How to store these transparent fragments to lower the demand for memory becomes more and more important. In addition, current fragment storage support techniques for order-independent transparency [Amor06] [Witt01] still have some defects to be improved such as large storage requirement and high memory access frequency. Therefore, our objective is to design a transparent fragment storage system which places order-independent-arrival transparent fragments in such an organized way that reduces the memory requirement and memory access frequency in comparison with previous works. In addition, for the purpose to further reduce the memory requirement of proposed transparent fragment storage system, we also use leading 0s elimination technique to strip the redundant part of fragment data.

The rest of this thesis is organized as follows: In Chapter 2, we introduce an overview of graphics pipeline, transparency rendering operation and problem, and related works of fragment storage system for order-independent transparency. In Chapter 3, we propose the design of our transparent fragment storage system and the utilization of leading 0s elimination technique. In Chapter 4 we discuss and show our simulation environment and results. In chapter 5, we summarize our conclusions and future work.

Chapter 2 Background and Related work

In this chapter, we will give an overview of graphics pipeline. Then, we will introduce the definition of transparency, alpha blending operation, explain the transparency rendering problem, and expatiate on order-independent transparency. At the end of this chapter, we will present the details of two previous works related to hardware support techniques for order-independent transparency.

2.1 Graphics pipeline

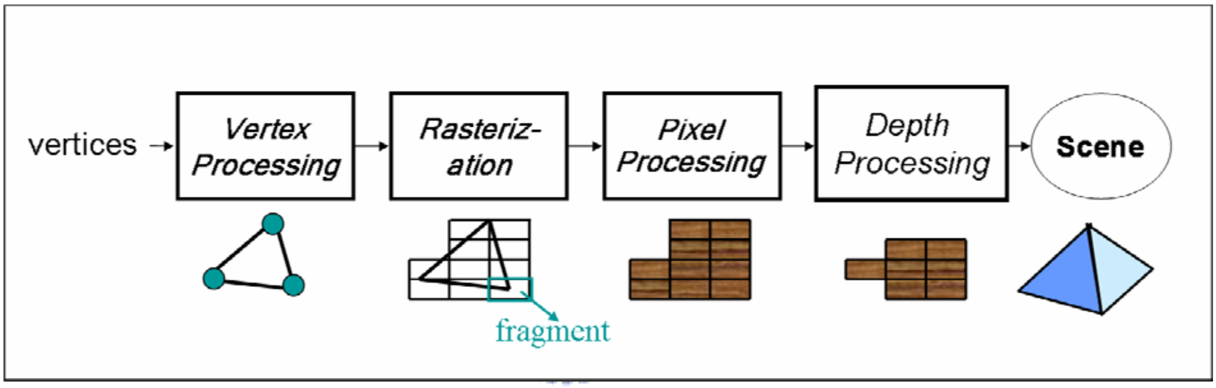


Figure 2-1   3D graphics pipeline

Graphics pipeline can be roughly divided into four stages: **vertex processing**, **rasterizarion**, **pixel (fragment) processing**, and **depth processing**, as shown in Figure 2-1. At vertex processing stage, vertices undergo coordinate transformation, lighting, and clipping operations. After vertex processing stage, these calculated vertices are sent into rasterization stage, which consists of two parts. The first part, called triangle setup, is to combine three vertices into a triangle, and the second part is to determine which squares of an integer grid in screen coordinate are occupied by the triangle and to assign a color and a depth value to each such square. Such generated image square is called **fragment**, which is defined as a pre-**pixel** before being sent to a screen. Fragments are then sent into pixel processing stage. At pixel processing stage, the color of fragments are calculated based on values interpolated from the vertices or determined by texture mapping [Watt00]. Finally, fragments occluded by other fragments and invisible at the final screen are discarded at depth processing.

The graphics pipeline is implemented on GPUs, designed with high parallel structure which makes it more efficient than CPU, and the two describe stages —vertex processing and pixel processing— are implemented as programmable stages, named vertex shading and pixel shading, on GPUs..

Since our system is designed for storing fragments, which are generated after rasterization; therefore, we are only concerned about the process between rasterization stage and pixel processing in graphics pipeline in this thesis.

2.2 Transparency and alpha blending

Translucent objects can be rendered by specifying the degree of transparency with a color. The value to represent the degree of transparency is defined as an **alpha (α) value**, which ranges from 0.0(completely transparent) to 1.0(completely opaque). Each fragment has its alpha value with its RGB color components. To obtain the final color of a pixel, the translucent fragments belonging to the pixel (i.e., fragments have the same x-y coordinate) are typically assumed to be rendered from back to front in visibility order, or depth order. The process of blending a translucent foreground with a background color to generate the effect of transparency is called **alpha blending**. Normally, the alpha blending equation (1) [Port84] is used for alpha blending, as shown below:

$$c = \alpha_f c_f + (1 - \alpha_f) c_b \qquad \text{Eq. (1)}$$

, where c is the final color of a pixel, c_f and α_f are the color and the alpha value of foreground transparent fragment, and c_b is the color of background fragment.

To clarify, consider an example shown in Figure 2-2. In Figure 2-2, six fragments are belonging to the same pixel, two of them are opaque (O_1 and O_3) and four of them are transparent (T_2, T_4, T_5, T_6, and T_7). The suffixes of fragments indicate the sequential order where the fragments are received. The fragments are viewed from the left. The final color of the pixel is obtained by the combination of the closest opaque fragment O_3 and the blending result of the transparent fragments processing from back to front: first T_7, second T_4 and finally T_6. That is, assume c_i and α_i represent the color and the alpha value of fragments, where i is fragment's received order, according to Eq. (1), the final color c of the pixel is equal to

$$c = \alpha_6 c_6 + (1-\alpha_6)\{\alpha_4 c_4 + (1-\alpha_4)[\alpha_7 c_7 + (1-\alpha_7) c_3]\}.$$

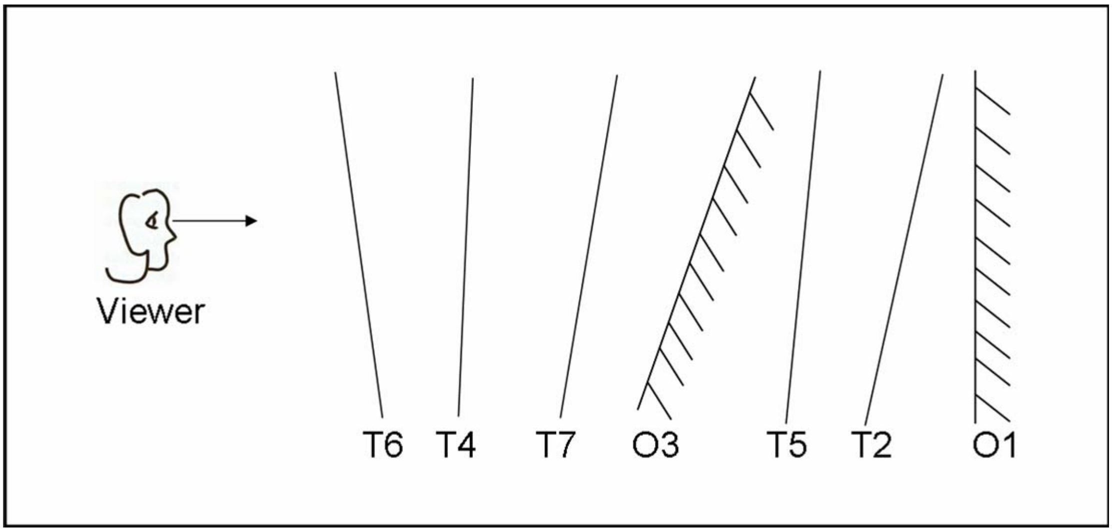


Figure 2-2 Example of fragment blending processing

2.3 Transparency rendering problem

The blending equation (1) is order-dependent, which means that transparent fragments require to be processed in their depth order, not in their arrival order. Thus, if we render transparent fragments in arbitrary order, it will produce an artificial result. For example, in Figure 2-2, fragment T_4 and T_6 come before fragment T_7, if we blend T_4 and T_6 with opaque fragment O_3 first, the blend T_7 later, according to Eq. (1), the final color c will be

$$
\begin{aligned}
c &= \alpha_7 c_7 + (1-\alpha_7)\{\alpha_6 c_6 + (1-\alpha_6)[\alpha_4 c_4 + (1-\alpha_4)c_3]\} \\
&= \alpha_7 c_7 + (1-\alpha_7)\alpha_6 c_6 + (1-\alpha_7)(1-\alpha_6)\alpha_4 c_4 + (1-\alpha_7)(1-\alpha_6)(1-\alpha_4)c_3
\end{aligned}
$$

But the correct final color should be

$$
\begin{aligned}
c &= \alpha_6 c_6 + (1-\alpha_6)\{\alpha_4 c_4 + (1-\alpha_4)[\alpha_7 c_7 + (1-\alpha_7)c_3]\} \\
&= \alpha_6 c_6 + (1-\alpha_6)\alpha_4 c_4 + (1-\alpha_6)(1-\alpha_4)\alpha_7 c_7 + (1-\alpha_6)(1-\alpha_4)(1-\alpha_7)c_3
\end{aligned}
$$

Thus, the incorrect result is produced due to the incorrect rendering order.

Since fragments are generated in arbitrary order at rasterization, not in depth order, several algorithms are proposed for correct transparent rendering. These algorithms can be classified as sorting based algorithms and order-independent transparency algorithms. Sorting based algorithms require the primitives (polygons) to be sorted from back to front with respect to the viewpoint. These sorting algorithms can further be classified into application sorting [Mamm89, Snyd98], hardware assistant sorting [Ever01], and hardware sorting [Amor06, Winn97] algorithms based on the method they use to sort the primitives. However, for application sorting algorithms, it is difficult to do depth sorting since objects in a scene may intersect each other and intersected parts need to be divided into several polygons. Even for those hardware assistant sorting algorithms, it is very time-consuming. Therefore, it comes out order-independent transparency.

2.4 Order-independent transparency

Order-independent transparency is defined as a process which renders transparent fragment in arbitrary order instead of sorting them in advance. There are several different kinds of order-independent transparency algorithms.

Some algorithms model the alpha value as a probability measure such as alpha-dithering [Will] [Muld98], or alpha-to-coverage. These algorithms sample the alpha value and interpret it as how much it covers the pixel to produce dithering-like transparent effect in images. These algorithms are single-pass rendering, do not require depth sorting, and do not handle intersected polygons in advance. However, since they are probability-measure algorithms, they also have chance to produce artificial results. Other order-independent transparency algorithms [Ever01] use multi-pass rendering method to process transparent fragments several times that render them in correct depth order. These multi-pass rendering algorithms are some kinds of fragment-level depth sorting technique; therefore, in general cases, they have the same defect as sorting algorithms have, that is, time consuming.

Thus, most order-independent transparency algorithms modified the traditional GPU architecture to solve time-consuming problem. Z^3 hardware technique [Joup99] is one of these modified hardware architecture which only renders a fixed number of transparency layers correctly. R-buffer(RB) [Witt01] is a modified hardware architecture which implements A-buffer [Carp84] software algorithm into hardware by adding an extra storage system to store transparent fragments associated with each pixel. WF (Weight Factor) hardware oriented algorithms [Amor06] precomputes the contribution factor of each fragment to the final color of pixel and propose an organized strategy to sequentially store transparent fragments corresponding to the same pixel. Since our research focuses on hardware storage support for order-independent transparency, we will introduce more details of R-buffer hardware architecture and WF hardware oriented algorithm, which are more related to our system design.

