Index Rendering: Hardware-Efficient Architecture for 3-D Graphics in Multimedia System

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***Abstract*—Real-time three-dimensional (3-D) graphics emerges rapidly in multimedia applications, but it suffers from requirements for huge computation, high bandwidth, and large buffer. In order to achieve hardware efficiency for 3-D graphics rendering, we propose a novel approach named index rendering. The basic concept of index rendering is to realize 3-D rendering pipeline by using asynchronous multi-dataflows. Because triangle information can be divided into several parts with each part capable of being transferred independently and asynchronously. At last, all data are converged by the index to generate the final image.**

Index rendering approach can eliminate unnecessary operations in traditional 3-D graphics pipeline. The unnecessary operations are caused by the invisible pixels and triangles in the 3-D scene. Previous work, deferred shading, eliminates the operations relating to invisible pixels, but it requires huge tradeoffs in bandwidth and buffer size. With index rendering, we can eliminate operations on both invisible pixels and triangles with less tradeoffs as compared with deferred shading approach.

The simulation and analysis results show that the index rendering approach can reduce 10%–70% of lighting operations when using flat and Gouraud shading process and decrease 30%–95% when using Phong shading. Furthermore, it saves 70% of buffer size and 50%–70% of bandwidth compared with deferred shading approach. The result also indicates that this approach of index rendering is especially suitable for low-cost portable rendering device. Hence, index rendering is a hardware-efficient architecture for 3-D graphics, and it makes rendering hardware easier to be integrated into multimedia system, especially in system-on-a-chip (SOC) design.

***Index Terms*—Rendering, rendering architecture, 3-D graphics.**

I. INTRODUCTION

THREE-DIMENSIONAL (3-D) graphics has emerged rapidly from technical areas to nontechnical areas, and it has also become a key module in multimedia systems. In fact, real-time 3-D graphics is expanding in high gear as a core technology in the areas of user interface, virtual reality, visualization, and entertainment. However, real-time 3-D graphics rendering is computation-intensive, which requires high bandwidth and large buffer memory. Recently, many systems [1]–[6] have proposed for various applications of real-time 3-D graphics, and most of them are performance-oriented architectures that require high hardware cost.

In order to realize real-time 3-D graphics in commodity hardware, one way to proceed is to make an attenuated version of traditional architecture, but it degrades the performance and image quality. An alternative method is to design a new rendering architecture, such as Talisman [7], [8]. This architecture employs techniques from two-dimensional (2-D) image processing and changes into 3-D image synthesis, but it is not compatible with traditional rendering architecture. Therefore, all air position indicators (APIs) and programs should be rewritten to fit into this architecture. A better approach is to design a new hardware-efficient architecture compatible with a traditional architecture. Deferred shading is one of the kinds of architecture. It rearranges the operations in traditional rendering pipeline to eliminate redundant operations on invisible pixels. However, it suffers from large internal bandwidth and buffers, which is hard to be implemented in commodity system.

Furthermore, hardware efficiency is another important issue. Generally speaking, 3-D applications on PCs are performance-oriented, and the advancement of rendering hardware is driven by brute-forced VLSI technology. However, it limits the 3-D applications on low-cost portable devices. In low-cost portable devices, most functions are application-oriented. Hence, the high performance is not the only issue, and the importance of hardware efficiency emerges. This is because low hardware efficiency not only wastes hardware resource but it also leads to power problems.

Hence, in this paper we propose a new approach, index rendering, for hardware-effective 3-D graphics rendering. It can further eliminate unnecessary operations on both invisible pixels and hidden triangles and avoid huge tradeoffs of deferred shading. The organization of this paper is described as following: In Section II, we first review 3-D graphics rendering pipeline. By observing the traditional rendering pipeline, we can find that data rate dominates the behavior of rendering pipeline. We also introduce the approach of deferred lighting here. Then, we introduce our new approach and its referential architecture in Section III. In Section IV, we present the analysis and simulation results from different architectures. Finally, we conclude this paper in Section V.

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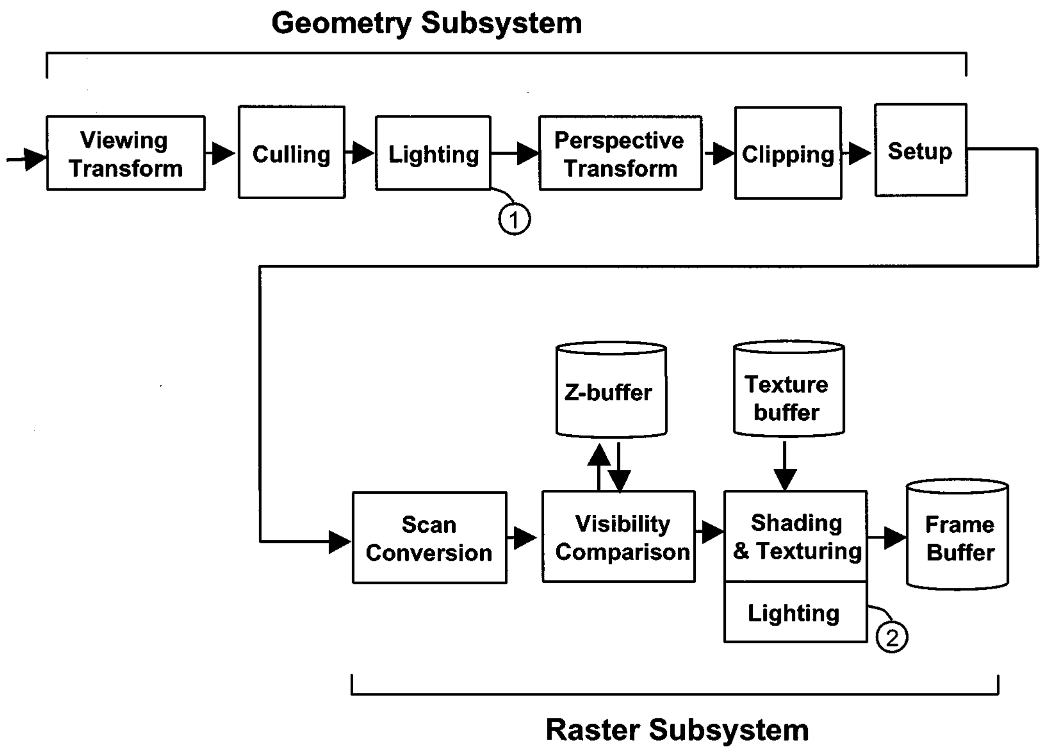


Fig. 1. Traditional 3-D graphics rendering pipeline.

II. Background

A. 3-D Graphics Rendering Pipeline

Polygon-based rendering is one of the mainstream methods to generate 3-D graphics. Its rendering job can generally be divided into two parts: 1) geometric subsystem and 2) raster subsystem. The geometry subsystem transforms the polygons in 3-D coordinates vertices, and then maps them into 2-D coordinates. Raster subsystem receives output of geometry subsystem, and renders the transformed polygons to generate final images for display. These two subsystems are pipelined for high throughput in general. Fig. 1 is an example of traditional 3-D Graphics rendering pipeline.

1) Transformations: As shown in Fig. 1, transformations are major operations in geometric subsystem. It can be handled by 4×4 matrix operations. In 3-D graphics rendering, the essential transformations are viewing and perspective. The viewing transformation transforms objects from the world space to the view space; while the perspective transformations transforms the view space to the projection space and then maps it into 2-D screen coordinates.

2) Culling and Clipping: Culling operation culls away some invisible polygons to eliminate unnecessary operations, and back-faced culling is the most popular one. Back-faced culling utilizes the order of vertices to denote the polygon as front-faced or back-faced, and then filters out the back-faced polygons. Furthermore, it can cull away those polygons that are too small to display. On the other hand, clipping operation can discard the out-of-sight polygons. Because only polygons existed in view volume can be displayed on screen, the polygon located outside the boundaries are discarded.

Although back-faced culling and clipping can eliminate some invisible polygons; however, there are other invisible polygons that can be hidden somewhere because they may be fully covered by each other. Hence, a lot of invisible polygons still reside in pipeline, and the visibility of these polygons can only be decided after visibility comparison.

3) Lighting: Lighting is an essential operation to calculate illumination on assigned position by illumination model. In order to simulate lighting effect in the real world, illumination model is usually complex. Phong illumination model [19] is the popular one, which is expressed as

$$I = I_a \times K_a + [I_i \times K_d(\boldsymbol{L} \cdot \boldsymbol{N}) + I_i \times K_s(\boldsymbol{H} \cdot \boldsymbol{N})^n] \quad (1)$$

where

I_a	intensity of the ambient light;
I_i	intensity of the light source;
$\boldsymbol{L}$	unit vector from pixel to the light source;
$\boldsymbol{N}$	normal vector of the pixel;
$\boldsymbol{H}$	$= (\boldsymbol{L} + \boldsymbol{V})/2$, where $\boldsymbol{V}$ is the vector from the pixel to the viewer;
n	gloss to model the highlight;
K_a, K_d, K_s	coefficients to model the characteristic of the material.

In this equation, the third term as a specular term is related to exponentiation. Furthermore, each vector needs to be normalized before applying to this equation, and normalization requires calculation of reciprocal square root. Several attempts have been made to reduce lighting operations with Taylor series approximation [12], [13] and angular interpolation [14], [15] being the two major ways. Although a lot of attempts had been made to

TABLE I
POLYGON-LEVEL AND PIXEL-LEVEL SHADING PROCESS IN THREE SHADING METHODS

	Flat Shading	Gouraud Shading	Phong Shading
Polygon-level	*Lighting Operation* on center of each polygon	*Lighting Operation* on each vertices	-
Pixel-level	Fill all pixels in a polygon with the same color	Color interpolation for all pixels in a polygon	Normal Interpolation and *Lighting operation* for all pixels in a polygon

solve this problem, lighting operation still remains the bottleneck in 3-D graphics rendering. The lighting operation may be performed in the locations labeled by ① and ②, as shown in Fig. 1, while the real location depends on the shading scheme. We shall discuss this later.

4) Setup: Setup is the operation to prepare the necessary information for further rasterization in raster subsystem. In the setup operation, two kinds of data are generated. The first type is the data related to shape information, while the second one is related to color information.

Because triangles are described by vertices in geometry subsystem, the setup stage helps rasterize stage to scan-convert triangles into a group of pixels. Traditionally, the setup stage decomposes triangles into two scanline-aligned parts with each part being described by left-side edge, right-side edge, and maximal and minimal y-coordinates boundaries. Regarding the setup for color information, the job of setup stage depends on the shading method.

5) Raster Subsystem: In conventional rendering pipeline, raster subsystem handles rasterization. Rasterization consists of three subtasks: 1) scan conversion; 2) visibility comparison; and 3) shading. At the beginning of initiating raster subsystem, the scan conversion decouples polygon into several spans, and then generates a group of pixels. The groups of pixels denote the area that these triangles cover on display.

