DESIGNING GRAPHICS ARCHITECTURES AROUND SCALABILITY AND COMMUNICATION

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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June 2001

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Abstract

Communication forms the backbone of parallel graphics, allowing multiple functional units to cooperate to render images. The cost of this communication, both in system resources and money, is the primary limit to parallelism. We examine the use of object and image parallelism and describe architectures in terms of the *sorting* communication that connects these forms of parallelism. We introduce an extended taxonomy of parallel graphics architecture that more fully distinguishes architectures based on their sorting communication, paying particular attention to the difference between sorting *fragments* after rasterization, and sorting *samples* after fragments are merged with the framebuffer. We introduce three new forms of communication, *distribution*, *routing* and *texturing*, in addition to sorting. Distribution connects object parallel pipeline stages, routing connects image parallel pipeline stages, and texturing connects untextured fragments with texture memory. All of these types of communication allow the parallelism of successive pipeline stages to be decoupled, and thus load-balanced. We generalize communication to include not only interconnect, which provides communication across space, but also memory, which functions as communication across time. We examine a number of architectures from this communication-centric perspective, and discuss the limits to their scalability. We draw conclusions to the limits of both image parallelism and broadcast communication and suggest architectures that avoid these limitations.

We describe a new parallel graphics architecture called “Pomegranate”, which is designed around efficient and scalable communication. Pomegranate provides scalable input bandwidth, triangle rate, pixel rate, texture memory and display bandwidth. The basic unit of scalability is a single graphics pipeline, and up to 64 such units may be combined.

Pomegranate's scalability is achieved with a novel "sort-everywhere" architecture that distributes work in a balanced fashion at every stage of the pipeline, keeping the amount of work performed by each pipeline uniform as the system scales. The use of one-to-one communication, instead of broadcast, as well as a carefully balanced distribution of work allows a scalable network based on high-speed point-to-point links to be used for communicating between the pipelines. Pomegranate provides one interface per pipeline for issuing ordered, immediate-mode rendering commands and supports a parallel API that allows multiprocessor applications to exactly order drawing commands from each interface. A detailed hardware simulation demonstrates performance on next-generation workloads. Pomegranate operates at 87–99% parallel efficiency with 64 pipelines, for a simulated performance of up to 1.10 billion triangles per second and 21.9 billion pixels per second.

Acknowledgements

I would like to thank my advisor, Pat Hanrahan, for his continual guidance. His advice has been invaluable, as has his patience with my forays into activities far removed from being a graduate student. I thank the other members of my reading committee, Bill Dally and Mark Horowitz, for their time and attention to detail. Bill Dally has provided a great engineering perspective that I have had the pleasure of being exposed to in multiple classes as well as personally. Mark Horowitz was a source of many insightful suggestions throughout my career at Stanford. I owe a large debt of gratitude to Kurt Akeley. I have had numerous enlightening discussions with him, and he has given me a deeper understanding of graphics architecture. Kurt's thoughtful comments on my thesis clarified not only my writing but also my ideas.

Stanford has been a wonderful place to go to school, in large part because of the people I had the good fortune to work with. In particular, Homan Igehy, Gordon Stoll, John Owens, Greg Humphreys and Ian Buck have all taught me a great deal. The certainty with which I argued with them all was nearly always because I was wrong. They, together with Jeff Solomon, Craig Kolb, Kekoa Proudfoot, Matt Pharr and many others have made being a graduate student very enjoyable.

The coincidences of my brother Adam attending graduate school at Stanford, David Rodriguez self-employing himself in Sunnyvale, and Michael and Tien-Ling Slater relocating to Berkeley have all made my time outside of school much more pleasurable.

I thank my parents for encouraging me to go to graduate school when I needed to be pushed, for their enthusiasm when I thought I would leave to go get rich, and for their constant encouragement to write my thesis when I was dragging my heels.