2.5 Related works

2.5.1 R-Buffer hardware architecture

R-buffer (RB) [Witt01] is a graphics hardware architecture which implements A-buffer software algorithm [Carp84]. Figure 2-3 shows the R-buffer graphics architecture. The

R-buffer architecture is a standard graphics pipeline with additional hardware support: a proposed recirculating fragment buffer, called R-buffer, pixel state memory, and a second z-buffer. In rasterization stage, the objects are rasterized into fragments in arbitrary depth-order. After rasterization, a transparent fragment is sent to the R-buffer, and the depth value of an opaque fragment is compared with the depth value in z-buffer to find the closest opaque fragment which needs to be placed into frame buffer. The transparent fragments behind the closest opaque one are discarded. Then, each transparent fragment in R-buffer is read out iteratively to find the furthest one to be blended with the fragment in frame buffer.

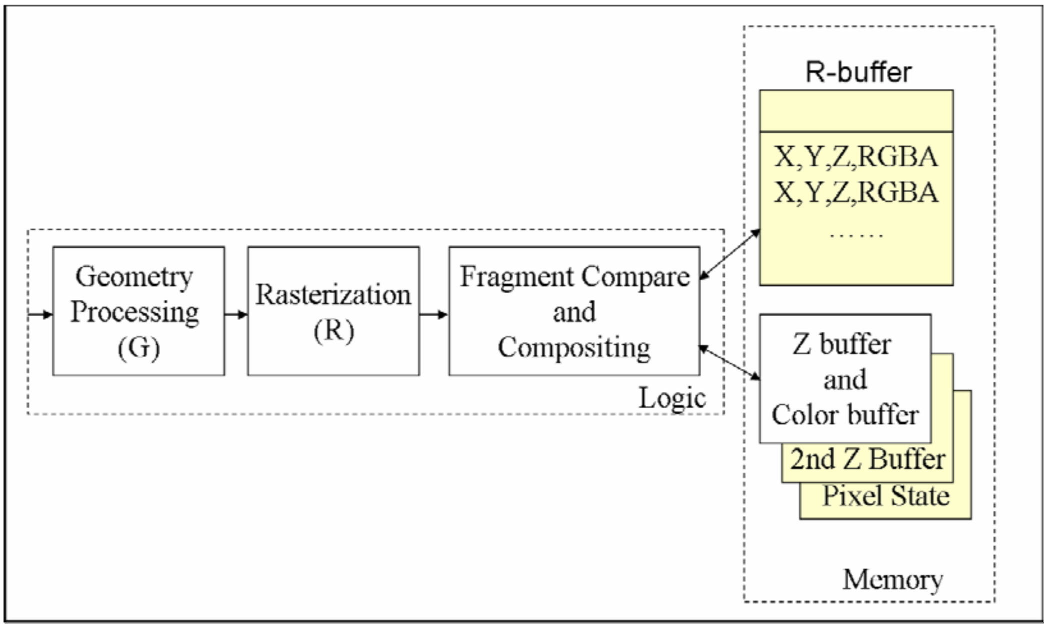


Figure 2-3 R-buffer graphics architecture scheme [Witt01]

Figure 2-4 shows the high level R-buffer algorithm. Phase 1 rasterizes the primitives into fragments and places the closest opaque fragment into frame buffer, the furthest transparent fragment's depth value into second z-buffer. Phase 1 is equivalent to early z test with the exception that unoccluded transparent fragments are sent into R-buffer and second z-buffer is updated with the depth value of the furthest visible transparent fragment. After all fragments are generated, in phase2, the transparent fragments in R-buffer are discarded if they are occluded by the opaque fragments in frame buffer. If the R-buffer is not empty, the phase3 is processed iteratively to find the transparent fragment whose depth value matches the depth in the second z-buffer from R-buffer and blend that transparent fragment with the fragment in frame buffer, and then, drop that transparent fragment from R-buffer. When the R-buffer is empty, the whole process is finished.

```
initialize frame buffer
Phase1(geometry, framebuffer, R-bufferNext)
While(!empty(R-bufferNext))
{
    swap(R-bufferNext,R-buffercurrent)
    Phase2/phase3X(R-bufferCurrent, framebuffer,R-bufferNext)
}
```

Figure 2-4 R-buffer high level algorithm [Witt01]

The R-buffer is a FIFO (first-in-first-out) memory which stores transparent fragments in the sequence that they arrive. The information of each transparent fragment —the location (x, y), the depth value (z), the color value (RGB) with alpha value(A or α)— needs to be stored in the R-buffer. Pixel state memory stores each pixel's current state. The second z-buffer stores the depth value of the furthest visible transparent fragments per pixel. The memory size of the R-buffer is proportional to the number of transparent fragments after early z test. The memory size of the second z-buffer is equivalent to the original z-buffer. In pixel state memory, each pixel needs three bits to record its current value; thus, the memory size of the pixel state memory is equal to three multiplied by the screen size. To sum up the memory requirement of R-buffer architecture, we list the R-buffer memory requirement equation as follow:

$$Memory_{total} = M_{R\text{-}buffer} + M_{2nd\text{-}z\text{-}buffer} + M_{state\text{-}memory}$$

2.5.2 Hardware oriented algorithm based on weight factors computations

For the convenience of explaining this algorithm [Amor06], we called it WF (Weight

Factor) hardware oriented algorithm in brief. WF hardware oriented algorithm is based on the precomputation of the contribution of each fragment to the final color of the pixel with the specialized storage scheme. Figure 2-5 shows the generic structure of WF hardware oriented algorithm. Phase 1 and phase 2 of WF hardware oriented algorithm are similar to those of R-buffer high level algorithm, shown in Figure 2-4. In phase 1, fragments are sequentially generated and the current closest opaque transparent is placed into frame buffer while the transparent fragments are stored into another buffer, called M_{buffer}. In phase 2, all transparent fragments stored in M_{buffer} are analyzed and discarded if they are occluded by the closest opaque fragment stored in frame buffer. In phase 3, each transparent fragment in M_{buffer} is compared with other fragments belonging to the same pixel in order to compute its weight factor and the blending of the fragment is performed.

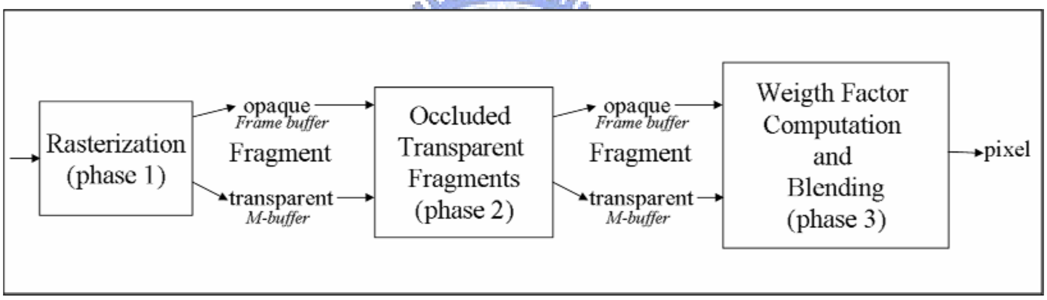


Figure 2-5 Generic structure of WF hardware oriented algorithm

The weight factor computation is based on the analysis of the blending equation (1). By breaking the recursivity of the blending equation (1), the equation can be revised as:

$$c = \sum_{i=0}^{n} w_i \alpha_i c_i \qquad \text{Eq. (2)}$$

, where there are n transparent fragments and one opaque fragment belonging to the pixel which has the final color *c*, c_i is the color of the transparent fragment *i*, α_i is the alpha value of fragment *i*, and w_i is the weight factor of the transparent fragment *i*. The weight factor w_i is computed by the accumulative contribution of all transparent fragments *j* in front of the transparent fragment *i* ($Z_j < Z_i$). The equation of w_i can be written as:

$$w_i = \prod_{j=0}^{n} a_j \qquad \text{Eq. (3)}$$

with

$$a_j = \begin{cases} 1-\alpha_j & \text{if } Z_j < Z_i \\ 1 & \text{otherwise.} \end{cases} \qquad \text{Eq. (4)}$$

```
     /* SETUP */
1    Z_buffer = ∞ ;
2    for(i=0 ; i≦n; i++){
3        if(Z_i < Z_buffer){
4            if(α_i<1){ E_i → M_buffer; w_i=c_i* α_i ; }
5            if(α_i ==1){ Z_buffer=Z_i ; c=c_i; }
6        }
7    }
8    /* OCCLUDED TRANSPARENT FRAGMENTS */
9    for all E_i in M_buffer {
10       if(Z_i < Z_buffer) { M_buffer → E_i ;}
11       else{ c_i*=(1-α_i); }
12   }
13   /* WEIGHT FACTOR COMPUTATION */
14   for all E_i in M_buffer{
15       for all E_j in Mbufer with j > i {
16           if(Z_i<Z_j) { w_j*=(1-α_i);}
17           else {w_i*=(1-α_j)}
18       }
19       /* additional of contributions */
20       c+=w_i ;
21       M_buffer → E_i ;
22   }
```

Figure 2-6 WF hardware oriented algorithm

The WF hardware oriented algorithm is outlined in Figure 2-6. It can be basically divided into three stages: SETUP (line 1-6), OCCLUDED TRANSPARENT FRAGMENTS (line 9-12), WEIGHT FACTOR COMPUTATION (line 14-22). Assume that there are n+1 fragments are processed sequentially to the same pixel. In SETUP stage, if a fragment is transparent, it is placed into M_{buffer}; otherwise, if a fragment is opaque and closest to the view point at the time, it is stored into frame buffer and Z-buffer is updated by its depth value. Note that some transparent fragments are visible when they are compared to the front-most opaque fragment at the time they arrive, but a closer opaque fragment may arrive later and occlude them. Therefore, in the second stage, OCCLUDED TRANSPARENT FRAGMENTS, those transparent fragments in M_{buffer} are discarded for the reason that they are occluded by the closest opaque fragment. In the last stage, WEIGHT FACTOR COMPUTATION, each fragment is compared with all those following in the M_{buffer} in order to compute its weight factor. Obviously, these three stages in Figure 2-6 are the same as the three phases in Figure 2-5.