Hence, the operations before scan conversion are polygon-level operations, and they become the pixel-level operations after scan conversion. Shading operation colors each pixel for display, and texture mapping is also applied here. Visibility comparison determines the visibility of each pixel, and Z-test is the most common algorithm.

6) Shading: Shading is the operation to color each pixel on display. Since lighting calculation is compute-intensive, it is appropriate to avoid applying lighting on all pixels. Hence, several shading methods have been developed, and three shading methods are generally utilized: flat shading, Gouraud shading and Phong shading. The simplest method is flat shading. It only applies lighting once for each polygon, and then shades all pixels inside this polygon with the same color. The number of lighting operations is smallest, but the image quality is very poor. Another method, Gouraud shading [20], can generate better image quality. It applies lighting on vertices of each polygon, and then shades each pixel inside polygon by interpolating color on vertices. Because it can render polygons with smooth color gradation, its result is more acceptable and widely utilized today. However, it cannot produce highlight inside the polygons and suffers from Mach Band effect. Among the three methods, Phong shading [19] can generate the best image quality, but it needs a lot of calculations. In Phong shading, the lighting operation is applied to each pixel inside polygons. Several researchers have proposed to support Phong shading by hardware [16]–[18]. However, Phong shading is computation-intensive, and its hardware implementation costs a lot of chip size.

7) Relationship Between Lighting and Shading: In Table I, we list the relationship between lighting and shading operation. As shown in Fig. 1, in both flat shading and Gouraud shading, lighting operation is executed in the box labeled ①, while in Phong shading the lighting operation is performed in box labeled ②.

Among three shading schemes, the major difference is where the lighting operation is located in polygon-level or in pixel-level. In flat shading and Gouraud shading, lighting operations are in polygon-level, and therefore the number of lighting operations is in proportion to polygon number. On the other hand, the number of lighting operations is related to the pixel number. Because each polygon can be decomposed into dozens or hundreds of pixels, the number of lighting operations in Phong shading are dozens or hundreds times more than those in flat and Gouraud shading.

Hence, computation requirement is a tradeoff of image quality, and one of major reasons is attributed to the high computation requirement of lighting operations. Phong shading generates higher image quality but demands huge computation power. Real-time 3-D graphics makes this condition even worse, because rendering system needs to render 3-D scenes over 24 to 30 times/s. The lighting operation leads to two problems. The first problem is in the high-end system. Since Phong shading and high resolution are needed for high image quality, the total number of lighting operation is very huge and becomes a bottleneck, even though high-end system equips high computation power. On the other hand, the complexity of lighting calculation also leads to a problem in low-end system, even in the flat shading scheme. Because CPU handles lighting calculation in low-end system, the complexity of illumination equation causes large burden for CPU. It is infeasible to implement real-time 3-D graphics for consumer electronics, especially for some low-cost low-power portable devices.

8) Texturing: Texturing operation provides a simple method for adding realistic detail to 3-D graphics. It maps the digital images stored in texture buffer onto the surface of specific polygons. In different modes for texturing, texture operation unit may fetch texture buffer 1, 2, 4, 8, or more times for each pixel. Therefore, huge bandwidth requirement is the major problem of texturing operation.

B. Observations on Traditional Rendering Pipeline

1) Invisible Polygons and Pixels: 3-D graphics rendering is a process to render 3-D models into 2-D images. Because of reduction in dimension, a lot of information loses during this process. Hence, in 3-D graphics rendering, dimension reduction causes a lot of polygons and pixels to be invisible.

The polygon is a shape defined by vertices, and its size is very flexible. The reasons to make a polygon invisible may be attributed to the following: back-faced, outside the view volume, covered by other polygon or too small to display. Among these four reasons, back-faced and too small of polygons can be eliminated in culling operation, whereas the polygons outside the view volume are removed in clipping operation. However, the polygon fully covered by other polygon can only be decided after visibility comparison. Therefore, in traditional rendering pipeline, the operations in connection with fully covered polygon are unavoidable.

On the other hand, if a pixel is invisible, it is covered by another pixel with the same coordinates. Because of dimension reduction, a lot of distinguished pixels in 3-D are projected into the same coordinates on 2-D screen; therefore, the ratio of invisible pixels is very high. However, in traditional rendering pipeline, the data flow for pixel operations are regular and straightforward. Although invisible pixels can be discarded after visibility comparison, they still cause "bubbles" in pipeline, thus lowering the memory and hardware utilization.

2) Heterogeneous Data Flows in Pipeline: In traditional rendering pipeline, another problem is generated due to heterogeneous data flows. Polygon and pixel are major data types in rendering pipeline. However, there are dozens to hundreds times difference in terms of the numbers of data. Moreover, the sizes of polygon are various. The massive and irregular expansion on data amount causes problems in data flows.

Besides data amount, the operations on these two data flows have different attributions. In geometry subsystem, the data flow related to polygon requires a lot of computation power. The data flow in geometry subsystem is relatively regular, and generally needs no external memory access. On the other hand, the computation in raster subsystem is relatively simple. However, huge bandwidth is required, especially on depth buffer and texture buffer access.

Hence, in traditional rendering pipeline, some areas are computation-bound, and some areas are memory-access-bound. However, traditional method handles them in a long synchronous pipeline. Even you design to speed up the capability somewhere, but this speed-up may be cancelled in pipeline stall elsewhere.

3) Different Types in Polygon Information: There are two major parts in polygon information, as listed in Table II. The first part is related to geometry, which keeps the geometrical characteristics of a polygon in 3-D space. Hence the shape and depth of this polygon can be described. The second part of polygon information is related to color, and it describes how a polygon should be shaded, colored or textured. The lighting calculation needs to use the second part of polygon information.

TABLE II
DIFFERENT PARTS IN POLYGON INFORMATION

Classification	**Description**
Geometry Information	Vertices Coordinates (X,Y,Z)
Color Information	Intrinsic Color
	Surface Attribute
	Surface Normal Vector
	Lighting Directing Vector
	View Direction Vector
	Texture Coordinates

Although two parts of polygon information have little relationship, they are transferred together in traditional 3-D graphics rendering pipeline. This method cannot explore parallelism in data operations, and causes limitations when arranging operations in pipeline.

C. Data Rate Changing in Pipeline

1) Types of Data Rate: Data rate dominates the behavior of data flows in 3-D rendering pipeline. In order to discuses the characteristics between different designs, we can roughly classify data rate in rendering pipeline into five major types: 1) triangle rate; 2) reduced triangle rate; 3) pixel rate; 4) reduced pixel rate; and 5) scan-out rate.

"Triangle rate" is the data rate before scan conversion in rasterization. We call this data rate "triangle rate" instead of "polygon rate" because triangle is the major type of polygon in rendering pipeline. This rate is also a common benchmark to indicate how many triangles the hardware can handle within a period of time. "Reduced triangle rate" is a modified triangle rate after deleting invisible triangles. This rate seldom appears in previous architectures because it is hard to eliminate invisible triangles in the traditional rendering pipeline.

"Pixel rate" is the data rate rendered after scan conversion and before visible comparison. In scan conversion, each polygon is converted into dozens to hundreds of pixels. Hence, the data rate increases dozens to hundreds times more as compared with triangle rate. On the other hand, "reduced pixel rate" is the data rate after visible comparison. In the area of reduced pixel rate, pixels that fail in visibility comparison are discarded, and therefore the data rate is reduced.

"Scan-out rate" is related to the scan-out mechanism. In order to illustrate image data, the pixel values in frame buffer must be scan-out for display. Generally speaking, scan-out proceeds after the entire rendering task is finished, and hence the visible pixels on display are fixed. This rate is relatively steady.

This classification can be utilized for the analysis on bandwidth and calculation. Besides scan-out rate, other four data rate is related to complexity of 3-D scene. On the other hand,

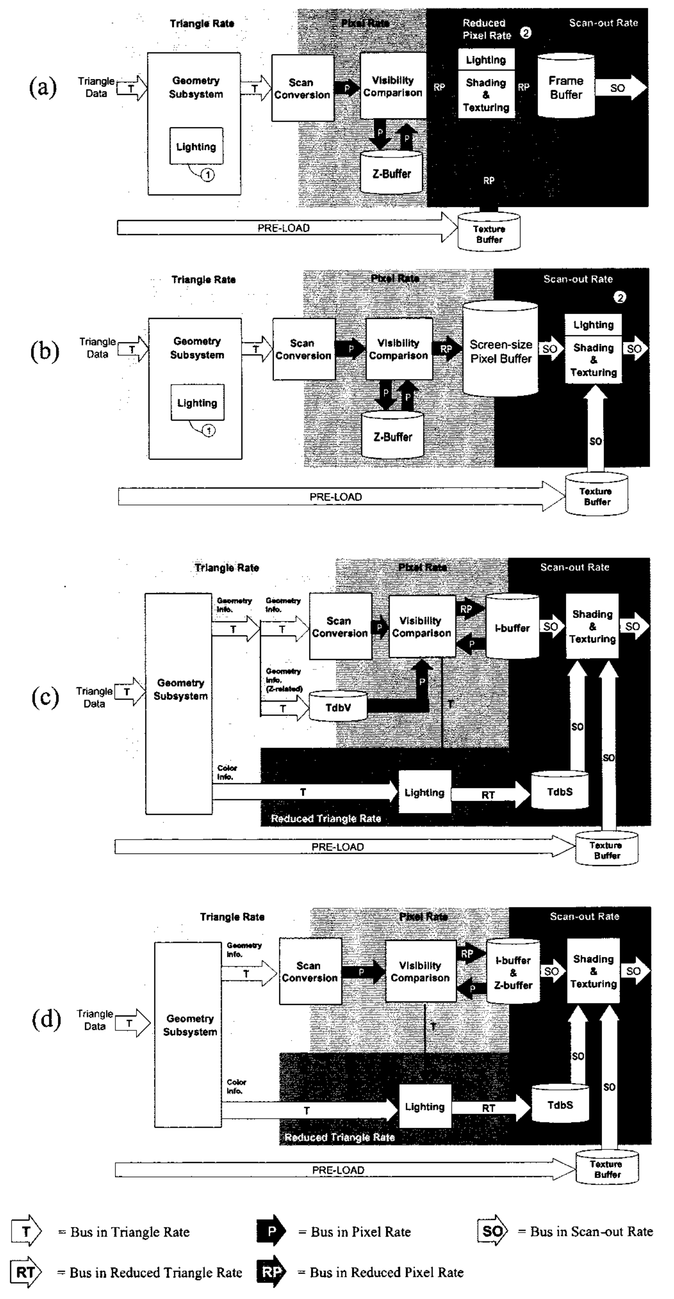


Fig. 2. Illustration of data flow in different rendering pipelines: (a) traditional; (b) deferred shading; (c) index rendering, depth value stored in TdbV and I-buffer; (d) index rendering, depth value stored in Z-buffer.

scan-out rate is much different. It is related to screen coordinates and is not affected by scene complexity.