Finally, I thank the Fannie and John Hertz Foundation for its support, as well as DARPA contract DABT63-95-C-0085-P00006.

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Chapter 1

Introduction

Scalability is a time machine. A scalable graphics architecture allows the combination of multiple graphics pipelines into a greater whole, attaining levels of performance that will be unattainable for years with a single pipeline. Parallel graphics addresses exactly those problems which exceed the capabilities of a single pipeline – problems such as scientific visualization, photorealistic rendering, virtual reality and large-scale displays. Once all of the available task parallelism has been exploited by providing dedicated hardware support for each stage of the pipeline, the path to increased performance is multiple pipelines, or data parallelism. The crucial element to exploiting data parallelism is communication.

Graphics architectures are most broadly classified by where they “sort.” The sort is the point in the architecture which transitions from object parallelism to image parallelism, and is literally the point where primitives are sorted by their screen location. The choice of where and how to perform this sort has an enormous impact on the resulting graphics architecture. Although the sort is generally the most visible form of communication in graphics architecture, communication takes place at other points in most architectures, with often significant ramifications. In part, this thesis presents an analysis of graphics architectures from a joint perspective of scalability and communication, examining their interdependence and discussing the results and limitations of different architecture choices.

We draw conclusions as to the main obstacles to building a scalable parallel graphics architecture, and use these observations as the foundation for a new, fully scalable, graphics architecture called “Pomegranate.” In the second half of this thesis we describe Pomegranate’s architecture and operation. Simulation results demonstrate Pomegranate’s scalability

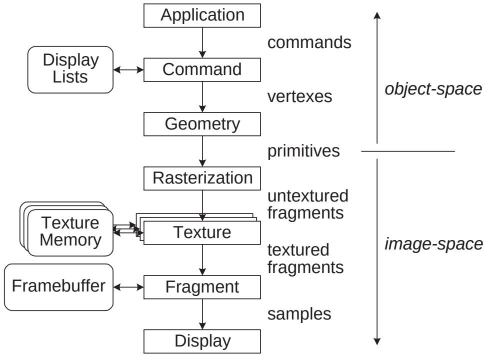


Figure 1.1: The Polygon Rendering Pipeline

to high degrees of parallelism.

We begin by describing the graphics pipeline and how we measure its performance. We then frame our discussion of communication and scalability in graphics architecture. Finally, we summarize the contributions of this thesis.

1.1 Graphics Pipeline

The polygon rendering pipeline, or graphics pipeline, takes as input commands that specify vertex positions, colors, geometric normals, texture coordinates, and other vertex attributes, and commands that specify the plane of projection, point of view, lighting model, etc., and computes as output an image of the polygons described by the input. The sequence of operations performed by the graphics pipeline is constant, but most operations may be configured by the application, and may be enabled or disabled as well. Our model of the graphics pipeline is shown in figure 1.1. The pipeline consists of seven stages: application, command, geometry, rasterization, texture, fragment and display. We have chosen the stages of the pipeline shown here both because they correspond well to our mental model of the operation of hardware, as well as clearly defining different points where communication may be used.

The application generates the command stream that controls the graphics pipeline. These commands specify both the locations and various material and geometric attributes of polygon vertices, as well as setting the configuration of the pipeline. These commands are input to the command processor which manages the interface between the graphics system and the host processor.

The command processor provides the graphics pipeline's interface to the application. It accepts the application's vertex commands and tracks their effects on the graphics state. State that the application does not modify is persistent. For example, if the application sets the color to red, then every subsequent vertex will be red, until a new color specified. The command processor bundles each incoming vertex together with the tracked vertex attributes, and passes them to the geometry processor. The command processor additionally interprets display lists, which are execution macros for a number of graphics commands. The use of display lists avoids the the specification of the same commands multiple times, reducing application computation, and the lists may be stored in graphics memory, reducing interface bandwidth.