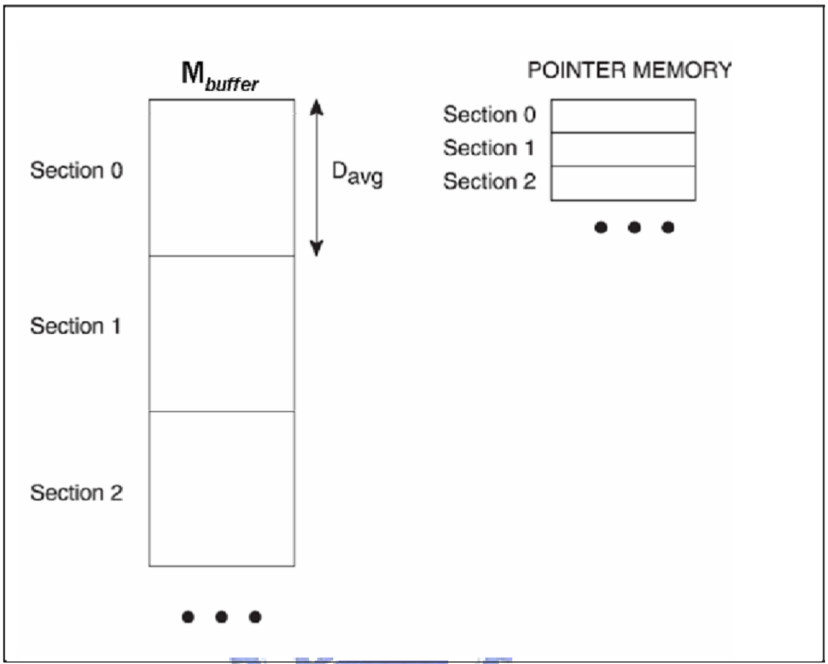


Figure 2-7 Organized memory scheme of WF algorithm

The organized memory scheme of WF algorithm is shown in Figure 2-7. It suggests that transparent fragments belonging to the same pixel are stored sequentially and connectedly in the M_{buffer}. M_{buffer} is organized in sections of D_{avg} words, where D_{avg} is the average number of fragments per pixel. Each pixel has it corresponding storage section, with capacity for D_{avg} fragments; that is, for a system with $W \times H$ pixels, $W \times H$ sections would be required and a pixel i in a system has a corresponding section i in M_{buffer}. To extend the storage capabilities, a pointer memory is added so that more than one section can be dynamically assigned to a given pixel. The information stored per section of a pointer memory indicates that whether one section is sufficient (by storing a NULL pointer) or whether the following-coming fragments are stored in another section (by storing the section index). For example, if there are F transparent fragments belonging to a pixel i, where F is larger than D_{avg}, the first D_{avg} fragments are stored in section i of M_{buffer}, and the following F- D_{avg} fragments are stored in another section j ($j \geqq W \times H$). The section i of a pointer memory stores the section j index. If section j is still insufficient to store F- D_{avg} fragments (i.e., F- $D_{avg} > D_{avg}$), the rest F-$2 \times D_{avg}$ fragments are stored to another section k ($k>j$), and so on.

Chapter 3 Design

In this chapter, our transparent fragment storage system is proposed. The objective of our transparent fragment storage system is to reduce the memory requirement and memory access of transparent fragments for order-independent transparency. In addition, we also propose a leading 0s elimination technique to compress fragment data size and further reduce the memory requirement of the proposed transparent fragment storage system. This chapter is organized as follows: in section 3.1, the system design overview is introduced; in section 3.2 our transparent fragment storage system is proposed; in the last section of this chapter (section 3.3), we present the leading 0s elimination technique.

3.1 Design overview

The overview of our proposed transparent fragment storage system is shown in Figure 3-1. There are three components in our transparent fragment storage system: **start-section address table (SSA Table)**, **T-buffer, and next-section address (NSA Table).** After rasterization stage, the polygons are segmented into several fragments in arbitrary order. Then, opaque fragments continue the pixel processing procedure while transparent fragments are stored into our **transparent fragment storage system (TFSS)**. The details of our transparent fragment storage system will be introduced in section 3.2. In addition, we also design **leading 0s elimination**, which is the process that reduces a fragment data size by eliminate the leading 0s of fragment's color components (RGB). The details of leading 0s elimination will be introduced in section 3.3.

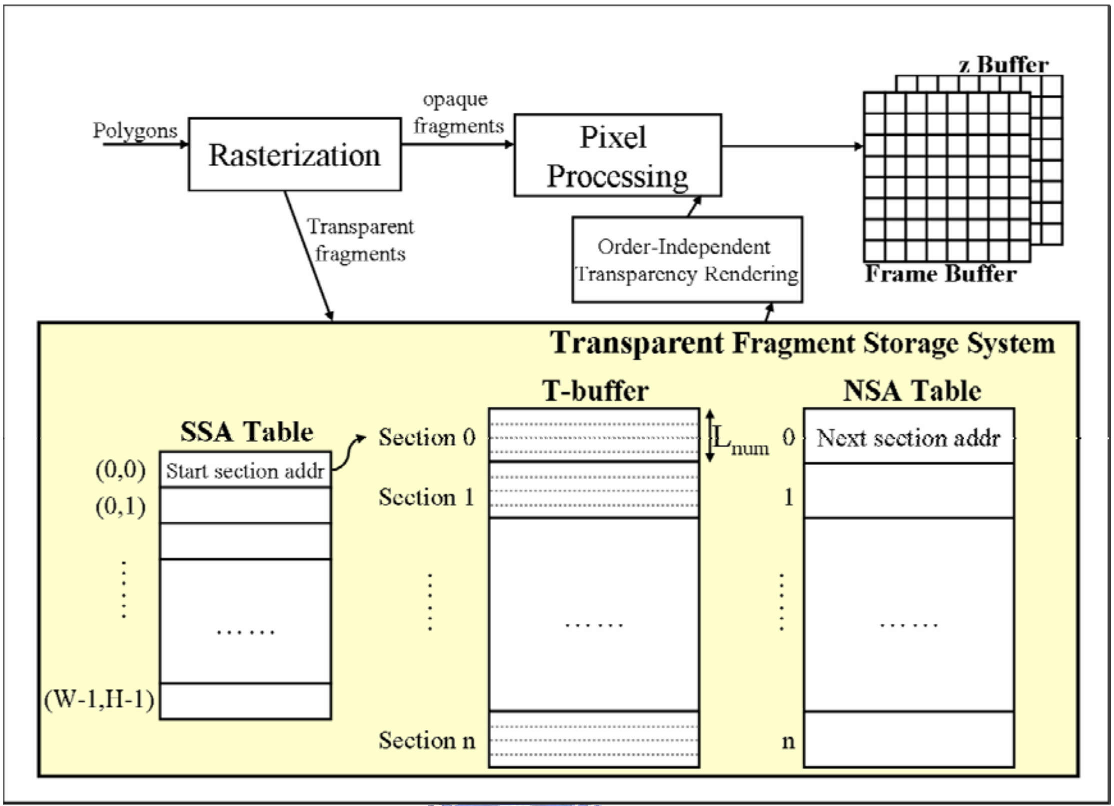


Figure 3-1 the design diagram of transparent fragment storage system

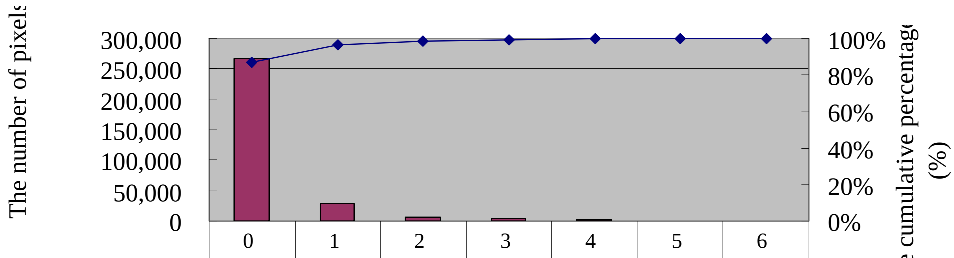
3.2 Transparent Fragment Storage System

3.2.1 Statistics and observation for the distribution of transparent fragment

Figure 3-2 shows a frame image in DOOM3. We analysis the number of transparent fragments of each pixel in this frame and obtain the result in Figure 3-3 and Figure 3-4. Figure 3-3 is a gray-level image, and black color indicates that the number of transparent fragments of a pixel is 0, while white color indicates that the number of transparent fragments of a pixel is 7, that is, the maximum number of transparent fragments of a pixel in the frame. The transparent fragment numbers of a pixel between 0 and 7 and their corresponding colors are shown at right side of Figure 3-3. More detail of statistics of the transparent fragment number in the frame is shown in Figure 3-4. We find that not all pixels in a frame have transparent fragments. However, in WF proposal, each pixel is assigned the same size of memory space, no matter whether the pixel has transparent fragments or not. Thus, if we use a transparent storage support proposed in WF proposal, it needs a large memory space and parts of them are unused resulting in unnecessary memory cost.

Figure 3-2 frame in DOOM3

Figure 3-3　number of transparent fragments per pixel expressed by grayscale image



	0	1	2	3	4	5	6
the number of pixels	266,978	28,818	6,387	3,637	1,145	234	1
cumulative percentage of pixel number	86.91%	96.29%	98.37%	99.55%	99.92%	100.00%	100.00%

The number of transparent fragment per pixel

the number of pixels　cumulative percentage of pixel number

Figure 3-4　statistics of the number of transparent fragments per pixel

3.2.2 The structure of transparent fragment storage system

In this section, we will introduce the structure of TFSS. As the section 3.1 is described, the design diagram of transparent fragment storage system (TFSS) is shown in Figure 3-1. The storage scheme of TFSS is to store transparent fragments in an organized way based on their coordinate; that is, transparent fragments belonging to a pixel are stored serially in TFSS. The transparent fragment storage system (TFSS) is composed of three components: SSA Table, T-buffer, and NSA Table. The structure and the function of each component in TFSS will be described in 3.2.2.1 to 3.2.2.3.

3.2.2.1 SSA(Start-Section Address) Table

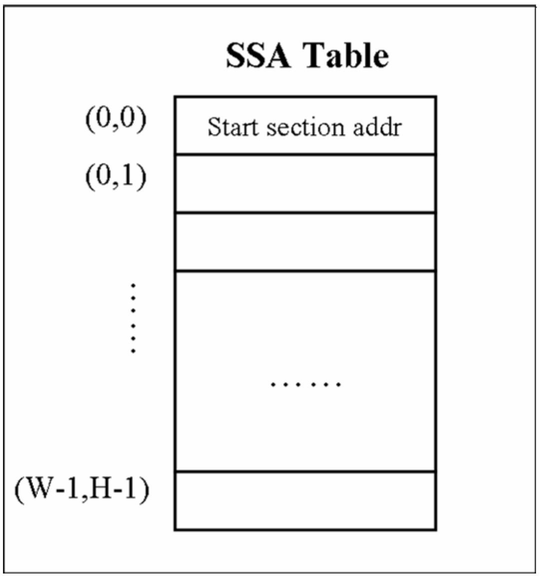


Figure 3-5 diagram of SSA Table

As shown in Figure 3-5, SSA Table has W times H entries, where W is defined as the width of a screen, and H is defined as the height of a screen. Each pixel p in a screen has a corresponding entry e_p in SSA Table and each entry in SSA Table stores the address of start section for pixel p. Namely, pixel p has assigned the entry e_p in SSA Table. If a pixel does not have the start section— the pixel does not have transparent fragmentS— a nullified address is stored in the corresponding entry in SSA Table.

3.2.2.2 T-Buffer

T-buffer is a storage space for transparent fragments. As shown in Figure 3-6, T-buffer is organized in sections of L_{num}, where L_{num} represents the maximum number of transparent fragments that can be stored in a section. Each section stores transparent fragments with the same x-y coordinate; that is, fragments belonging to the same pixel are stored gregarious within one section in T-buffer. There might be more than L_{num} transparent fragments which have the same x-y coordinate. Thus, more than one section should be assigned to a pixel to extend the capability for storing variable number of fragments. We use NSA Table to record the address of next section which is assigned to store the following fragments.