2) Data Rates in Traditional Rendering Pipeline: Fig. 2(a) shows the data flow and data rate in traditional rendering pipeline. Different gray levels are used to shade different areas of data rates. The shaded area can show how the data rate affects the operations. If an operation falls in one data rate area, it means that the total operation number is related to the data rate. Because the position for lighting operation depends on shading scheme, two lighting blocks are shown in this illustration and labeled with different marks. In flat shading and Gouraud shading, lighting operation is in the box labeled ①, while in Phong shading the lighting operation is performed in box labeled ②.

The entire geometry subsystem runs in triangle rate. The scan conversion is the bridge between triangle rate and pixel rate. The visibility comparison works in pixel rate. Generally speaking, the shading and texture operations can be placed before or after visibility comparison in rendering pipeline, which may be running in either pixel rate or reduced pixel rate. This option depends on the hardware architecture designer. Because the number of operation is smaller when running in reduced pixel rate, we place the shading and texture operations in reduced pixel rate in Fig. 2(a).

Generally speaking, the relationships of different data rates are

$$\begin{aligned}\text{Pixel Rate} &> \text{Reduced Pixel Rate} \gg \text{Triangle Rate}\\ &> \text{Reduced Triangle Rate}.\end{aligned}$$

On the other hand, scan-out rate is directly proportional to the resolution of display and refresh rate. The lower the display resolution, the smaller is the scan-out rate. In general case, the scan-out rate is much smaller than both pixel rate and reduced pixel rate, because most pixels on display cover a lot of invisible pixels. On the other hand, there is no significant relationship between scan-out rate and triangle rate. The relationships among scan-out rate, pixel rate, and reduced pixel rate are

$$\text{Pixel Rate} > \text{Reduced Pixel Rate} \gg \text{Scan-out Rate}.$$

Fig. 2(a) we can also see the effect of data rate on bandwidth. The arrow labeled T means one data bus related to triangle rate. In the same way, P denotes the pixel rate, RP denotes the reduced pixel rate, and SO means scan-out rate. Because P and RP are the areas of high data rate in general case, we fill up the arrows with black and gray colors. Furthermore, the arrow that points to texture buffer is labeled "$\mathsf{PRE-LOAD}$," because data of texture buffer is loaded before rendering.

D. Deferred Shading

In traditional rendering pipeline, shading and texture operations fall in pixel or reduced pixel rates. This can be extravagant since a lot of shaded and textured pixels are covered in final image. Moreover, a lot of texture bandwidth is wasted on hidden pixels. In order to avoid this redundancy, a method of deferred shading was proposed. This architecture was first proposed in Deering's Triangle Processor and Normal Vector Shader [9], and implemented in PROOF [10], Pixel-Planes 5 [1], and PixelFlow [2], [11]. This approach defers the shading and texture operations until the entire image has been rendered. Because the visibilities of all pixels are determined, only visible pixels on the final image can be shaded and textured. Therefore, this approach can eliminate unnecessary operations on hidden pixel, and makes the pixel-level operations computation-effective. The data flow in deferred shading approach is illustrated in Fig. 2(b). The shading and texturing operations are moved into the area of scan-out rate, and hence the number of total operations reduced.

However, in order to support the deferred shading, the function of frame buffer changes, which leads to buffer size and bandwidth problems. In traditional pipeline, the frame buffer keeps the results, the RGB color values of each pixel, after the shade and texture operations. Typically, 16–32 bits are required to store a pixel in frame buffer. On the other hand, in deferred shading approach, because all pixels are not shaded and textured before final scan-out, a screen-size pixel buffer is needed to store all information for further shading and texturing operations. Since shading and texture parameters often over 100–200 for one pixel, the approach of deferred shading requires large screen-size pixel buffer and high bandwidth.

Why does the approach of deferred shading cause huge buffer and bandwidth requirement? The problems are caused by the parameters associated with shading and texturing. These parameters are related to original triangle such as X_0, Y_0, R_0, R_{dX}, R_{dY}, G_0, G_{dX}, G_{dY}, B_0, B_{dX}, B_{dY}, S_0, $S_{dX}, S_{dY}, T_0, T_{dX}$, and T_{dY}. In traditional rendering pipeline, all pixels belong to a triangle are shaded and textured one by one. Within a period of time, the shading and texture units handle a group of pixels from the same triangle. There is a temporal locality on pixel information. Hence, the parameters can be kept in shading and texture hardware for reuse. However, in deferred shading approach, shading and texture operations are in the area of scan-out. This temporal locality is broken. Each pixel needs to carry a copy of parameters of original triangle up to shading and texture operations. Therefore, although deferred shading approach can reduce shading and texture operations, it pays tradeoffs for occupying large-sized screen pixel buffer, and huge bandwidth.

Furthermore, the advantage on shading operation is limited. The advantage of deferred shading benefits mostly only to Phong shading, but little to flat and Gouraud shading. This condition is caused by the location of lighting. Because of complex illumination equation, lighting is the most computation-intensive task in shading operation. Lighting in Phong shading appears at pixel-level, whereas it appears at polygon-level in flat and Gouraud shading, as shown in Table I. Because deferred shading approach reduces pixel-level shading operations, lighting can be eliminated only in Phong shading, but it cannot be eliminated in flat and Gouraud shading. Therefore, the advantage of deferred shading cannot reduce lighting calculations for flat and Gouraud shading.

III. Index Rendering

To retain the advantages of deferred shading without its drawbacks being attached, we propose a novel approach named index rendering. This approach requires less buffer size and bandwidth than that in deferred shading. Moreover, we utilize our deferred lighting technique for the architecture design, and hence we can eliminate unnecessary lighting operations for all kinds of shading methods. Hence, index rendering is a hardware-efficient architecture, and it can be utilized in real-time 3-D graphics rendering in both high-performance and low-end systems.

A. Concepts of Index Rendering

The first concept of index rendering is fetching and generating pixel information on demand. Instead of transferring pixel information in graphics pipeline, we fetch and generate them when needed. Therefore, each pixel does not need to carry huge information through both the area of pixel rate and the screen-size pixel buffer. This avoids high bandwidth and large screen-size pixel buffer in the graphics pipeline. To fetch pixel information from buffer, we use *index* as a key. Index is a serial number of triangles in current 3-D scene, and each pixel from the same triangle carries the same index number. Therefore, only the index is saved in the screen-size buffer, and only 10–20 bits are required for each pixel. In index rendering approach the screen-size buffer is named I-buffer (index buffer). The triangle information for shading and texture operations are stored in another buffer to be named TdbS (triangle data base for shading). When shading and texture mapping are performed, each pixel can fetch parameters from its parent triangle via the index obtained from TdbS. Hence, with TdbS, the approach of index rendering only needs to store just one copy of triangle parameter for each triangle. Unlike deferred shading approach, the parameter of one triangle may be duplicated into a lot of copies for all visible pixels. Hence the buffer size becomes greatly reduced in index rendering than in deferred shading.

Index rendering not only defers shading, but also defers lighting. We propose deferred lighting in [22], and it is the second concept of index rendering approach. Table I shows that the lighting is polygon-level operation in flat and Gouraud shading. As discussed in deferred shading, we know deferred shading approach cannot reduce polygon-level operations, and therefore the lighting operations cannot be eliminated in flat and Gouraud shading. However, in index rendering approach, it is possible to defer polygon-level operations. The shading and texture parameters are stored in TdbS, which can only be fetched when scanned out. Because the parameters in TdbS are ineffective before all pixels in a 3-D scene are processed, the operations to generate parameters for TdbS can be asynchronous. Hence, for each triangle, the lighting operation can be deferred until the visibility of this polygon is decided. Therefore lighting operation on invisible polygon can be saved.

In order to support these concepts, index rendering divides triangle information into several parts and handles them asynchronous. In general, there are two major parts in pixel information: The first one is related to geometry, which keeps the geometrical characteristics of a polygon in the 3-D space. This part can be further divided into XY-related and Z-related. XY-related geometric information describes the shape of a polygon on display, whereas z-related geometric information denotes depth. The second part of pixel information is related to color, which describes how a polygon should be shaded, colored or textured. Index rendering can handle each part of pixel information separately and asynchronously, and index is the key to reunite all information to generate final result in shading operation.

B. Architecture of Index Rendering

In this section, a new architecture for index rendering is proposed as shown in Fig. 3. (An earlier architecture of index rendering without deferred lighting was proposed in a previous paper [23].) This new architecture we propose is to realize raster subsystem in multimedia system. It receives and renders triangles to generate 3-D scenes, and then it outputs result to the integrated multimedia system. Its external interface is very similar to traditional rendering pipeline, and hence this approach

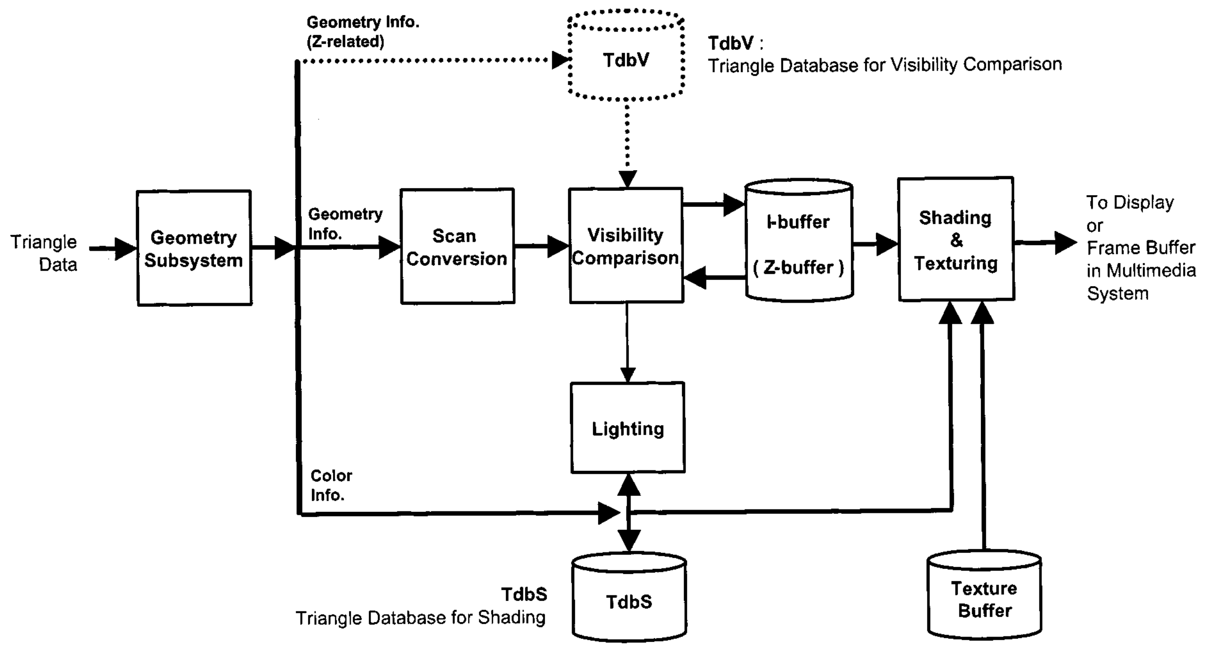


Fig. 3. Architecture of index rendering.

is compatible to the conventional 3-D graphics module in integrated multimedia system.