The geometry processor transforms the application specified vertices, which exist in their own local coordinate system, by application specified transformation matrices, mapping the vertices to their screen locations. The geometry processor similarly transforms the vertex geometric normals, and evaluates a lighting model. The transformed vertices are then assembled into primitives, which may be culled if they do not lie on the screen, or clipped to the boundary of the screen if they intersect it. The resulting screen-space primitives are then sent to the rasterizer.

The rasterizer receives primitives, which are specified by the location, color and texture coordinates of their vertices on the screen. The rasterizer emits a fragment for every pixel location a primitive overlaps. Each fragment includes pixel coordinates, color, depth, and texture coordinates, interpolated from the primitive's vertices.

The texture processor textures the stream of fragments from the rasterizer. For each fragment it retrieves a texel neighborhood from the current texture and filters the texels to compute a final texture color, which is then combined with the fragment's color. The application specifies the texture images which are used by the texture processor. Modern graphics pipelines may include multiple texture processors, with the output color of each texture processor taken as the input color to the next. In this case the rasterizer interpolates independent texture coordinates for each texture processor.

The fragment processor accepts the stream of texture fragments from the last texture processor, and combines it with the framebuffer. Typically the fragment processor composites the fragments according to the results of a depth test, updating the color stored in the framebuffer only if the incoming fragment is closer to the eye than the sample already in the framebuffer. The fragment processor may be configured to perform a number of additional operations, such as blending the incoming fragment color with the color already present in the framebuffer.

The display processor continually reads the contents of the framebuffer and sends it to the display.

The command processor, texture processors and the fragment processor in our pipeline are connected to memory systems. The command processor may have direct access to a local memory system to store display lists or other retained-mode constructs, without having to use the application's memory system resources. Similarly, the texture processors in most modern systems have a locally attached memory system for high-bandwidth access to the texture store. Finally, the fragment processor is attached to the framebuffer. Here the representation of distinct memory for each task is schematic, in many modern architectures there is a single unified memory system that satisfies all of these uses.

The pipeline in figure 1.1 is annotated with what is communicated between each of its stages. Although not labeled separately, the memory provides communication as well. Instead of providing communication in space, by connecting separate functional units, memory provides communication in time, allowing data computed or specified at one time to be used at a later time. We discuss the cost of communication in both interconnect and memory in section 2.3.

The transition from communication of object-space primitives and commands to screen-space primitives and commands is mirrored in the use of parallelism within the graphics pipeline. All parallel graphics architectures will initially exploit object parallelism, at least at the level of processing the input command stream, and in the end will exploit image parallelism when driving the display. However, the transition from object-space primitives to screen-space primitives does not dictate where the transition from object parallelism to image parallelism must occur. Section 3.1 discusses the use of object-space and screen-space parallelism in the graphics pipeline.

The pipeline we have just described has a stateful immediate-mode interface and ordered semantics. There are other choices that could have been made, and in section 2.1 we discuss the implications of these choices and their alternatives, both for application programmers and hardware architects.

In a conventional microprocessor pipeline, each instruction accepts a fixed number of inputs, typically two, and computes a constant number of outputs, typically just one. In contrast, the computation in a graphics pipeline is much more variable. A single triangle may be located outside of the viewing frustum, in which case it requires little computation, and its processing ceases during the geometry stage of the pipeline, or a triangle may cover the entire screen, in which case the rasterization and subsequent stages of the pipeline will spend a proportionally large amount of time processing it. Generally neither the location nor the area of a primitive on the screen is known a priori, and by extension, neither is the amount of computation required to process the primitive.