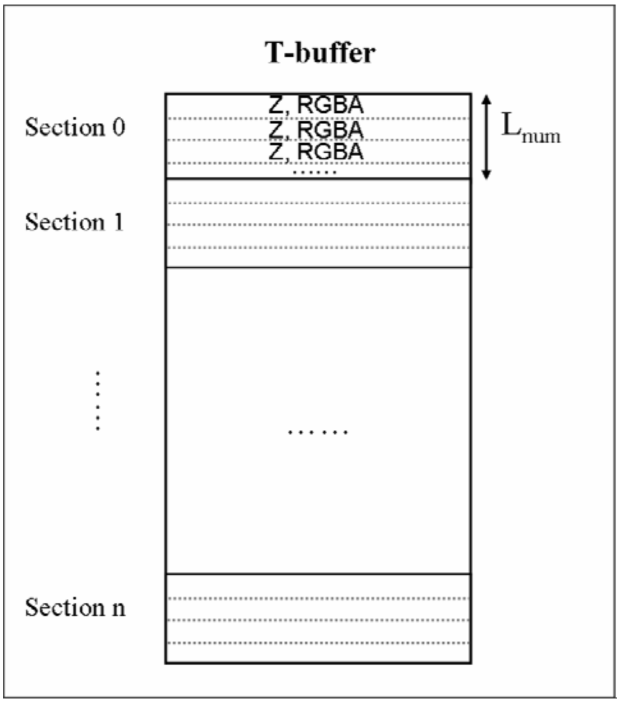


Figure 3-6 the structure of T-buffer

3.2.2.3 NSA(Next-Section Address) Table

If the number of transparent fragments is more than the number that one section is capable of storing, the excess fragments will be stored in another section. Then, the address of the section is recorded as the next-section address in NSA Table. Figure 3-7 shows the diagram of NSA Table. The number of entries in NSA Table is equivalent to the number of sections in T-buffer and there is a one-to-one correspondence between entries in NSA table and sections in T-buffer. However, if one section is sufficient to store transparent fragments of a pixel, there is no need to assign another section, and thus, the NULL pointer is stored instead of the section address.

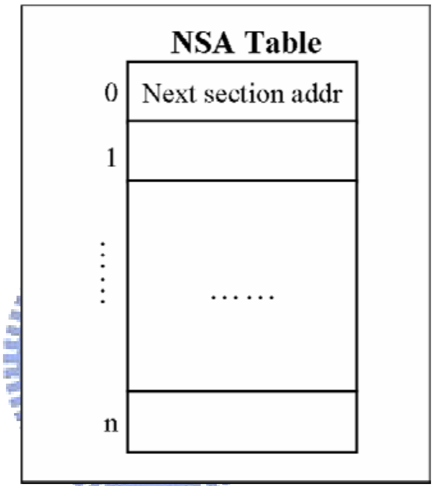


Figure 3-7 diagram of NSA Table

3.2.3 The access process of transparent fragment storage system

In this section, the access process of transparent fragment storage system is described. The process for storing fragments into TFSS is described in 3.2.3.1; the process for reading fragments from TFSS is described in 3.2.3.2.

3.2.3.1 The process for storing transparent fragments into TFSS

First of all, before a transparent fragment with the location (x_i,y_j) is stored into T-buffer, the address of start section $s_{(i,j)}$ is read from the corresponding entry $e_{(i,j)}$ in SSA Table. If $s_{(i,j)}$ of T-buffer, the start section, is full, the address of next section n_s which is available (not full) for storing fragments is read from the entry e_s of NSA Table. After the address of section n_s is obtained, the fragment is eventually stored into section n_s of T-buffer. If there is no start section or no next section for a given pixel, the new empty section in T-buffer is assigned for that pixel, and the address of the new section is recorded in SSA Table as the start-section address or in NSA Table as the next-section address for the pixel. Figure 3-8 shows the flowchart of the process for storing fragments into TFSS.

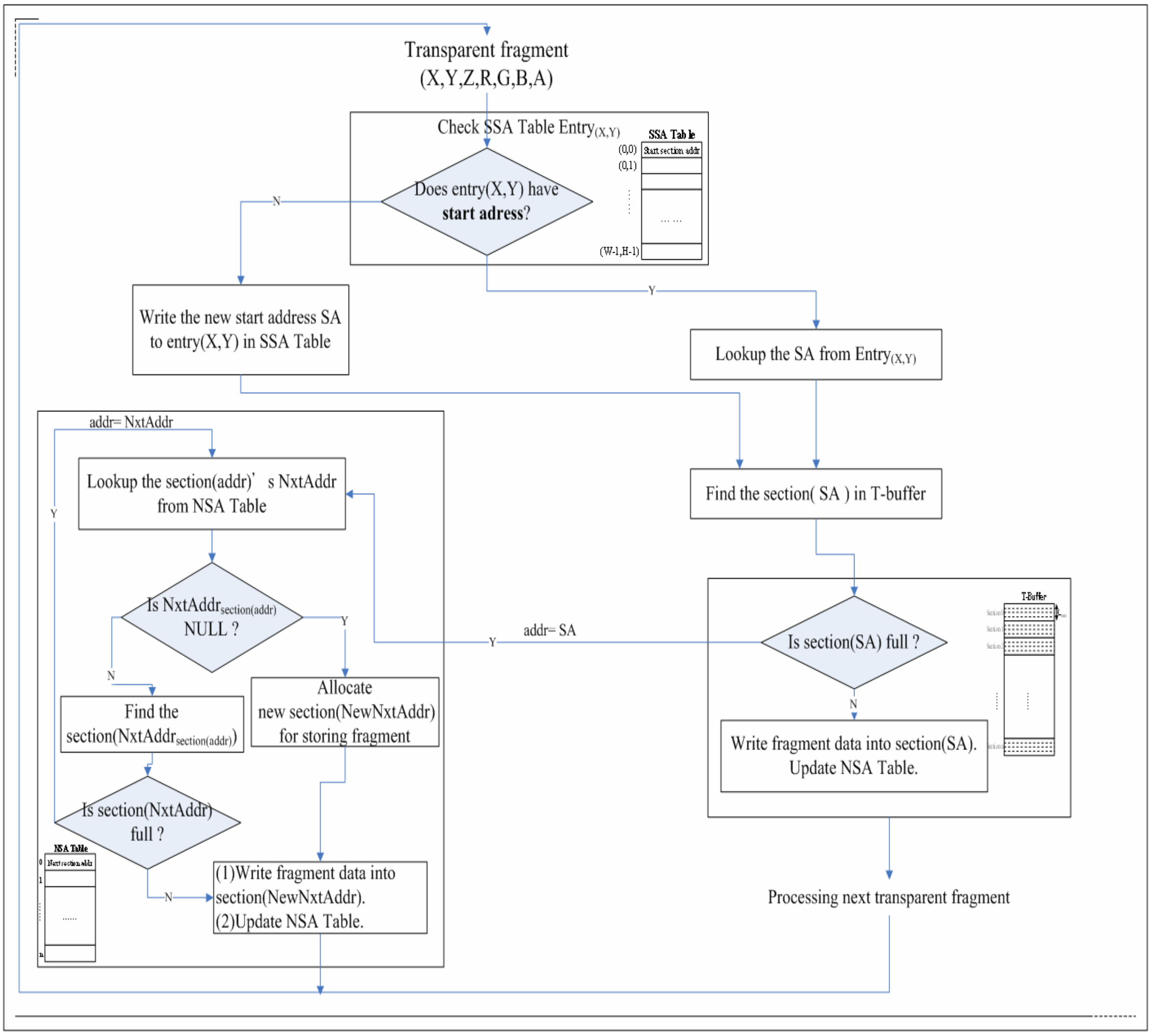


Figure 3-8 flowchart of the process for storing fragments into TFSS

3.2.3.2 The process for reading transparent fragments from TFSS

For each pixel $p_{(i,j)}$ in a screen, the start-section address is read from its corresponding entry $e_{(i,j)}$ in SSA Table. If there is no start-section address for a pixel, the process is continued to read the start-section address from the next entry $e_{(i,j+1)}$ for the next pixel. Otherwise, transparent fragments belonging to $p_{(i,j)}$ are accessed from the start section $s_{(i,j)}$ of T-buffer and the address of next section n_s can be read simultaneously from the entry s of NSA Table. If there is no next section for $p_{(i,j)}$, instead, the NULL is stored in entry s of NSA Table, the process is continued for the next pixel. Otherwise, the fragments in the next section n are accessed from T-buffer and the address of the next section n' of section n can be looked up simultaneously from the entry n of NSA Table. This process is recursively done until there is no next section for pixel (x_i,y_i). Figure 3-9 shows the flowchart of the whole process for reading fragments from TFSS.