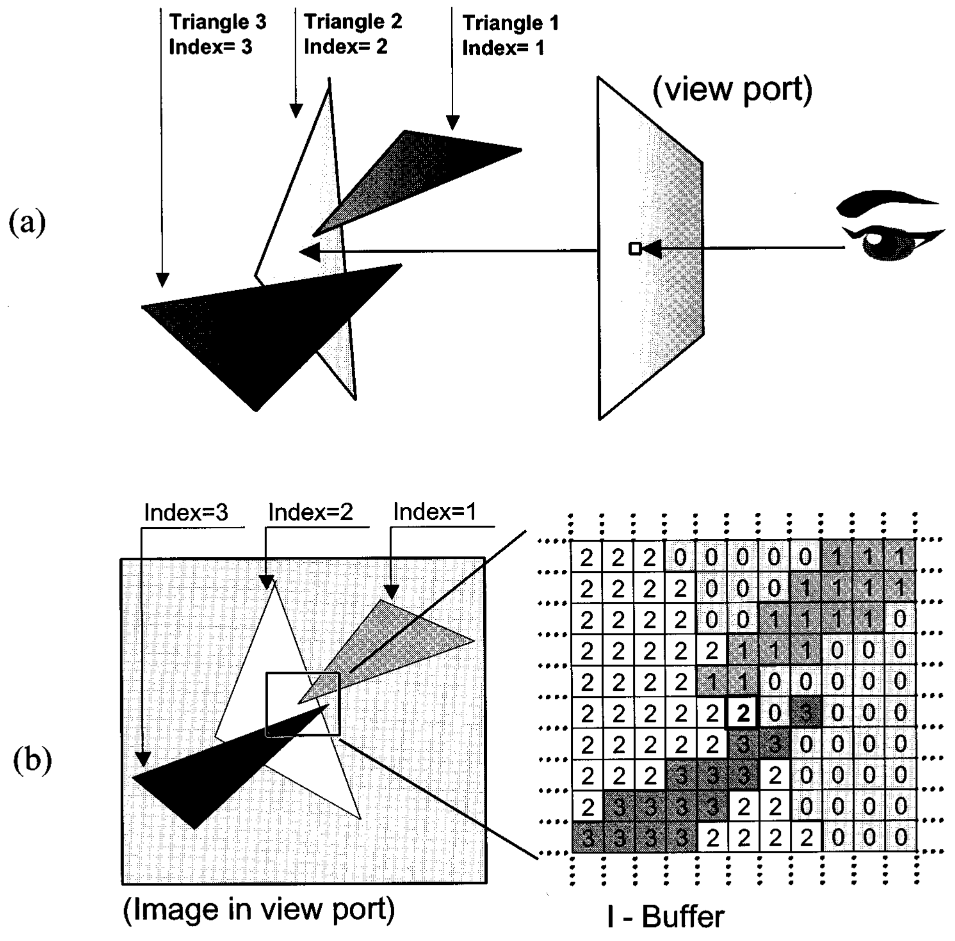
Fig. 3 shows the major blocks of index rendering. The block labeled by dotted line is optional when using different methods of visibility comparison. In order to render 3-D graphics image, each triangle is assigned to a unique index number. After passing the operations in geometry subsystem, the triangle information is separated into several parts and sent to different modules. The part related to color is sent to TdbS (triangle database for shading), and the part related to geometry is sent to scan conversion block. In scan conversion block, the polygon is decomposed into a group of pixels with index number and depth values. Then, visibility comparison tests the depth of pixels, and records the index number of visible pixels in I-buffer. After whole polygon is scan-converted, visibility signal of the polygon is sent to lighting block. If the polygon is visible, lighting block carries on polygon-level shading operations for this polygon. Operations of lighting block can be asynchronous with that of scan conversion block to optimize data flow. The shading and texturing block will not fetch data in I-buffer and TdbS to generate the final image until all polygons in a 3-D scene are scan-converted into I-buffer and all triangle information in TdbS are ready.

1) I-Buffer: The I-buffer (index buffer) plays an important role in index rendering. It is a screen-size buffer to store index number. For each pixel on screen, I-buffer records the index of triangle nearest to view port. That is, for each position on screen coordinates, the I-buffer records which triangle to intersect with its tracing ray. Hence this buffer stores the index pattern of first-order ray tracing, as shown in Fig. 4.

2) Triangle Databases: Triangle databases are buffers to store triangle information of which it is addressed by index number. Because index number dominates address space, the size of triangle database is related to maximal index number. Therefore, maximal index number is an important term in design specification, and it limits the maximal visible triangle number in a 3-D scene. Because the triangle information is separated for asynchronous operations, there are different types of triangle database to store each part of triangle information: one is related to geometry, whereas the other is related to color. The color information is stored in TdbS . The geometric information can be further divided into XY-related and Z-related. XY-related geometric information is utilized in scan-conversion block to generate the shape of polygons, not necessarily to be stored. Z-related geometric information is sent to scan-conversion block to generate pixel depth, but it also needs to be stored in TdbV (triangle database for visibility comparison) if visibility comparison without Z-buffer is required. We shall discuss this in next subsection.

For example, if we synthesize 3-D scene by Gouraud shading with texture mapping, the typical information in each database is listed in Table III.

3) Visibility Comparison: Visibility comparison is a process to remove hidden pixels by using their depth values. Z-buffer algorithm is the most common method for visibility comparison. In Z-buffer algorithm, visibility comparison unit receives a pixel containing both depth value and current (x, y) coordinates, and then it fetches the related depth value from Z-buffer. After comparing the depth value, nearest depth value will be kept in Z-buffer. In index rendering, we can employ the Z-buffer algorithm for depth comparison, and the design of Z-buffer entries is coexistent with I-buffer, as shown in Fig. 5. Therefore both I-buffer and Z-buffer can be fetched and stored at the same time. Whenever a new pixel passes the visibility comparison, both Z-buffer and I-buffer are updated at the same time. If Z-buffer exists in index rendering architecture, TdbV is not needed, and therefore the dotted box and dotted lines in Fig. 3 are unnecessary.



2	2	2	0	0	0	0	0	1	1	1
2	2	2	2	0	0	0	1	1	1	1
2	2	2	2	0	0	1	1	1	1	0
2	2	2	2	2	1	1	1	0	0	0
2	2	2	2	1	1	0	0	0	0	0
2	2	2	2	2	2	0	3	0	0	0
2	2	2	2	2	3	3	0	0	0	0
2	2	2	3	3	3	2	0	0	0	0
2	3	3	3	3	2	2	0	0	0	0
3	3	3	3	2	2	2	2	0	0	0

Fig. 4. Illustration for index buffer (I-buffer): (a) first-order ray-tracing and (b) data stored in I-buffer.

TABLE III
TYPICAL INFORMATION IN TRIANGLE DATABASE FOR GOURAUD SHADING

Triangle Information		Database		Base variables	Differential variables
		Name	Description		
Geometry information	(X,Y-related)	-	-	X_{LEFT}, X_{RIGHT} Y_{UPPER}, Y_{BOTTOM}	$Slope_{LEFT-EDGE}$ $Slope_{RIGHT-EDGE}$
	(Z-related)	TdbV	Triangle database for visibility comparison	X_0, Y_0, Z_0	Z_{dX}, Z_{dY}
Color Information		TdbS	Triangle database for shading	X_0, Y_0 R_0, G_0, B_0 S_0, T_0	R_{dX}, R_{dY}, G_{dX}, G_{dY}, B_{dX}, B_{dY} S_{dX}, S_{dY}, T_{dX}, T_{dY}

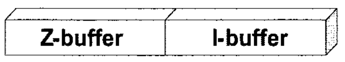


Fig. 5. Buffer entry of Z-buffer and I-buffer.

On the other hand, index rendering can also realize visibility comparison without Z-buffer. The depth value, Z, can be generated by linear expression as follows:

$$Z_{(X,Y)} = Z_0 + (X - X_0) \times Z_{dX} + (Y - Y_0) \times Z_{dY}. \quad (2)$$

The parameters Z_0, Z_{dX}, Z_{dY}, X_0, and Y_0 are stored in TdbV. Because the I-buffer keeps the index number of visible pixel, I-buffer can replace the functions of Z-buffer. The operation of depth comparison by different methods is illustrated in Fig. 6. Depth value is fetched directly from Z-buffer by conventional method, but it is real-time generated from linear expression by second method.

4) Lighting: Lighting operation calculates illumination in a 3-D scene by illumination model. In conventional rendering pipeline for flat or Gouraud shading, lighting operation locates

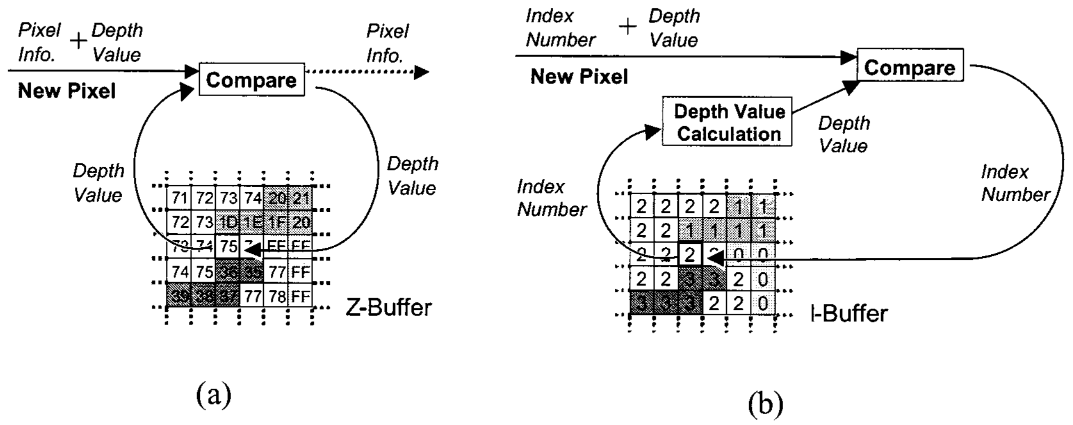


Fig. 6. Temporal storage for visibility comparison: (a) depth value stored in Z-buffer and (b) depth value stored in TdbV and I-buffer.

in geometry subsystem, and it does not appear in raster subsystem. Nevertheless, since our index rendering can eliminate the redundant lighting operations by deferred lighting, we place this unit in our architecture in order to demonstrate the feasibility of this lighting operation. The data path from visibility comparison block to lighting block is the key in terms of deferred lighting design, as shown in Fig. 3. It transmits a signal to indicate whether current polygon is visible or not. If all pixels of one polygon fail in visibility comparison, this polygon is invisible. Hence lighting calculation on this invisible triangle is unnecessary, and the information of this triangle can be discarded.