The dynamic amount of processing required for each primitive presents the fundamental challenge to exploiting data parallelism in a graphics architecture. Although geometric processing imbalances can be significant, the primary difficulty is the widely varying amount of rasterization processing required per primitive. In broad strokes, there are two approaches to addressing this problem in data parallel graphics. The first, more commonly used approach, is to partition the output space (screen) across the rasterizers. Thus large primitives will be processed by many pipelines, and small primitives by just a single pipeline. The primary difficulty to these *image parallel* schemes is choosing a partition that achieves a good load balance without excessive duplication of work. The second approach is to partition the input space (primitives) across the rasterizers. Architectures based on this approach typically assume that, given a sufficiently large number of primitives, each pipeline will have a balanced amount of work. The main challenge of such *object parallel* approaches is that this is in fact a poor assumption. We discuss these approaches to parallelism, and the communication they require, in chapter 3. In chapter 4 we present an extended taxonomy of architectures, and discuss examples of each.

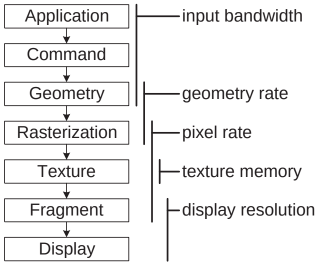


Figure 1.2: Parallel Graphics Performance Metrics. Each of the performance metrics will be governed by the stages indicated as well as any communication between the stages.

1.2 Performance Metrics

We identify five key performance metrics, shown in figure 1.2, for evaluating a parallel graphics architecture: input bandwidth, geometry rate, pixel rate, texture memory and display resolution.

Input bandwidth is the rate at which the application can generate commands, pass them to the command processor and have them accepted by the geometry processor. In this case, it is assumed that the limiting factor is command submission and that the primitives are small and simple enough to be neither geometry nor pixel rate limited.

Geometry rate is the rate at which the geometry processor can transform, light and clip input primitives and transmit the results to the rasterizer. Recent geometry processors are fast enough that they are often limited by input bandwidth for immediate-mode applications, unless they are performing complicated lighting or texture coordinate generation.

Pixel rate is the rate at which the rasterizer can accept primitives, scan convert them, and emit fragments. The pixel rate is similarly dependent on the rate at which the texture processor can texture the fragments and the fragment processor can merge the fragments with the framebuffer.

Texture memory is the amount of memory available for unique textures. If an architecture replicates texture memory, for example, providing a complete copy of all textures for each texture processor, then the unique texture memory is the total amount of texture memory divided by the replication factor.

Display resolution is the resolution and number of displays which can be supported.

Each of these performance metrics is determined not only be the compute and memory capacity of its particular stages, but also by the communication mechanisms which connect those stages.

1.3 Communication

Communication forms the backbone of parallel graphics, allowing multiple functional units to cooperate to render images. How various architectures use communication to distribute the parallel computation will be our be primary means of differentiating them. Communication serves two main purposes within parallel graphics. First, it enables the *fan-out* and *fan-in* of parallel computations. Nearly all parallel graphics architectures fan-in parallel computation at the display – communication is used to route the parallel computation of the frame by multiple pipelines to a display or displays. Most architectures additionally use communication to fan-out an input serial command stream, distributing its work over the pipelines. The second purpose of communication is to garner *efficiency*. Communication helps us garner efficiency by allowing us to load-balance work across pipelines and reduce duplication of memory and computation.

Communication allows us to balance the computational load across the various pipelines so that the pipelines are uniformly utilized. Load-balancing is necessary because even if the same number of primitives is given to every pipeline, those primitives will differ both in the amount of geometric work required and the amount of rasterization work required. Given that the amount of work required per primitive is generally not known a priori, the work may either be distributed dynamically, relying on work estimators and feedback to balance the load, or statically, relying on a statistical load balance. We will see that in practice load-balanced static partitions are quite difficult to implement efficiently.

Communication allows us to reduce duplication of memory by, for example, partitioning the framebuffer among the pipelines and sorting work to the appropriate pipeline, rather than providing a duplicate framebuffer for each pipeline. Similarly, we may choose to partition the texture memory among the pipelines in the system and communicate texture reads between pipelines rather than replicating the texture store on each pipeline. In the same vein, communication allows us to perform a computation once and communicate the result to all the necessary recipients, rather than having them each perform the computation. For example, communication between geometry and rasterization allows each primitive to be transformed and setup only once, although multiple rasterizers may be responsible for the computation of its fragments.