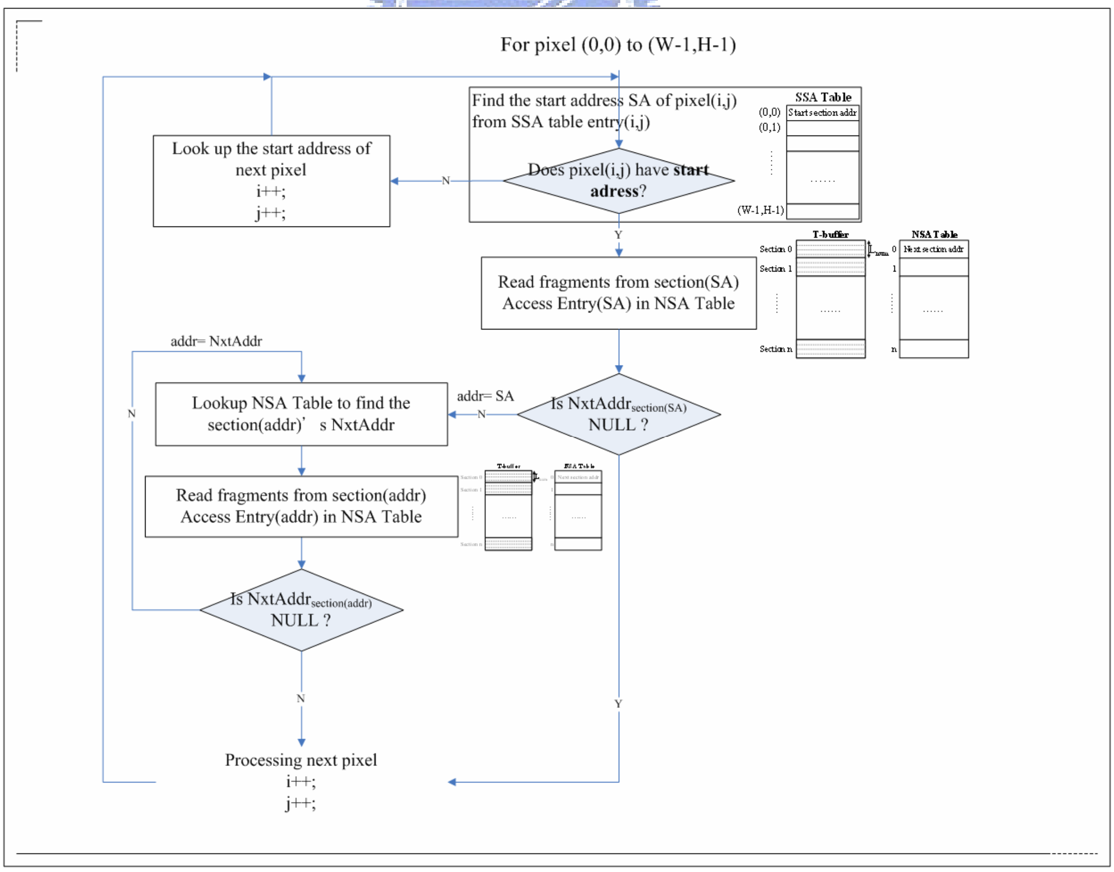


Figure 3-9 flowchart of the process for reading fragments from TFSS

3.3 Leading 0s elimination

3.3.1 Statistics and observation of fragment data length

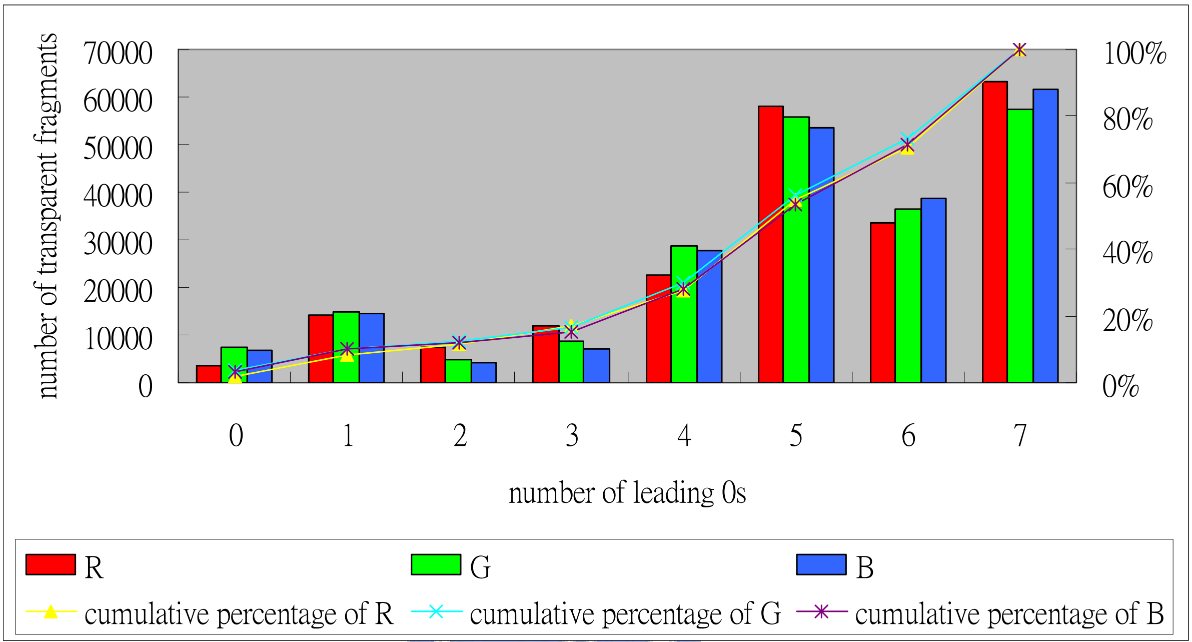


Figure 3-10 distribution of the number of leading 0s of fragments

Figure 3-10 shows the distribution of the number of leading 0s of fragments before multiplied by alpha value in frame130. In Figure 3-10, the horizontal axis represents the number of leading 0s of a fragment, ranging from 0 to 7 for each 8-bit color component; the vertical axis represent the number of transparent fragments. The yellow, light blue, and purple curves in Figure 3-10 represent the cumulative percentage of fragments in accordance with the number of leading 0s. As we can see, about 80% fragments, their effective value of each color component only use less than 4 bits.

When RGB color components of a fragment are multiplied by fragment's alpha value, the number of leading 0s of each of RGB color components will increase, as shown in Figure 3-11. This phenomenon gives us a thought that it does not need full 8-bit memory space to store each color component of a transparent fragment; that is, we can eliminate leading 0s of each color component of a transparent fragment before it is stored into T-buffer to further reduce the memory requirement of transparent fragment storage system.

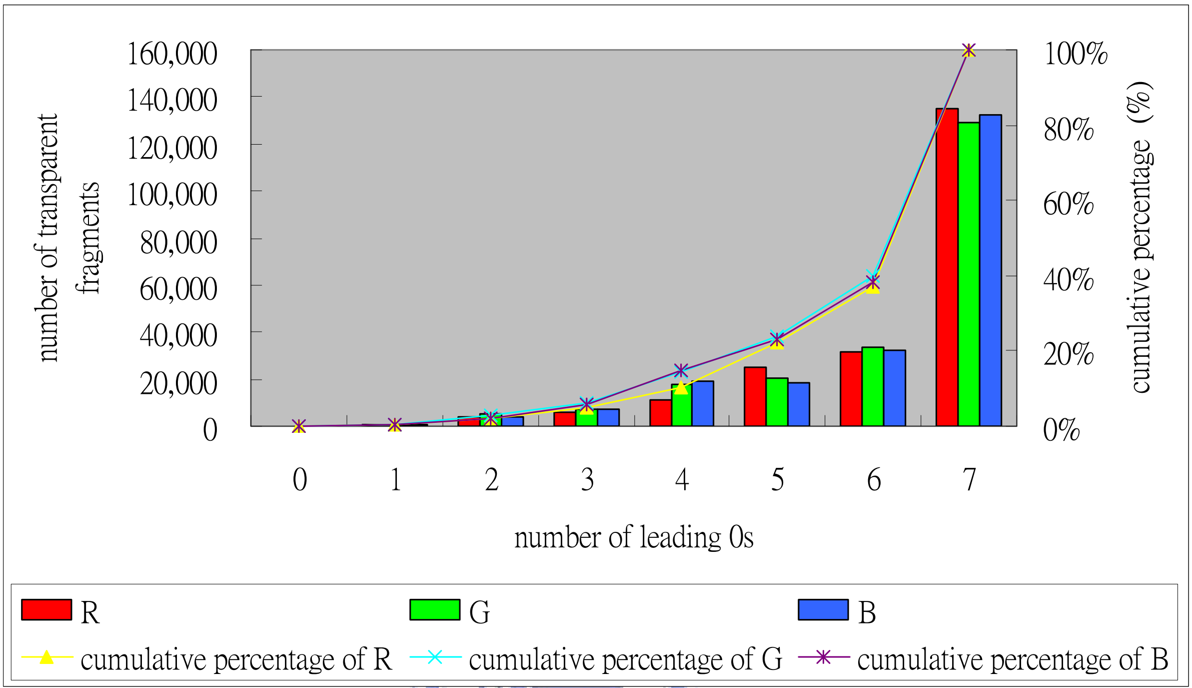


Figure 3-11 the number of leading 0s of fragments after multiplied by alpha value

The original cumulative percentage curve of transparent fragments is compared with the cumulative percentage curve after multiplied by alpha value, as shown in Figure 3-12, where line1-R,G,B represent the former and line2-R,G,B represent the latter. Line3-R,G,B in Figure 3-12 represent the cumulative curve of transparent fragments when we choose the minimum number of leading 0s among RGB color components as the number of leading 0s of each color component. We observe that there is a little difference between line2 and line3, and it implies that perhaps a fixed-length leading 0s elimination to RGB color component of a fragment can achieve approximate memory reduction ratio as variable-length leading 0s elimination.

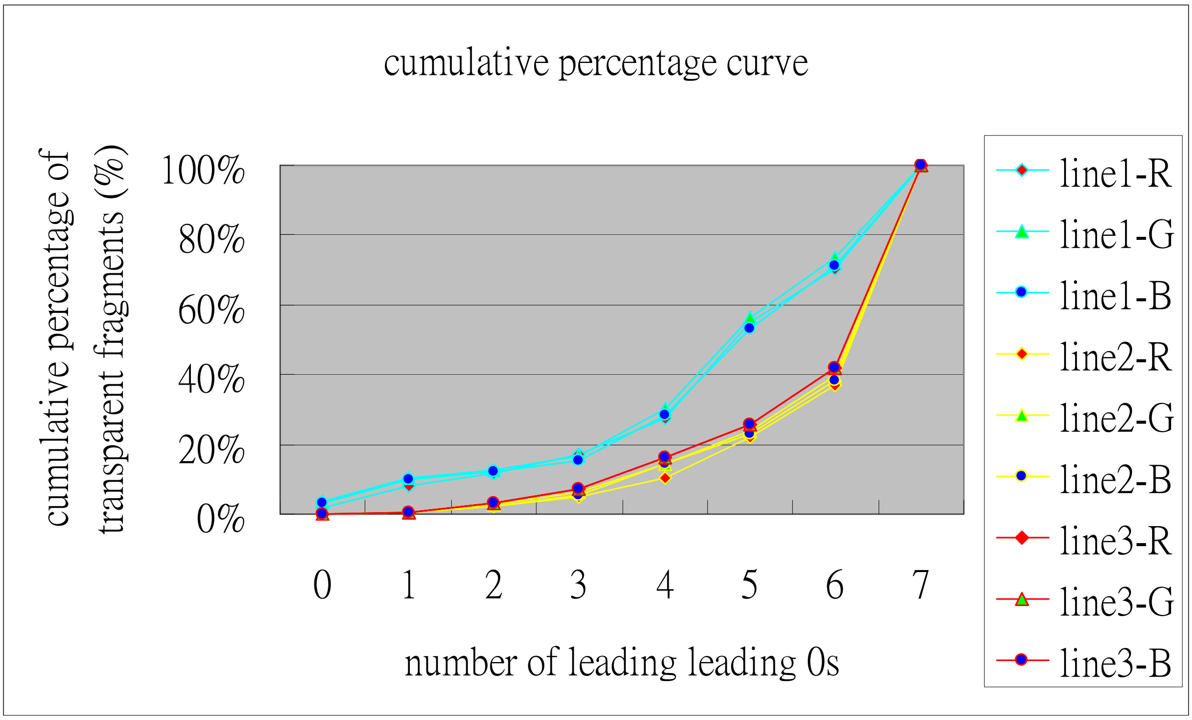


Figure 3-12 cumulative percentage curves of transparent fragments

3.3.2 Main idea of leading 0s elimination

According to the statistics and observation in 3.3.2, we decide to use a leading 0s elimination to further reduce the memory requirement for transparent fragments. Leading 0s elimination is a simple and quick process that eliminates the leading zero bits of three color component data(RGB) simultaneously until leading 1 occurs in any one of the three color components. Notice that we do not eliminate all leading zero bits from each color component, instead, we just eliminate the minimum number of leading 0s among RGB color components; that is, fixed-length leading 0s elimination for each RGB color component of a transparent fragment.

The operation of leading 0s elimination is simple. First, eliminate leading zero bits of three color components (RGB) simultaneously until leading 1 occurs in any one of the three color components. Then, shift the RGB color component data to the right by several bits based on fragment's alpha value. Finally, record the length of RGB color component after elimination.

As shown in Figure 3-13, for leading 0s elimination, an additional design component, called **Length Table**, is added into our transparent fragment storage system to support variable-length fragment data retrievals. Length Table records the length of RGB color components of a fragment after leading 0s elimination. There is a one-to-one correspondence between entries in Length Table and sections in T-buffer; that is, each entry in Length Table records the lengths of fragments in its corresponding section and each entry in Length Table can record at most L_{num} lengths of fragments, where L_{num} represents the maximum number of transparent fragment that can be stored in a section.