This architecture is applicable for three shading methods. For flat and Gouraud shading, lighting is applied for polygon-level. If a new polygon is received and its index number is $\boldsymbol{i}$, its color information is temporarily stored in $\boldsymbol{i}$-th entry of TdbS , and lighting is deferred until the signal is identified for its visibility. If this signal shows that polygon is visible, the data in $\boldsymbol{i}$-th entry of TdbS will be read into lighting block for lighting calculation, and the result is written back into the original entry. On the other hand, if this signal indicates that polygon is invisible, this polygon information will be discarded. The index number $\boldsymbol{i}$ can be reassigned and the space of $\boldsymbol{i}$-th entry in TdbS can be freed for another polygon. Hence, triangle database only keeps the visible triangles in a 3-D scene.

Furthermore, in Phong shading, lighting calculation is applied at pixel-level. Therefore, lighting is deferred until final scan-out. In this case, the parameter for shading is still stored in TdbS . If one pixel needs to be shaded, and its index number is $\boldsymbol{i}$, the data of $\boldsymbol{i}$-th entry of TdbS is sent to lighting block. After lighting calculation, the result is sent to shading block to generate final result.

5) Shading and Texturing: Shading and texturing block generates color for each pixel. As for shading, in flat shading, the shading block can directly fill the pixel with the uniform color of its parent triangle, and the color value is stored in TdbS . In Gouraud shading, color interpolation is necessary. The linear expression is applied to calculate each value, and all necessary parameters are fetched from TdbS . For example, in order to shade pixel (X, Y) by Gouraud shading, we check index number stored in coordinates (X, Y) in I-buffer. If this index number is $\boldsymbol{i}$, we can find out the polygon information of $\boldsymbol{i}$-th triangle in TdbS , such as $X_0, Y_0, R_0, G_0, B_0, R_{dX}, R_{dY}, G_{dX}, G_{dY}, B_{dX}$ and B_{dY}. Than, the color of this pixel can be calculated from the following linear expressions:

$$\begin{aligned} R_{(X,Y)} &= R_0 + (X - X_0) \times R_{dX} + (Y - Y_0) \times R_{dY} \\ G_{(X,Y)} &= G_0 + (X - X_0) \times G_{dX} + (Y - Y_0) \times G_{dY} \\ B_{(X,Y)} &= B_0 + (X - X_0) \times B_{dX} + (Y - Y_0) \times B_{dY}. \end{aligned} \tag{3}$$

On the other hand, Phong shading interpolates normal vectors and applies lighting on each pixel. In this case, the linear expression is also capable of interpolating vectors, and TdbS can store the parameters for vector interpolations. If Taylor series approximation is utilized, TdbS becomes the storage of parameters for Taylor series.

On the other hand, the texture coordinates can also be generated by linear expressions. With (S, T) coordinates, we can fetch texture buffer for texture mapping. Because the texturing operation is in scan-out rate now, it can avoid a lot of redundant fetching on texture buffer resulted from the absence of invisible pixels. The linear expressions for texture coordinates generation are as follows:

$$\begin{aligned} S_{(X,Y)} &= S_0 + (X - X_0) \times S_{dX} + (Y - Y_0) \times S_{dY} \\ T_{(X,Y)} &= T_0 + (X - X_0) \times T_{dX} + (Y - Y_0) \times T_{dY}. \end{aligned} \tag{4}$$

6) Scan Conversion: In index rendering, since shading operation is deferred, the scan conversion becomes light-weighted. The major task of scan conversion is to issue pixels inside the shape of triangle. Because we use Z-buffer algorithm for visibility comparison, the calculation of depth value is needed in scan conversion. In general case, depth value can be generated by simple calculation of addition. Each pixel issued from scan conversion carries index number, depth value, and its (x, y) coordinates only. Hence, high-speed scan conversion can be achieved and parallel algorithms can be employed, such as Pineda's parallel polygon rasterization algorithm [24].

C. Data Flow in Index Rendering

The data flow and data rate of index rendering are illustrated in Fig. 2(c) and (d). Both architectures of Fig. 2(c) and (d) are approaches of index rendering, and their difference is the method

TABLE IV
HARDWARE LEVELS FOR ANALYSIS AND SIMULATION

Hardware Levels	Parameters			Performance	
	Resolution	Frame Rate	Triangle / scene	Triangle / sec	Pixel / sec
High Performance	1024x768	30	64K	1920K	46.9M
	800x600	30	64K	1920K	46.9M
Middle Performance	800x600	30	16K	480K	11.7M
	640x480	30	16K	480K	11.7M
Low-End	320x200	24	4K	96K	2.3M
	200x150	24	4K	96K	2.3M

TABLE V
TRIANGLE NUMBERS OF 3-D OBJECTS

3-D object	(a)	(b)	(c)	(d)	(e)
Name	*Polyhedron*	*Dolphins*	*Castle*	*Policeman*	*Teapot*
Triangle Number	32	1451	6432	6016	12338
Back-face culled before simulation?	No	Yes	Yes	Yes	No

to store depth value. In Fig. 2(c), both I-buffer and TdbV are used to store the depth value. In Fig. 2(d), the depth value is stored in Z-buffer.

Besides the advantage of placing shading and texturing operations in scan-out rate, there are two key points in the data flow of index rendering: The first one is the design of I-buffer and TdbS. Because of this design, we can replace the huge and high-bandwidth pixel buffer with small and low-bandwidth buffers, I-buffer, and TdbS . Therefore, the approach of index rendering can employ the advantage of deferred shading without suffering from its drawbacks.

Moreover, we can reduce the number of lighting operations, even in Gouraud and flat shading methods. The reason is that the approach of index rendering moves the lighting operation from geometry subsystem into the area of "reduced triangle rate," and this is the second key point.

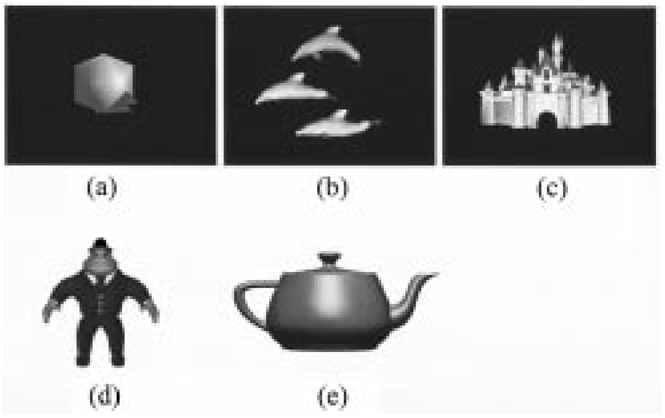


Fig. 7. Three-dimensional objects for simulation.

IV. ANALYSIS AND SIMULATION

For further analysis and simulation, reasonable assumptions are needed to demonstrate the outcome generated from the issues discussed in this paper. We discuss three architectures: traditional, deferred shading and index rendering. When realizing 3-D graphics on hardware, cost is an important issue. Therefore we roughly classify the capability of 3-D graphics hardware into three levels: 1) high-performance; 2) middle-performance; and 3) low-end. Furthermore, to show the reduction of lighting calculation, we simulate several 3-D objects with different resolutions and shading methods to show the capability of three architectures.

A. Analysis Parameters

1) Hardware Levels: For simulation, we roughly classify the capability of 3-D graphics into three levels: 1) high-performance; 2) middle-performance; and 3) low-end. Assumptions of three hardware levels are listed in Table IV. The major difference of three levels is the complexity of 3-D scene. The high-performance approach renders about 2M triangles/s. The middle-performance approach focuses on game and entertainment areas and targets on 480 K triangles/s. In the low-end approach, such as portable devices or PDA, 3-D graphics can be utilized as user interface, and its performance targets on 96 K triangle/s.

The second difference is the resolution. For each hardware level, we discuss two kinds of screen resolution; therefore, we can find how differently the resolutions can affect the result. Resolution 800×600 appears both on high-performance and middle-performance levels to find how the complexity of 3-D scene affects results under the same resolution. The third difference is frame rate. Because of persistence of human vision, higher frame rate is not necessary in general case. We assume that the frame rate is 30 in high- and middle-performance levels and it is 24 in low-end.