Rather than using communication to reduce duplication of memory, we can use memory to reduce communication. For example, it may be more efficient to replicate texture memory on each pipeline, rather than sharing it over a texture memory interconnect. Similarly, the application might put its commands into display lists which can be cached in the graphics system, so the commands do not utilize the scarce host interface bandwidth, or the host's scarce compute cycles. In effect, memory provides communication across time, allowing the architecture to use computations (textures, commands, etc.) at a time deferred from their specification.

We take a unified view of both interconnect and memory as communication. An interconnect provides communication across space, while a memory provides communication across time. In part, we analyze the differences in these forms of communication, and show how they may be interchanged.

1.4 Scalability

The performance of interactive graphics architectures has been improving at phenomenal rates over the past few decades. Not only have the speed improvements kept up with or exceeded Moore's Law, but each successive generation of graphics architecture has expanded the feature set. Despite these great improvements, many applications cannot run at interactive rates on modern hardware. Examples include scientific visualization of large data sets, photo-realistic rendering, low-latency virtual reality, and large-scale display systems. A primary goal in graphics research is finding ways to push this performance envelope, from the details of the chip architecture to the overall system architecture.

The past few years have also marked a turning point in the history of computer graphics. Two decades ago, interactive 3D graphics systems were found only at large institutions. As semiconductor technologies improved, graphics architects found innovative ways to place more functionality on fewer chips, and interactive graphics workstations made their way to the desktops of engineers. Today, the entire graphics pipeline can be placed on a single chip and sold at a mass-market price point. Because of the enormous economies of scale afforded by commodity parts, this trend has a significant impact on how high-end systems must be built: it is much more cost effective to design a single low-end, high-volume system and replicate it in an efficient manner in order to create high-end, low-volume systems. For example, supercomputers used to be designed with unique, proprietary architectures and esoteric technologies. As microprocessors became commodity parts, these designs were replaced by highly parallel multiprocessor systems that made use of microprocessor technology.

In this thesis we examine graphics architectures from a perspective of scalability. We consider not only how well a particular implementation of an architecture works, but also how that architecture's performance scales with increasing parallelism. From our observations of existing architectures, we synthesize a new architecture, called "Pomegranate." The Pomegranate architecture, described in chapter 5, provides a way of scaling the base unit of a single graphics pipeline to create higher performance systems, with near linear performance increases in all of our graphics performance metrics.

In many fields, parallelism is employed not to solve the same problem faster, but instead to solve a bigger problem at the same speed. This is particularly true of interactive computer graphics. Humans interact well at frame rates between approximately 100Hz and 1Hz. Above 100Hz the improved performance is not perceivable, and below 1Hz the system loses interactivity. Thus, parallel graphics is generally used to visualize bigger problems, rather than the same problems faster.

This has a profound effect on how parallelism is managed. If we expect a system that is twice as large to be used to render scenes that are twice as large, then approaches which perform broadcast communication proportional to the size of the input, either over interconnects or by replicating memory, have a cost that grows as $O(n^2)$ – each of n units will require communication that scales as n. In order to be a truly scalable graphics architecture, Pomegranate was specifically designed to avoid the use of broadcast communication, and in chapter 7 we demonstrate its efficiency, and compare its performance to other graphics architectures.

1.5 Summary of Original Contributions

The original contributions of this work are in two areas. First, we present an analysis of parallel graphics architecture based on communication:

- **Extended Taxonomy** We present a detailed discussion of the types of communication used in parallel graphics. We distinguish four kinds of communication: *sorting*, which connects object and image parallel stages, *distribution*, which connects object parallel stages, *routing*, which connects image parallel stages, and *texturing*, which connects untextured fragments with texture samples. We show that while sorting has been the traditional focus of parallel graphics architecture, distribution, routing and texturing are just as critical. This motivates our introduction of an extended taxonomy of parallel graphics architecture. Our taxonomy more accurately describes the location of the sort, in particular distinguishing architecture which *sort fragments* from those which *composite images*. We analyze several hardware and software graphics architectures under our taxonomy, focusing on their use of communication and parallelism, and the resulting ramifications on the architecture's scalability.