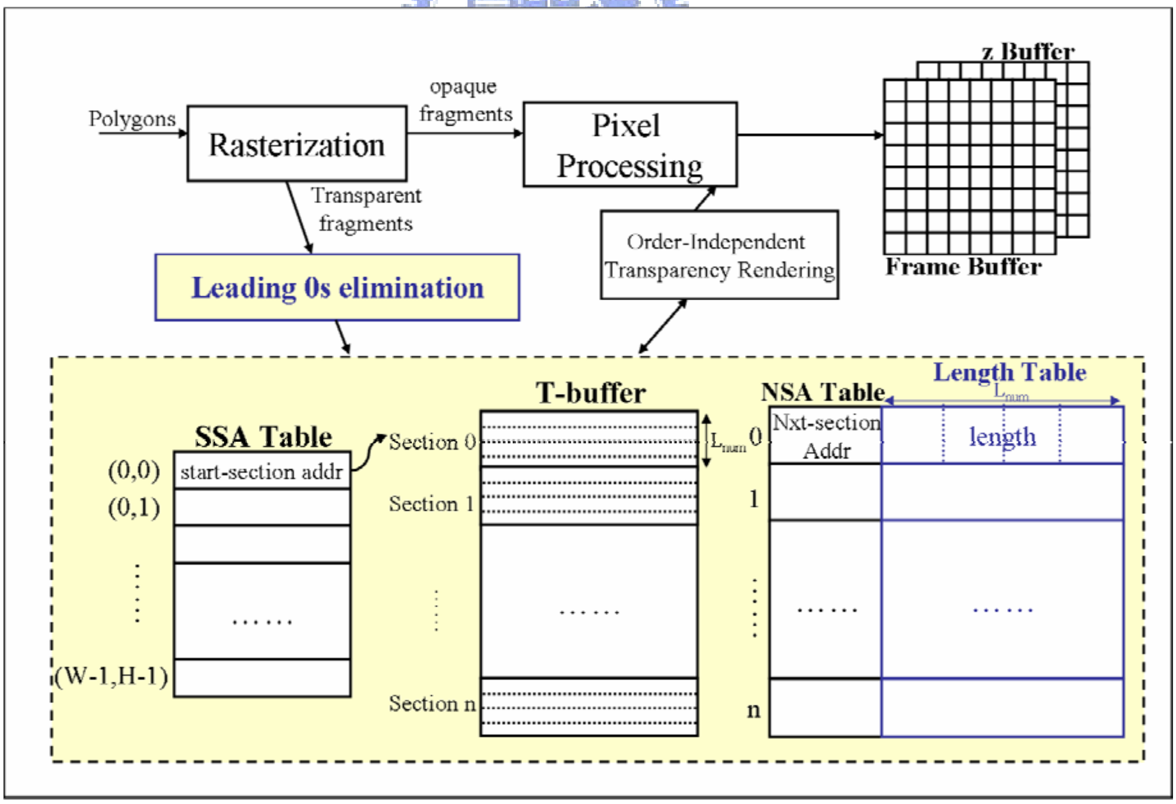


Figure 3-13 transparent fragment storage system with leading 0s elimination

3.3.3 Example of leading 0s elimination

Figure 3-14 shows an example of leading 0s elimination. Assume that each color component of a fragment is 8 bits, fragment's alpha value is 0.125, and the value of each color component is represented in binary format. First, the minimum number of leading 0s among RGB color components is two; thus, we eliminate two leading zero bits from each of three color components (RGB) simultaneously. Then, shift the RGB color component data to the right by 3 bits based on fragment's alpha value. Finally, record the length of RGB color component after elimination.

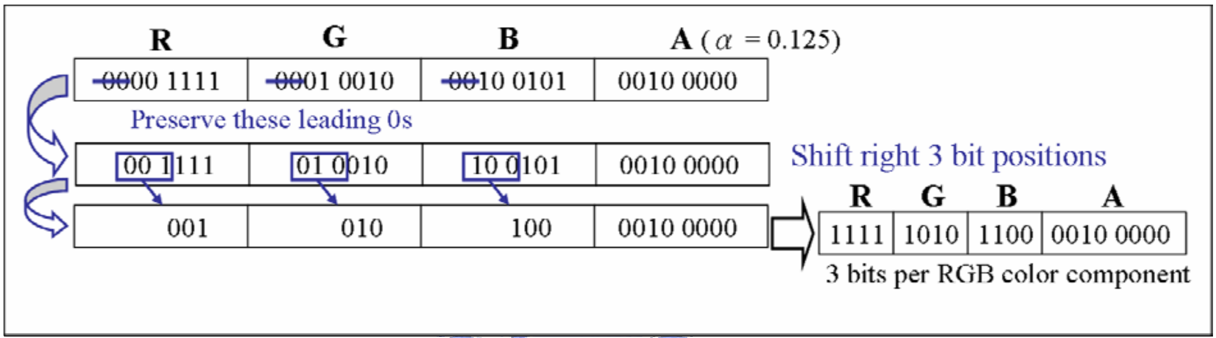


Figure 3-14 example of leading 0s elimination

Chapter 4 Evaluation Results

In this chapter, we first show our evaluation environment and the characteristic of input frame data (in section 4.1 and 4.2). Then, we show and analyze simulation results of memory requirement and execution time during rendering of each method: R-buffer, WF hardware oriented algorithm, and our TFSS design in section 4.3. In the last section, we briefly summarize our conclusion from the results.

4.1 Evaluation environment

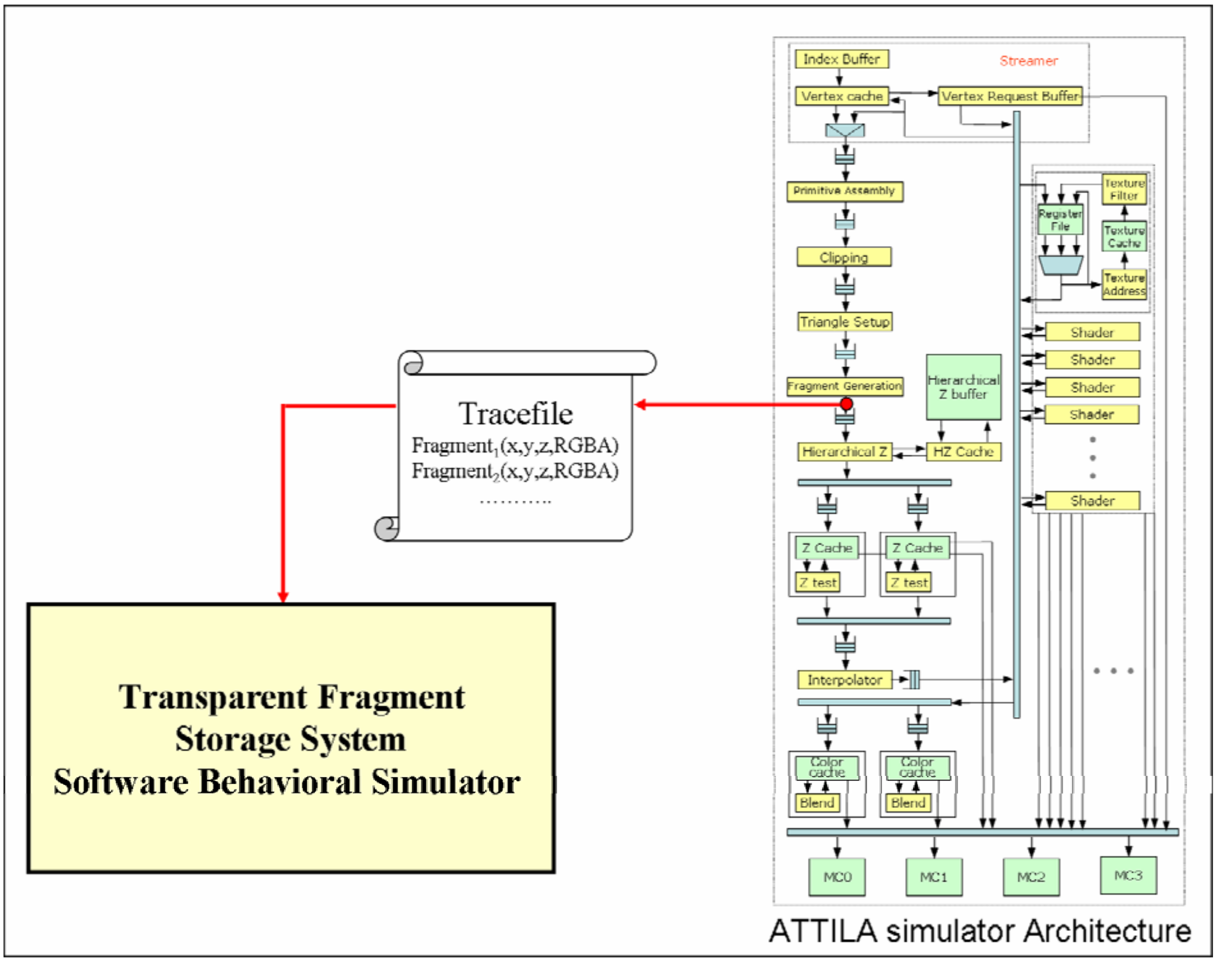


Figure 4-1 simulation flow and ATTILA architecture [Moya06]

Figure 4-1 shows the architecture of ATTILA simulator and when we dump trace of fragment data from ATTILA simulator for our simulator. We implemented a behavioral simulator of the architecture with the transparent fragment storage system in C++, and modified ATTILA simulator [Moya06] to output fragment information to a tracefile. The benchmark used in ATTILA simulator is QUAKE4 [Rave05], a modern graphics application. Figure 4-2 shows one frame appearing in QUAKE4. The tracefile outputted from ATTILA simulator contains the coordinates and RGBA color components of fragments in frames. Our simulator reads the tracefile and evaluates the memory requirement and access frequency time of transparent fragment storage system.

Figure 4-2 a frame appearing in QUAKE4

The simulation parameters are listed below:

- Display resolution: the number of distinct pixels in each dimension that can be displayed.
- Color component bit-width: the bit-width of each of the RGBA color components
- L_{num} : the maximum number of transparent fragments that a section in T-buffer can stores.
- $M_{section}$: the memory size of a section in T-buffer

In our simulator, we assume the display resolution is 640×480, the bit-width of each of RGBA color components is 8 bits, and modulate the value of L_{num} and $M_{section}$ to observe the memory requirements.

4.2 Test frame data

Frame	No. of fragments	No. of transparent fragments	No. of transparent fragments per transparent pixel	Transparency density	No. of pixels whose no. of transparent fragments = N				
N					1	2	3	4	5
Frame60	2,377,518	37,684	2.37	5%	5,812	956	6,633	2,279	189
Frame120	746,943	37,594	2.38	5%	5,723	956	6,634	2,278	189
Frame180	516,464	40,584	2.16	6%	8,713	956	6,634	2,278	189
Frame240	488,112	88,434	1.63	18%	32,588	12,040	7,235	2,279	189
Frame300	623,531	60,769	1.61	12%	26,082	2,729	6,636	2,179	121
Frame360	587,617	69,768	1.61	14%	27,421	7,094	7,006	1,569	173
Frame420	530,258	47,877	1.77	9%	15,728	3,290	6,770	1,296	15
Frame480	605,927	135,475	1.22	36%	95,226	8,716	6,711	671	0

Table 4-1 statistics of test frames

In this section, we provide statistics of eight test frames, which are dumped at the interval of 60 frames, as shown in Table 4-1. In Table 4-1, the second column indicates the total number of opaque and transparent fragments in each frame; the third column shows the number of transparent fragments in each frame; the fourth column shows the number of transparent fragments per transparent pixel; the fifth column shows the transparency density, which is defined as the percentage of transparent pixels in a frame (i.e. #transparent pixel/display resolution). The last column shows the distribution of transparent fragment layers per pixel in each frame. For example, in frame 120, 5723 pixels have 1 transparent fragment layer, 956 pixels have 2 transparent fragment layers, 6634 pixels have 3 transparent fragment layers, 2278 pixels have 4 transparent fragment layers, 189 pixels have 5 transparent fragment layers, and no pixel have more than or equal to 6 transparent fragment layers.