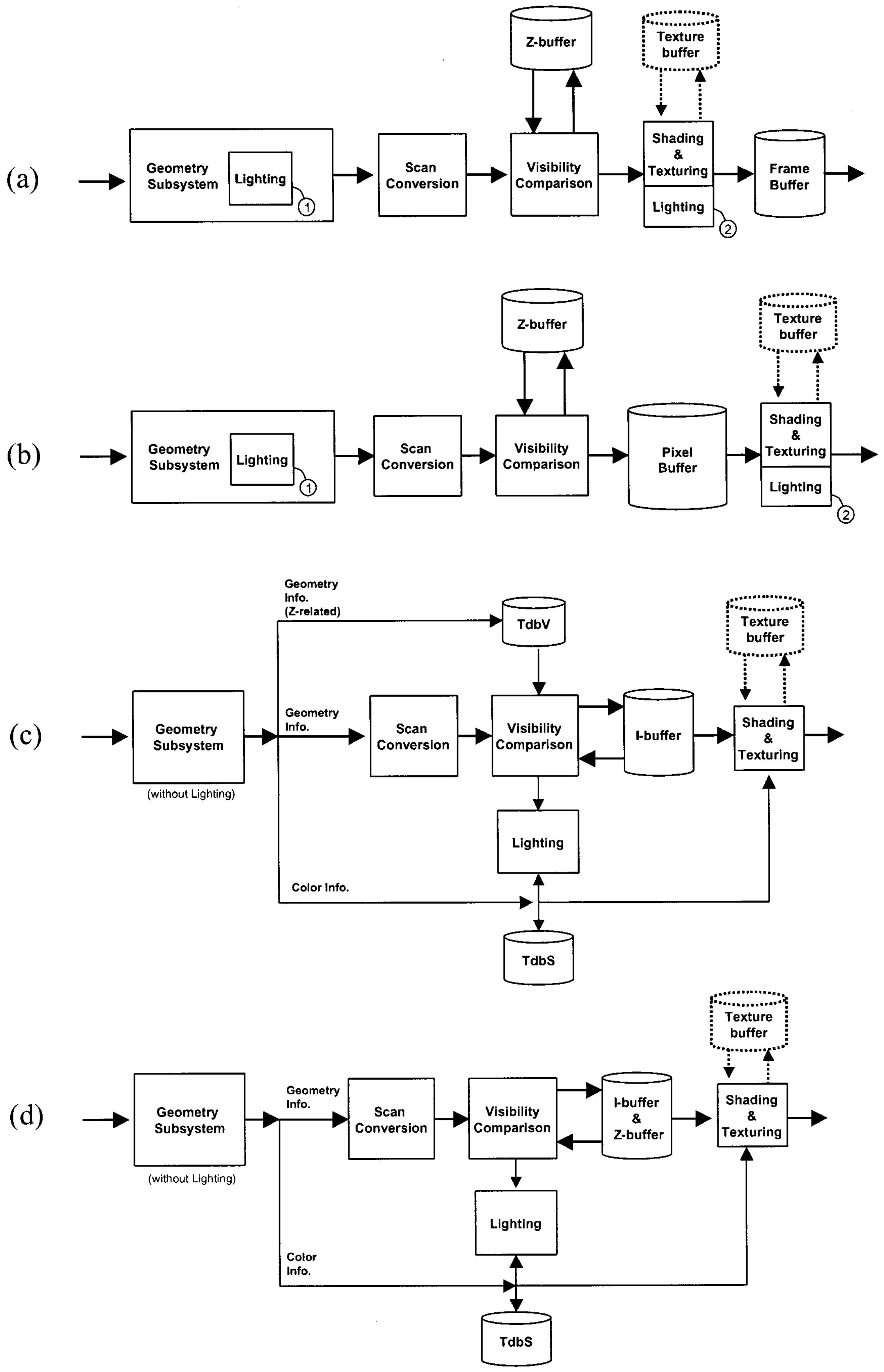


Fig. 8. Four types of architecture: (a) Type A (traditional pipeline); (b) Type B (deferred shading); (c) Type C (index rendering, depth value stored in TdbV and I-buffer); and (d) Type D (index rendering, depth value stored in Z-buffer).

TABLE VI
SUMMARY OF VARIABLES FOR ANALYSIS AND SIMULATION

Architecture Type	Hardware Level	Shading Method	Simulation Pattern
Type A	High Performance	Flat Shading	Polyhedron
Type B	Middle Performance	Gouraud Shading	Dolphins
Type C	Low-End	Phong Shading	Castle
Type D			Policeman
			Teapot

2) Simulation Patterns: In order to simulate the behavior of index rendering, we have utilized the Java [26] and Mesa [27] to develop our simulation environment. Mesa helps to handle the operations in geometry subsystem. It is capable of converting 3-D models into a lot of scanline-aligned triangles. Then, we write java programs to render the final images and to count the data rate. Hence we can get the information for analysis. In order to reflect the real case, we simulate the 3-D models to understand their requirements in data rate. Then, we utilize them to analyze the computation, buffer size and bandwidth requirements in hardware. Fig. 7 shows the 3-D objects for simulation patterns, and their triangle numbers are listed in Table V. The original resolution of 3-D objects is 640×480. For different resolutions, we scale these object models in order to control variables. For example, if we need to simulate 3-D scene in resolution 320×200, all object models are scaled into 0.5. In order to show the real reduction on triangle, we enable GL_CULL_FACE when generating intermediate simulation patterns except Polyhedron. Hence, the 3-D objects (b)-(d) are back-face culled before simulation, so the simulation can present more to reflect the real result caused by architecture designs.

Among five 3-D objects, the first one is Polyhedron with two colored triangles to simulate the 3-D objects at user interface for low-end system. The 3-D objects (b)-(d) are taken from the sample files of OpenGL developer tools of SGI [25]. Those models show the general objects in 3-D applications. "Dolphins" and "Policeman" illustrate the shape of animal and human. The bodies of "Dolphins" are simple and smooth, whereas the model of "Policeman" is complex and it consists of many parts. "Castle" is another model of different type with many walls cover each other, causing a lot of pixels in this model to become invisible. In order to simulate the condition in today's 3-D applications, these three models are back-face culled. "Teapot" is generated by function *glutSolidTeapot*( ) in Mesa, and modeled by a lot of small triangles. In high-performance system, most 3-D objects are modeled by a lot of small triangles to present curvy surface smoothly, and hence "Teapot" can simulate this condition in high-performance system.

3) Architecture Types: In the following analysis and simulation, we compare four architectures (Types A–D). Type A is the traditional rendering pipeline, and it equips the frame buffer and Z-buffer. Type B is deferred shading. For fair comparison, we use the direct method to model deferred shading in order to show its essential characteristics. This architecture needs Z-buffer for visibility comparison and pixel buffer to keep information for each pixel on screen. Type C and D are approaches of index rendering with different methods of visibility comparison. Type C utilizes I-buffer and TdbV to generate depth value in real-time, while Type D uses conventional Z-buffer to store depth value temporally. Four architectures are illustrated in Fig. 8. There are additional notations in Fig. 8(a), (b) to show where the lighting operation is executed. In flat shading and Gouraud shading, lighting operation is in the box labeled ①, while in Phong shading the lighting operation is performed in box labeled ②.

We summarize all four variables for analysis and simulation in Table VI. These four variables are: 1) architecture type; 2) hardware level; 3) shading method; and 4) simulation patterns.

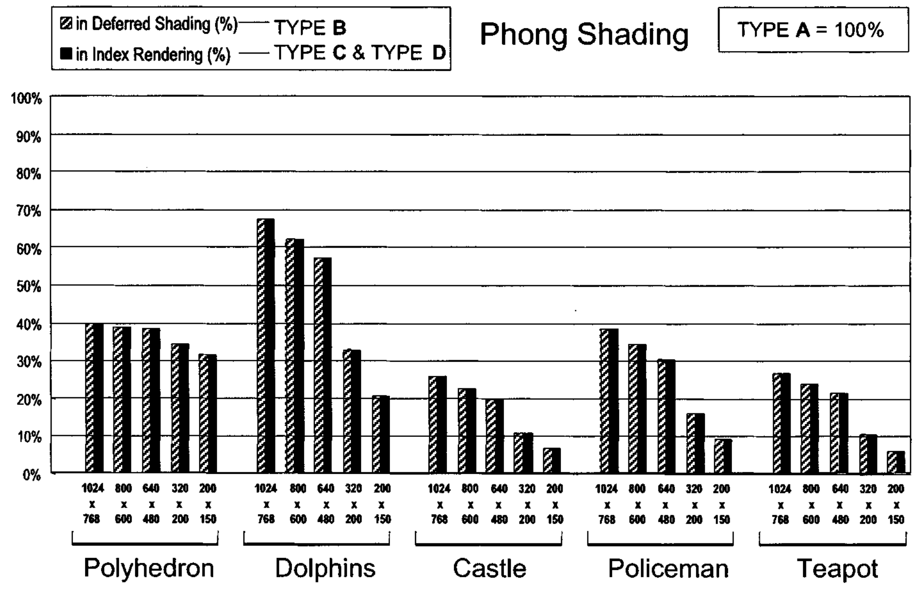
B. Numbers of Lighting and Texture Operations

1) Numbers of Lighting Operation: The major advantage of index rendering and deferred shading is the reduction of lighting operation. Fig. 9 shows the simulation result for numbers of lighting operation, which is compared with traditional rendering method (Type A). We set the number of lighting operations in Type A as 100% in Fig. 9. In this figure, both types of index rendering (Type C, D) have the same results, because the method of visibility comparison is not related to the number of lighting operation. Therefore, we only illustrate two data on each trial: deferred shading (Type B) and index rendering (Type C, D).

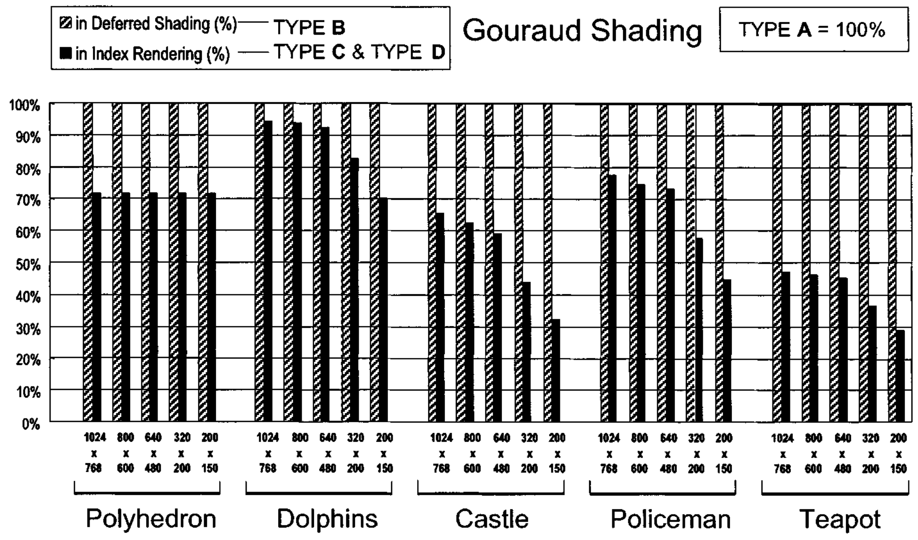
2) Lighting in Phong Shading: As shown in Fig. 9(a), we can find that deferred shading and index rendering reduce the same number of lighting operations, about 30% to 95%. This reduction becomes larger for complex 3-D objects and lower resolution. The reasons are that complex 3-D objects have more covered pixels in their model, and lower resolution leads to fewer visible pixels. Fig. 9(a) shows that deferred shading has significant improvement in Phong shading, and therefore we can know why some high-end 3-D hardware uses deferred shading to solve computation bottleneck, though it costs a lot on buffer size and bandwidth. With the same reduction in lighting operations, index rendering can provide better solution to solve this bottleneck with less cost.

3) Lighting in Gouraud and Flat Shading: However, deferred shading approach can not reduce lighting operations in flat shading and Gouraud shading, and hence the proportion of lighting number remains in 100% compared with traditional rendering pipeline (Type A), as shown in Fig. 9(b) and (c). On the other hand, because of the technique of deferred lighting, index rendering can reduce 10%–70% of lighting operation in flat and Gouraud shading. Complex models and lower resolutions also lead to better reduction, but the model of

(a)



(b)



(c)

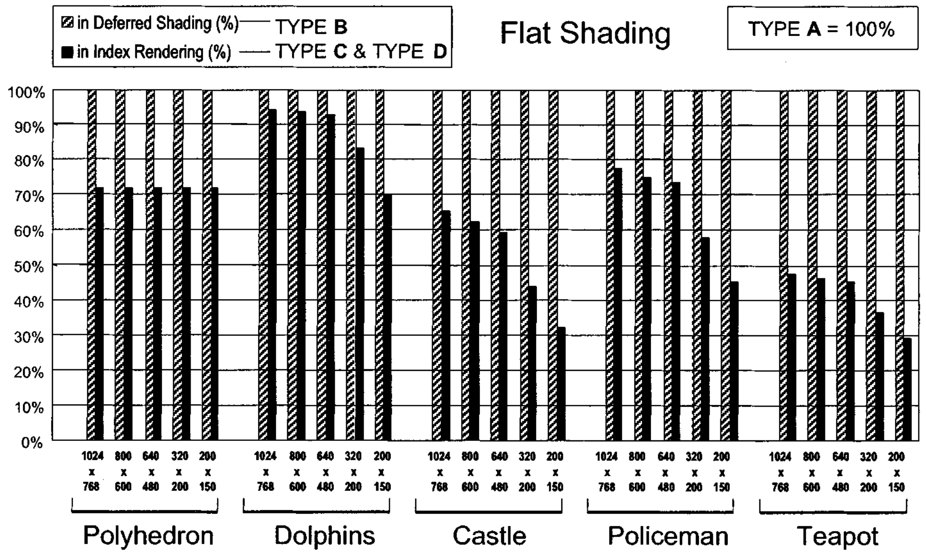


Fig. 9. Percentage of lighting operation number compared to traditional rendering pipeline (a) Phong shading, (b) Gouraud shading, (c) Flat shading.

TABLE VII
RELATIONSHIP OF ARCHITECTURES, BUFFERS AND PARAMETERS

	Z-buffer	Frame buffer	Pixel buffer	I-buffer	TdbS	TdbV
Architectures						
Type A	V	V				
Type B	V		V			
Type C				V	V	V
Type D	V			V	V	
Parameters which affect buffer size						
Resolution	V	V	V	V		
Scene Complexity (Max. Visible polygon No. in a scene)				V [*1]	V	V
Size of pixel/polygon color info.			V		V	

[*1] Size of I-buffer related to $\lceil \log_2$ (maximal visible polygon number in a scene) $\rceil$

Polyhedron is an exception. Polyhedron is constructed by quite large polygons, and the visibility of each triangle remains the same at different resolutions. Therefore, its lighting number does not change in low resolution because the reduction caused by deferred lighting is related to invisible polygons. Furthermore, although the proportions of lighting numbers of flat and Gouraud shading are the same in the figure, the original lighting number in Gouraud shading is three times more than that in flat shading. Therefore, the reduction is more significant in Gouraud shading.

4) Lighting Operation Number and Data Rate: In fact, the reduction on lighting operation number is related to the data rate. Referring to Fig. 2, we can find that: as for Phong shading, the lighting operation is located in the area of reduced pixel rate in traditional pipeline. On the other hand, the lighting operation is in the area of scan-out rate area in both deferred shading and index rendering approach. Hence, the Fig. 9(a) can be treated as comparison between "reduce pixel rate" and "scan-out rate."

On the part of Gouraud and flat shading, the lighting operation is located in the area of triangle in previous architectures, including both traditional pipeline and deferred shading approach. Hence deferred shading approach cannot reduce number of lighting operation. However, because of the technique of deferred lighting, index rendering approach can move the lighting operation into the area of reduced triangle rate. Therefore, Fig. 9(b) and (c) is also the result of comparing "triangle rate" and "reduced triangle rate." Moreover, because most models are back-face culled before simulation, the result can reflect the real reduction of lighting operation.

5) Number of Texture Operation: Referring to Fig. 2, in traditional rendering pipeline, the texture operation is in the area of reduced pixel rate. However, in deferred shading approach, it is moved to the area of scan-out rate. Hence, the reductions on texture operation and texture buffer bandwidth are also the advantages of defer shading approach. Index rendering approach retains the advantages. Therefore, for comparisons of both operation and of bandwidth, the results are also the comparison between "reduce pixel rate" and "scan-out rate." Their percentage figures are the same as Fig. 9(a).

C. Buffer Analysis

1) Buffer Size: The characteristic of each kind of buffer is listed in Table VII, and relationships between different architectures and buffers are marked. Among six kinds of buffers, resolution affects the size of Z-buffer, frame buffer, pixel buffer and I-buffer. Scene complexity affects the size of two triangle databases TdbS and TdbV because triangle databases must keep information of all visible polygons on screen. Furthermore, scene complexity also affects I-buffer, because the length of index equals to $\lceil \log_2$ (maximal visible polygon number in a scene) $\rceil$. Within both approaches of deferred shading and index rendering, color information should be stored for shading operations, and hence it affects the size of pixel buffer and TdbS . We do not discuss the size of texture buffer here because its size is user-defined, and there is no direct relation with other simulation parameters, such as screen resolution and scene complexity.

Fig. 10 shows the buffer size of four architectures, and contribution of each type of buffer is labeled. Generally speaking, buffer size is larger in Phong shading than in Gouraud shading. The lower the resolution, the smaller is the buffer size. Among all kinds of buffers, the size of pixel buffer is the largest regardless of architecture type. Therefore, it makes overall buffer size huge in deferred shading (Type B), especially in Phong shading. The overall buffer size in deferred shading grows up quickly with increasing resolution, and it becomes several times more than that in traditional rendering pipeline (Type A). On the other hand, because index rendering (Type C, D) uses the concept of fetching and generating pixel information on demand, the overall buffer size is as small as Type A. Therefore, index rendering is more cost effective and feasible in the architectures of low-cost systems.

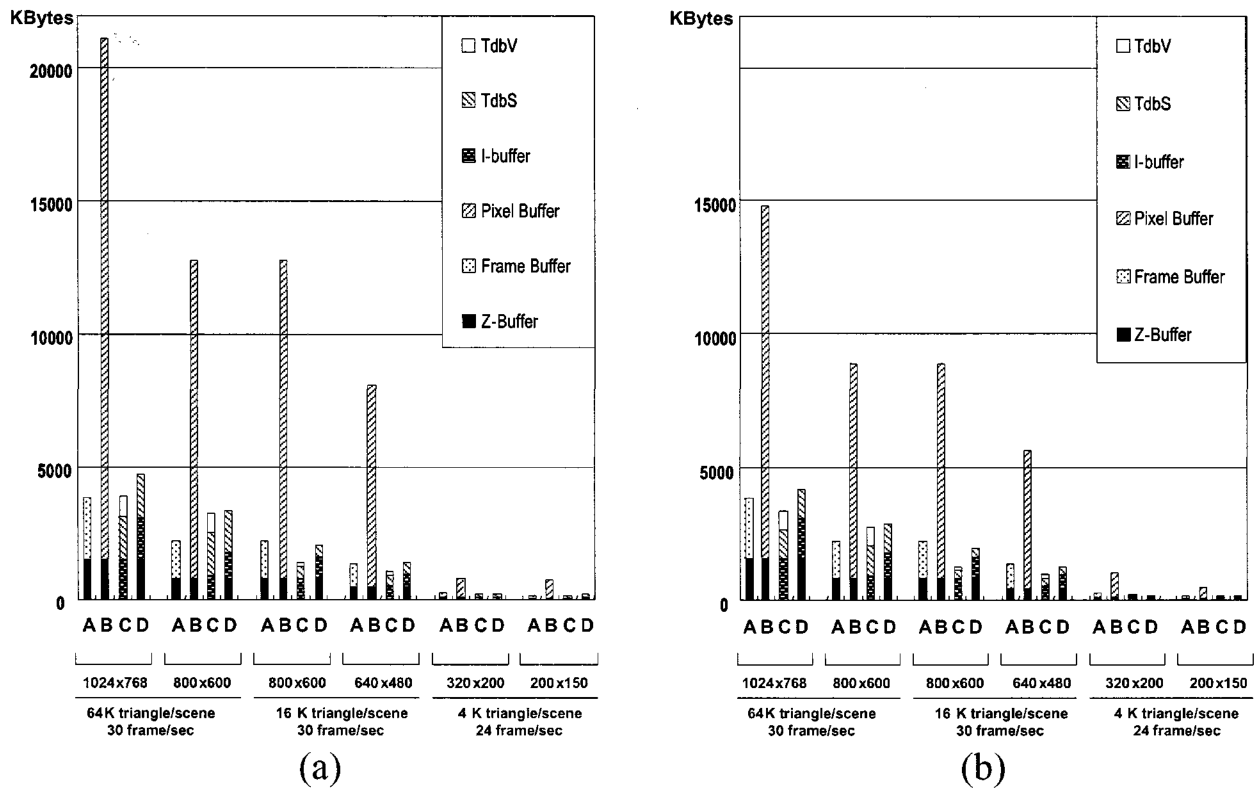


Fig. 10. Buffer sizes in four types of architecture: (a) Phong shading and (b) Gouraud shading.