4.3 Simulation results

In this section, we show the simulation results of memory requirements and access frequency time of fragments storage system. We compare the results of our design with two related works: R-buffer and WF hardware oriented algorithm.

4.3.1 Memory requirement

In order to evaluate our transparent fragment storage system (TFSS), we compare our storage design with two related works: R-buffer [Witt01] and WF hardware oriented algorithm [Amor06]. We list the memory requirements of each method in Table 4-2. The second column shows the name and the size of a transparent fragment storage space in each technique and the third column shows the name and the size of other storage supports in each storage system. In Table 4-2, N_f is defined as the number of transparent fragments, N_A is defined as the number of dynamic allocated sections in WF algorithm, and N_S is defined as the number of sections in T-buffer in our design; S_f is defined as the size of a fragment data (XYZ,RGBA), S_A is defined as the size of an address; M_{WF} is defined as the memory size per section in M-buffer in WF algorithm, and M_{TFSS} is defined as the memory size per section in T-buffer in our TFSS; W and H are defined as the width and the height of a display screen.

techniques	Transparent fragment storage system			
	transparent fragment memory		other storage supports	
	Name	size	Name	Size
R-buffer	R-buffer	$N_f \times S_f$	2nd Z buffer	= Z buffer size ($W \times H \times$Z's bytes)
			state memory	3(bits) $\times W \times H$
WF algorithm	M-buffer	$(W \times H + N_A) \times M_{WF}$	pointer memory	$S_A \times (W \times H + N_A)$
TFSS	T-buffer	$M_{TFSS} \times N_S$	SSA Table	$S_A \times W \times H$
			NSA Table	$S_A \times N_S$

Table 4-2 memory requirements of each of transparent storage systems

Based on the memory requirements listed in Table 4-2, we obtained the simulation result of memory requirement of each technique, as shown in Figure 4-3. We find that in average, our TFSS has the lowest memory requirement than two related works.

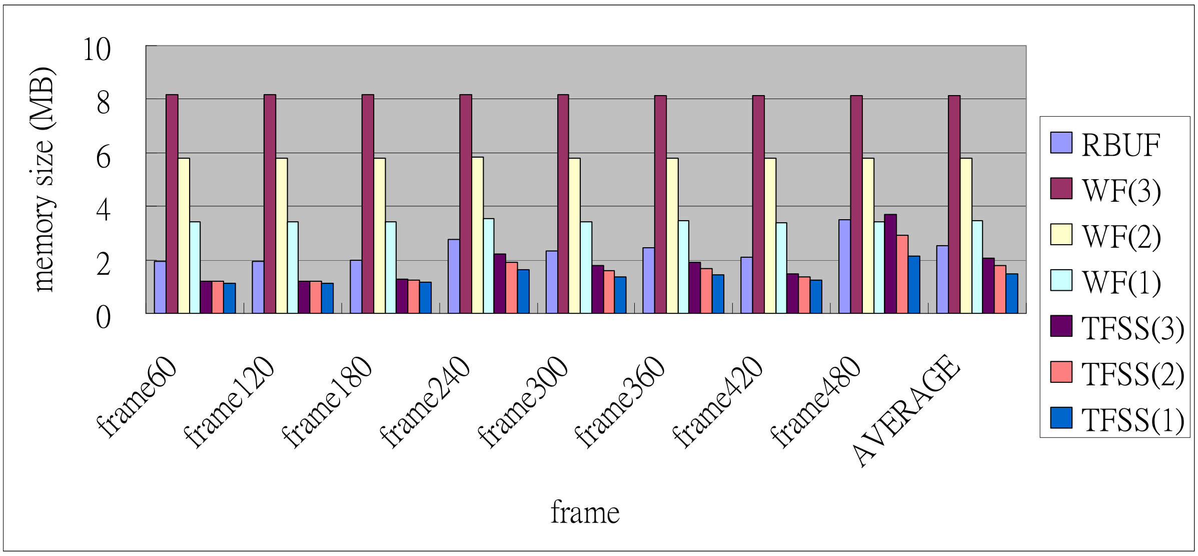


Figure 4-3 memory requirement comparison[1]

[1] WF(D_{avg}) represents WF algorithm has the capability for storing D_{avg} fragments per section in M-buffer TFSS(L_{num}) represents TFSS has the capability for storing L_{num} fragments per section in T-buffer

Notice that in frame480, the memory requirements of our TFSS with Lnum=3 are larger than those of R-buffer technique. We conjecture that this result is occurred by the weakly utilization of a section, which has the capability for storing three transparent fragments but only stores fewer than three fragments. As shown in Table 4-1, the proportion of pixels which have one transparent fragment in frame480 is much larger than those in other frames. In fact, the percentage of pixels with one transparent fragment in frame480 is about 30%, while it is only 2% to 10% in other frames. It indicates that about 30% of sections in T-buffer are weakly utilized in frame480. Therefore, it results in unnecessary memory cost and larger memory requirement of TFSS with Lnum=3 than of R-buffer.

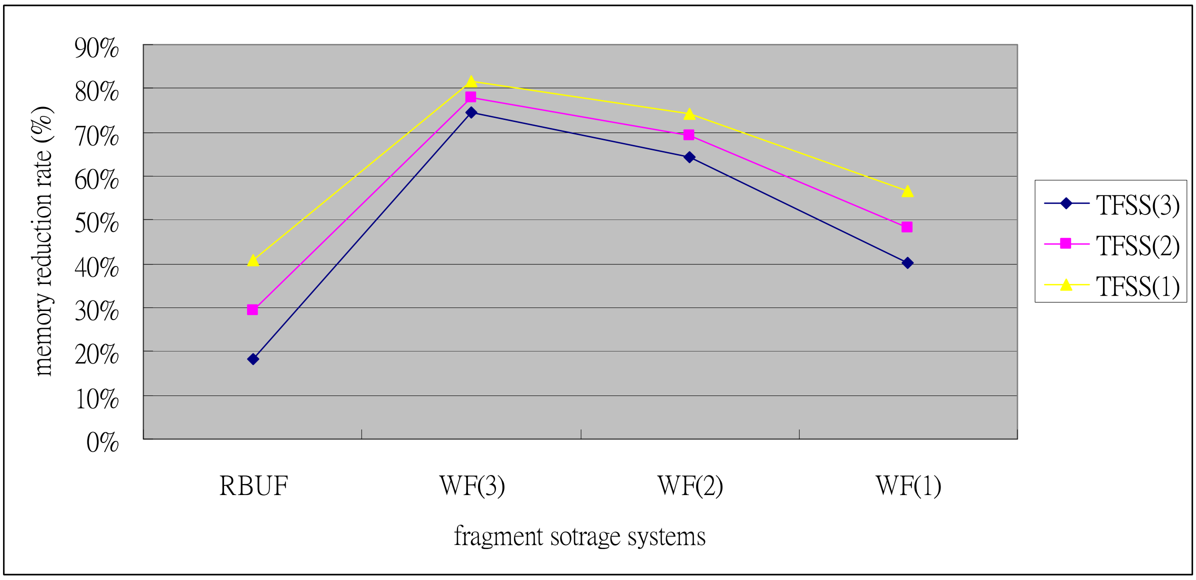


Figure 4-4 average memory reduction rate of TFSS

The average memory reduction rate of our TFSS is presented in Figure 4-4. As shown in Figure 4-4, our TFSS can achieve 18% to 41% memory reduction rate in comparison with R-buffer architecture, and 40% to 81% reduction rate in comparison with WF algorithms. It shows that our TFSS has great advantage over other related works.

Since the size of each fragment is reduced after leading 0s elimination, the memory size of each section within T-buffer in TFSS does not need as large as before. In our TFSS, without leading0s elimination, each section within T-buffer is L_{num}×8bytes large (Figure 4-3). We suppose that with leading0s elimination, each section is smaller than L_{num}×8bytes. Thus, we reduce the section size to evaluate the memory reduction ratio by leading 0s elimination. As we expect, the memory requirement of transparent fragment storage system will be further reduced by leading 0s elimination. We evaluate the memory requirement of our TFSS design with leading 0s elimination and compare the result with other related works, as shown in Figure 4-5. We notice that in each frame cases, including frame480, our design has the lowest memory requirement.

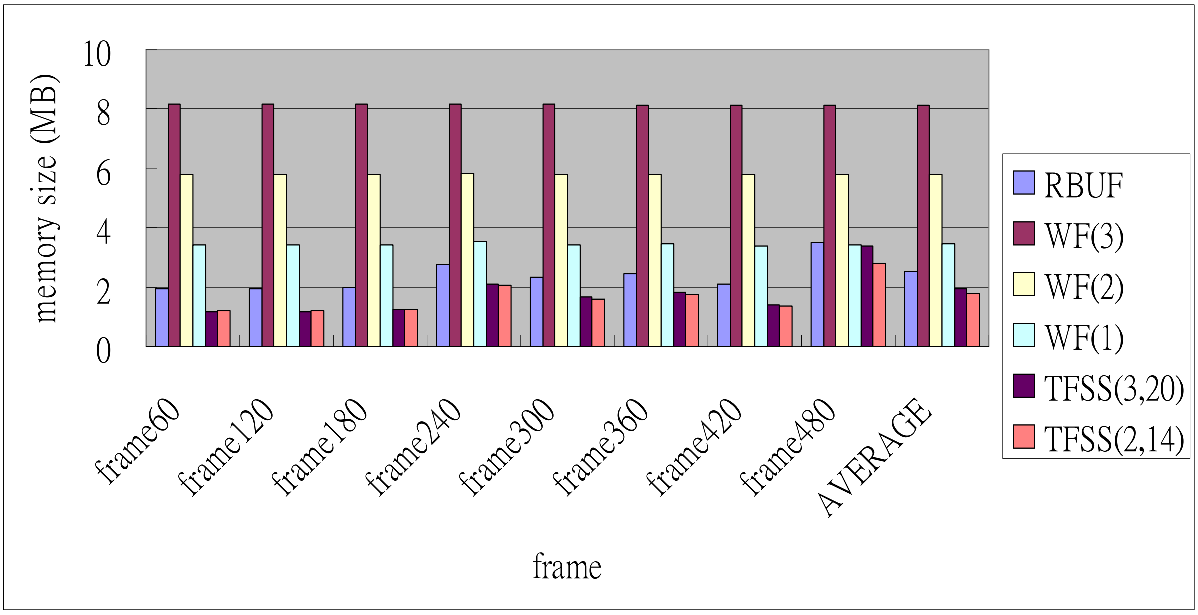


Figure 4-5 memory requirement comparison2

As we can see in Figure 4-6, in average, TFSS with leading 0s elimination can reduce 23% to 29% memory requirement in comparison with R-buffer, and reduce 44% to 79% memory requirement in comparison with WF algorithm.

[2] TFSS(L_{num},$M_{section}$) represents each section of T-buffer is $M_{section}$ bytes and has the capability for storing L_{num} transparent fragments.

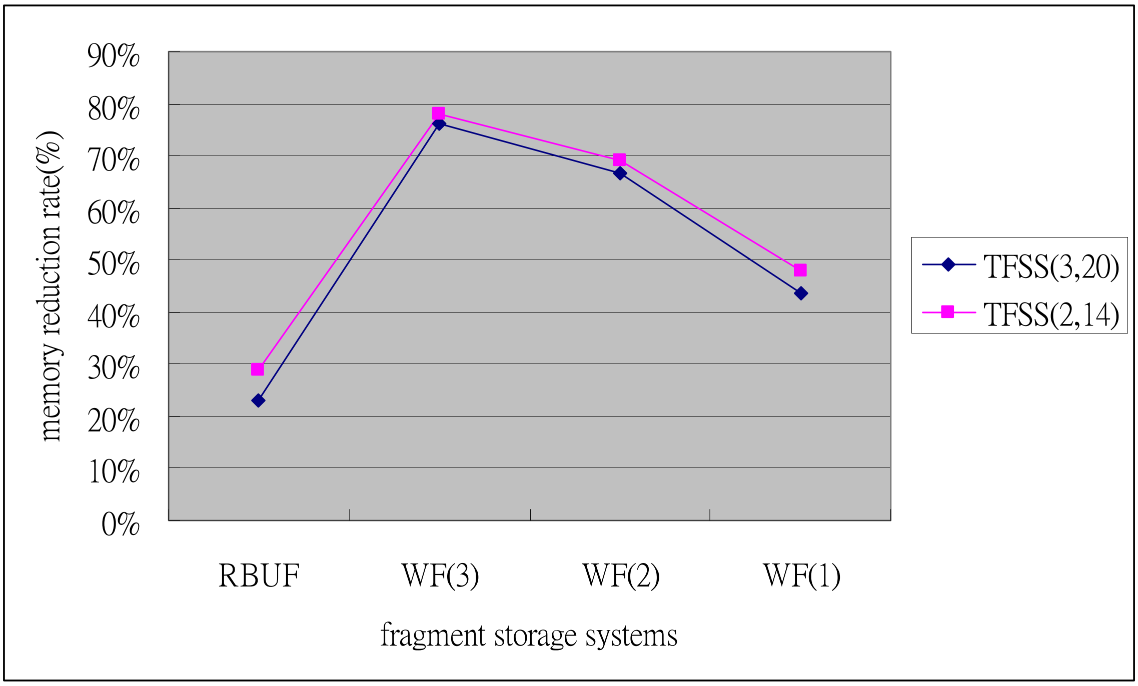


Figure 4-6 average memory reduction rate of TFSS with leading 0s elimination

4.3.2 time requirement

In First, we analyzed the memory access frequency of each technique. Suppose in one frame, N_i pixels have i transparent fragment, where i =0,1,2,3,…..n_{max}, n_{max} is the maximum number of transparent fragments that a pixel have in the frame. It infers that the number of pixels which have at least one transparent fragment is equal to $\sum_{i=1}^{n_{max}} N_i$, and the total number of transparent fragments is equal to $\sum_{i=1}^{n_{max}} (N_i \times i)$.

In R-buffer proposal, after rasterizing all fragments, $\sum_{i=1}^{n_{max}} N_i \times i$ transparent fragments are stored in R-buffer. In the first pass of reading R-buffer, $\sum_{i=1}^{n_{max}} N_i \times i$ transparent fragments are accessed and $\sum_{i=1}^{n_{max}} N_i$ transparent fragments are removed from R-buffer. In the second pass, $\sum_{i=1}^{n_{max}} N_i \times i - \sum_{i=1}^{n_{max}} N_i$ transparent fragments need to be accessed and $\sum_{i=2}^{n_{max}} N_i$ fragments are removed from R-buffer. In the p_{th} pass, $\sum_{i=1}^{n_{\max}} N_i \times i - \sum_{j=1}^{p-1}\sum_{i=j}^{n_{\max}} N_i$ need to be accessed and $\sum_{i=p}^{n_{\max}} N_i$ fragments are removed from R-buffer. Therefore, the total access frequency of R-buffer, denoted as $f_{R\text{-}buffer}$, is equal to

$$\sum_{i=1}^{n_{\max}} N_i \times i + (\sum_{i=1}^{n_{\max}} N_i \times i - \sum_{i=1}^{n_{\max}} N_i) + (\sum_{i=1}^{n_{\max}} N_i \times i - \sum_{i=1}^{n_{\max}} N_i - \sum_{i=2}^{n_{\max}} N_i) + ... + (\sum_{i=1}^{n_{\max}} N_i \times i - \sum_{j=1}^{n_{\max}}\sum_{i=j}^{n_{\max}} N_i)$$

After a fragment accessed from R-buffer, its depth value needs to be compared with the depth value stored in second z-buffer, and thus, the access frequency of second z-buffer, denoted as $f_{2nd\text{-}zbuffer}$, is equal to that of R-buffer. Moreover, each transparent fragment is eventually blended with the background fragment stored in frame buffer, and thus, the access frequency of frame buffer, denoted as $f_{frame\text{-}buffer}$, is equal to $\sum_{i=1}^{n_{\max}} (N_i \times i)$. The total memory access frequency of storage system in R-buffer architecture is equal to $f_{R\text{-}buffer} + f_{2nd\text{-}zbuffer} + f_{frame\text{-}buffer}$. It implies that the more transparent fragments in a frame or the more transparent fragments per pixel, the more memory access frequency of R-buffer architecture. We defined the execution time for order-independent transparency rendering is equal to the sum of memory access time and computation time. Assume that each memory access takes one cycle and as observed by [Amor06], the computation time during rendering for a pixel which has i transparent fragments is $\frac{i(i+1)}{2}$ cycles, we can easily figure out the execution time of R-buffer architecture.

In WF proposal, we assume that the pointer memory can be accessed simultaneously with M-buffer, and does not wait for being accessed after M-buffer access. Therefore, the access frequency of the pointer memory will not affect the time requirement of memory access and can be ignored. Since transparent fragments with the same x-y coordinate are stored sequentially and connectedly, we can access these transparent fragments at one pass from M-buffer and blend these fragments based on weight factor computation stage in Figure 2-6. Thus, the access frequency of M-buffer is equal to $\sum_{i=1}^{n_{\max}} N_i \times i$, and the memory access time is $\sum_{i=1}^{n_{\max}} N_i \times i$ cycles. As proposed by [Amor06], the computation time during rendering is $\frac{i(i-1)}{2}+1$ cycles, for a pixel with i transparent fragments.

In our approach, we adopt the weight factor computation algorithm proposed in [Amor06]. Thus, the access frequency of T-buffer is the same as the access frequency of M-buffer in WF proposal, and the computation time is also the same as that in WF proposal. However, in our approach, SSA Table needs to be accessed before accessing T-buffer in order to find the start section in T-buffer. Thus, SSA Table cannot be accessed simultaneously with T-buffer and the access frequency of SSA Table should be considered.

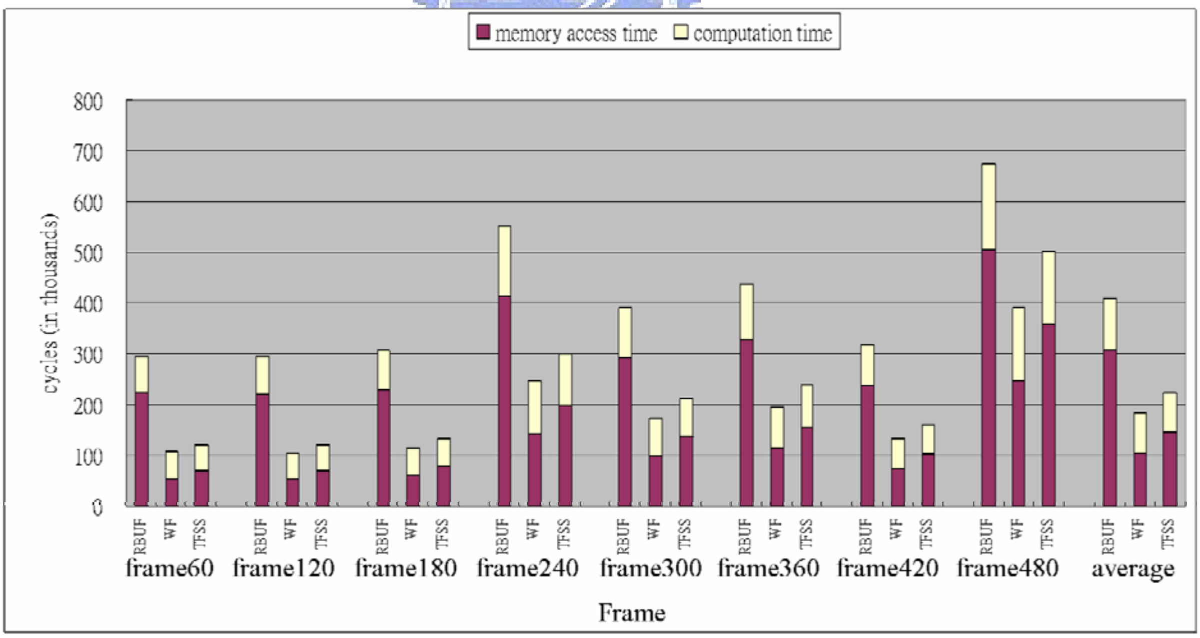


Figure 4-7 execution time comparison

Figure 4-7 shows the execution time during order-independent transparency rendering of each technique. As we expect, the execution time of R-buffer proposal is the higher than WF proposal and our approach, and WF proposal has the lowest access frequency. The execution time of our approach is just a little higher than WF proposal but is much lower than R-buffer architecture.

Overall, the results of our TFSS have been very positive, since TFSS significantly outperforms R-buffer in terms of time requirements and significantly outperforms WF algorithm in terms of memory requirements.

Chapter 5 Conclusion and Future Work

5.1 Conclusion

In this thesis, we propose a transparent fragment storage system for order-independent transparency, which fragments are stored in based on their x-y coordinate and supports pointer indexing to connect fragments belonging to the same pixel. The proposed transparent fragment storage system costs less memory requirement than other related works (R-buffer and WF proposals). Also, the execution time of the proposed storage system in this thesis is much lower than R-buffer.

For QUAKE4 benchmark, our transparent fragment storage system, in comparison with R-buffer architecture, reduces 29% memory requirement in average, and reduces 45% execution time. In comparison with WF proposal, although the execution time of our storage system is higher than WF proposal, our transparent storage system reduces 67% memory requirement in average. Moreover, with leading 0s elimination technique, our system can further achieve 72% reduction rate in comparison with WF algorithm. From the evaluation result, we find that as the number of transparent fragments per pixel increases, our storage system has more advantages on memory requirements and execution time for rendering.

5.2 Future work

In our observation, the utilization of leading 0s elimination can reduce 5% memory requirement of storage system. However, this leading elimination only eliminates fixed-length leading zero bits from RGB color components of a fragment. If we can eliminate variable-length leading zero bits—each color component of a fragment can have variable length after leading 0s elimination—perhaps more memory space can be reduced.

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Appendix A. Simulation Test Frame Images

Figure A-1 frame60

Figure A-2 frame120

Figure A-3　　frame180

Figure A-4　　frame240

Figure A-5 frame300

Figure A-6 frame360

Figure A-7　　frame420

Figure A-8　　frame480