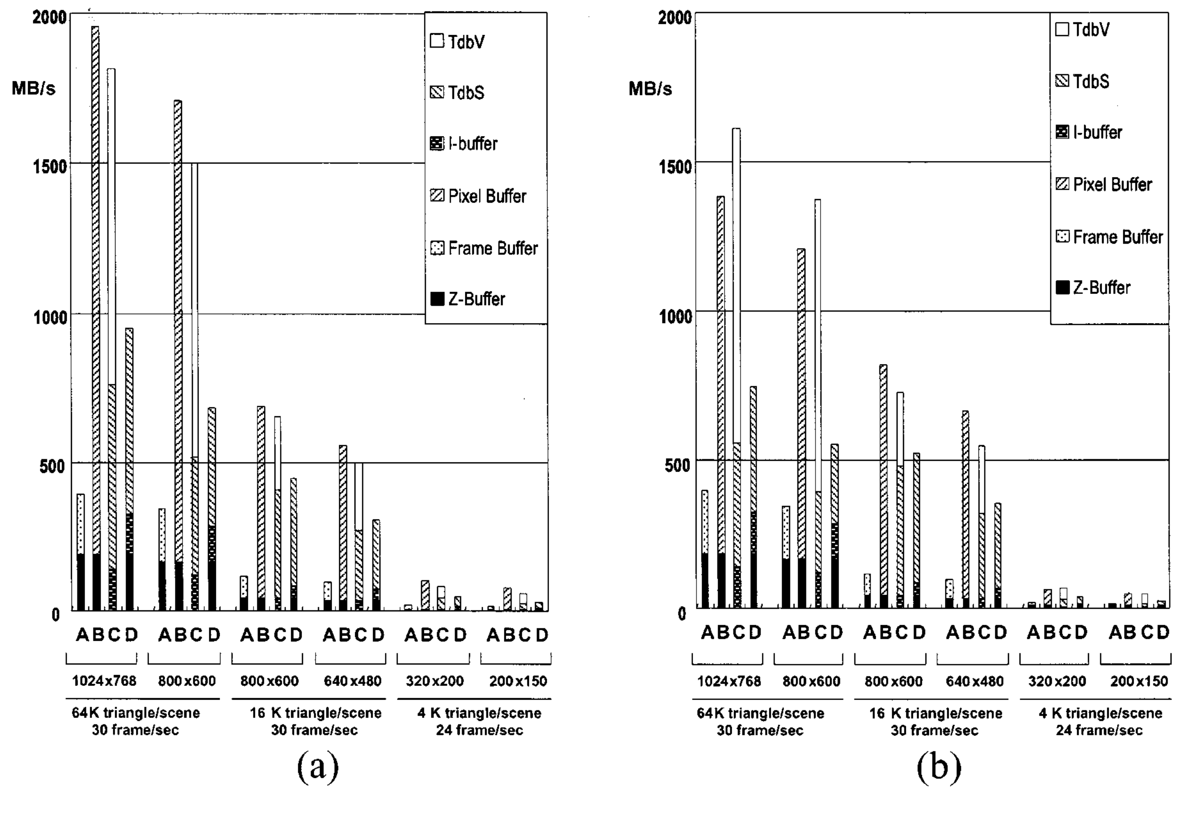
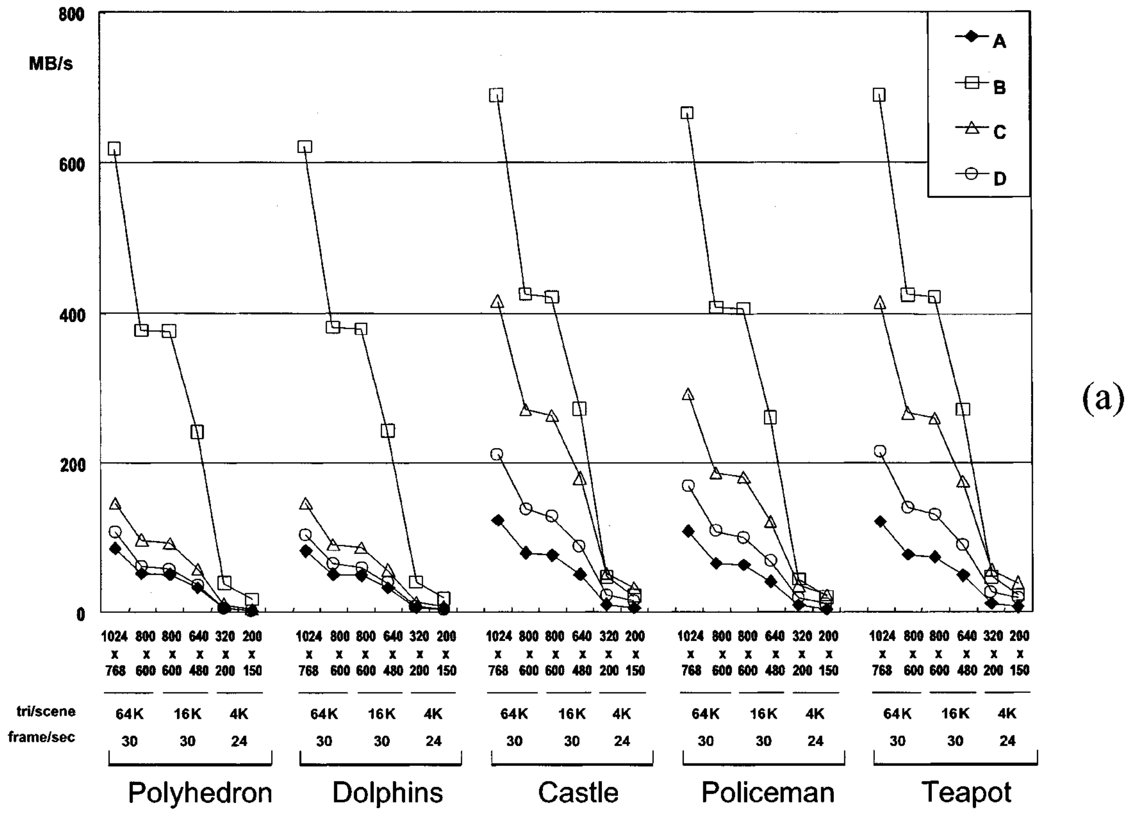


Fig. 11. Analysis of maximum bandwidth: (a) Phong shading and (b) Gouraud shading.

2) Maximum Bandwidth Analysis: Fig. 11 shows the result of bandwidth analysis for worst case. In the worst case scenario, we assume an animated 3-D scene that has maximal allowed polygon number of current architecture where all polygons are visible in each frame by rendering it in real-time to see its animation. This analysis can show the maximal bandwidth requirement. Among all types of architectures, the bandwidth of traditional rendering pipeline (Type A) is relatively small, but pixel



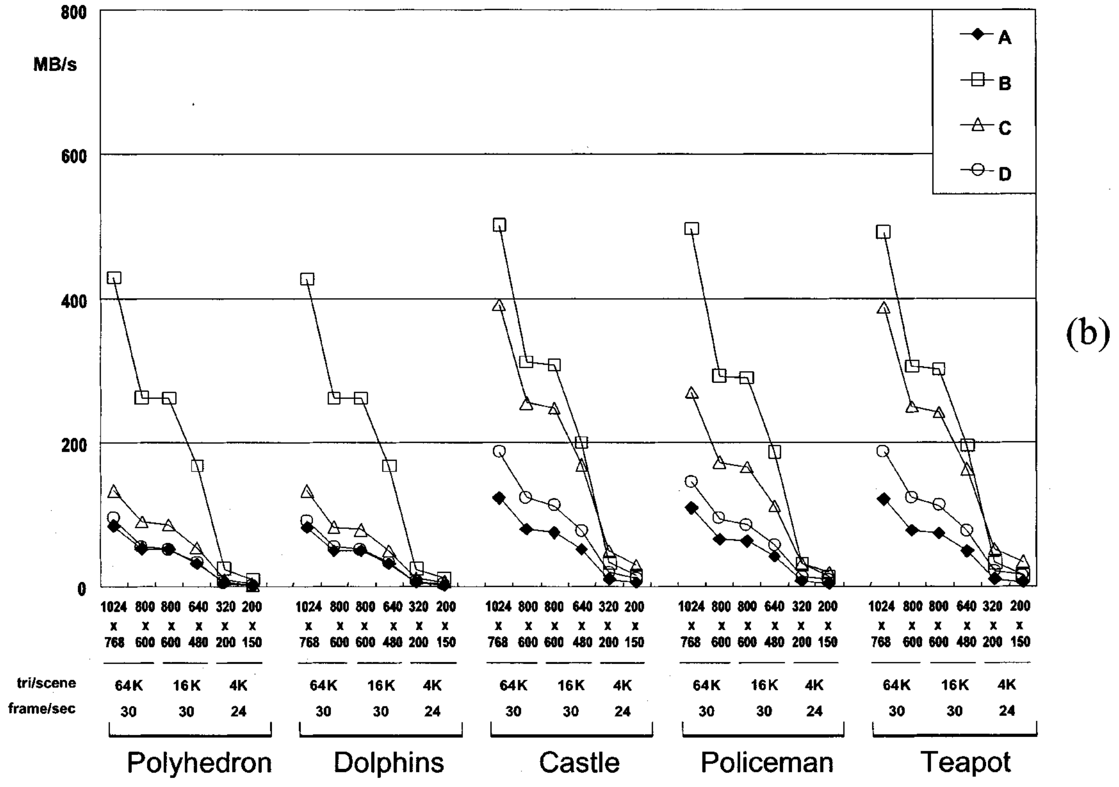


Fig. 12. Buffer bandwidth by simulation (a) Phong Shading, (b) Gouraud shading.

buffer in deferred shading has the largest bandwidth. Due to high bandwidth on large-sized buffer, pixel buffer becomes the bottleneck of deferred shading.

To solve this problem, index rendering uses two different strategies. The first one is to map high bandwidth access in a very small buffer, and makes this buffer small enough to be embedded on-chip to reduce cost effectively. Since on-chip buffer can support high bandwidth, using this architectural design can solve the limitation on bandwidth. This strategy is used in our Type C architecture. Although the bandwidth of TdbV is huge, and makes total bandwidth larger than deferred shading in some case, the size of TdbV is small enough to be embedded on-chip, as shown in Fig. 10. The size of TdbV is about 720 kB in high-performance, 168 kB in middle-performance, or 30 kB in low-end system. Hence, this buffer is small enough to be implemented cost-effectively by high-speed buffer, such as an embedded memory. Without the bandwidth of TdbV, the remained bandwidth is much smaller than deferred shading. The second strategy is to reduce the bandwidth directly by architectural design, and Type D uses this strategy. Type D employs index rendering, but utilizes traditional Z-buffer for visibility comparison. This method cannot optimize bandwidth with small high-speed buffer, but it has the capability to avoid high bandwidth caused by TdbV. This approach can also reduce the high bandwidth existed in deferred shading.

3) Bandwidth Simulation: In order to show bandwidth in real cases, we simulate 3-D models to see how it changes. Only the overall bandwidth is illustrated in Fig. 12 to simplify the figures. Among different types of architectures, traditional rendering pipeline (Type A) requires smallest bandwidth, while deferred shading (Type B) requires the largest. In this figure, we find index rendering approaches (Type C, D) greatly reduce bandwidth in simple 3-D objects, such as Polyhedron and Dolphins. In complex 3-D objects, the bandwidth in index rendering is still smaller than that in deferred shading. Although Type C also requires high bandwidth in some cases, small high-speed buffer can solve this problem. Type D is similar in low bandwidth to Type A, and hence this architecture is a more cost-effective method to realize index rendering.

V. Conclusion

In this paper, we propose a novel approach, index rendering, and its referential architecture for 3-D graphics rendering. This approach retains the advantage of deferred shading and eliminates its drawbacks. The basic concepts of index rendering are "fetching and generating pixel information on demand" and "deferred lighting." To support these concepts, index rendering separates pixel information into several parts and handles them asynchronously. The result shows index rendering can eliminate 10%–70% lighting operations in flat and Gouraud shading, and 30%–95% in Phong shading. Furthermore, it saves 70% buffer size and 50%–70% bandwidth as compared with deferred shading.

According to the analysis and simulation results, index rendering is hardware-efficient, and especially suitable for high-performance and low-end rendering systems. In the high-performance system, index rendering can reduce the same lighting and texture operations as deferred shading, but it requires smaller buffer and lower bandwidth. In the low-end system, index rendering can significantly reduce lighting operations in flat shading and Gouraud shading with the costs of buffer and bandwidth being acceptable (buffer size 130 kB–224 kB, bandwidth 15 MB/s–81 MB/s). Hence, index rendering can make 3-D graphics feasible in low-end systems and portable devices, such as mobile phone, PDA, etc. About antialiasing and transparency, Mammen's method [28] can be employed in index rendering. Hence, index rendering is capable of making 3-D rendering hardware-efficient and it is easy to be integrated into multimedia system of today, both in high-performance and low-end systems, especially suitable in system-on-a-chip (SOC) design.

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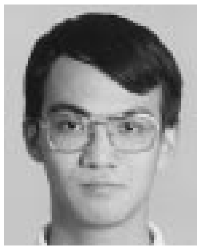

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