- **Insight to Limitations** We analyze the limitations of the architectures described under our taxonomy. We discuss the importance of the application visibility of work, so that the efficiency of the graphics system will depend only on application visible characteristics of the input. We consider the limitations of image parallelism, and argue that deferring image parallelism until fragment processing has strong advantages. We examine approaches to solving the limitations of a serial interface and conclude that for many applications a parallel interface is the only appropriate solution. Finally, we discuss the impact of efficiently supporting texturing, and conclude that object-parallel or coarse granularity image parallelism should be used.

Then we present Pomegranate, a new, fully scalable, graphics architecture. We originally described Pomegranate in [Eldridge et al., 2000], the description here is significantly expanded:

- **Designed for Communication Efficiency** Pomegranate's parallelism is chosen to not require the use of broadcast communication, but only general all-to-all communication. As a result, Pomegranate requires total interconnect bandwidth proportional to the number of pipelines. We demonstrate the achieved efficiency of Pomegranate's communication scheme, and discuss ways to address imbalances at high degrees of parallelism.
- **Scalable in All Performance Metrics** Pomegranate provides scalable input bandwidth, geometry rate, pixel rate, texture memory, and display bandwidth. Pomegranate is the first parallel graphics architecture to offer scalability in all these metrics. We show how the structure of Pomegranate's parallelism insures this scalability, and we present simulation results to validate our claims.
- **Support for Parallel Input** We support a parallel interface to the hardware that allows multiple applications to submit commands simultaneously and independently to the hardware. Familiar parallel programming primitives extend the API and express ordering constraints between the execution of these commands. We demonstrate the efficiency of Pomegranate's parallel interface with parallel applications that submit work with both partial and total orders.
- **Novel Ordering Mechanisms** We describe novel ordering mechanisms that we use to provide support for the ordered semantics of a serial command stream, and for the correct interleaving of multiple command streams under our parallel interface. We discuss the efficiency of this approach, as well as its ultimate performance limitations, which are reflected in a minimum granularity parallel work, and eventual communication limitations at high degrees of parallelism. We consider utilizing a dedicated communication mechanism as a possible solution to the second problem.
- **Simulated Performance to 64 Pipelines** We have constructed a detailed simulation of the Pomegranate architecture. We simulate Pomegranate's performance on three different applications, from 1 to 64 pipelines. We demonstrate excellent scalability, with 87% to 99% parallel efficiency on 64-pipeline systems.

- **Comparison to Other Architectures** By restructuring the Pomegranate simulator, we compare Pomegranate's performance to sort-first, sort-middle, and sort-last architectures. We find performance problems for each of these architectures on different applications. We examine the causes of the observed performance, and discuss how Pomegranate addresses these problems to obtain scalable performance.

We conclude by discussing design choices made in the Pomegranate architecture, and speculating on what choices might be appropriate in the future.

Chapter 2

Graphics Pipeline

The graphics pipeline described in the introduction is an OpenGL-style pipeline. We repeat the pipeline diagram in figure 2.1. A more detailed description of the OpenGL pipeline can be found in the OpenGL Reference Manual [OpenGL Architecture Review Board, 1997] and the OpenGL specification [Segal and Akeley, 1999]. We now discuss our motivation for choosing an OpenGL pipeline model, and the alternative choices that could have been made. We will also define our choice of terminology for describing graphics architectures. Given our pipeline model, we provide a detailed accounting of the cost of communication within the pipeline, and explain our extension of the graphics pipeline to accommodate a parallel interface.

We present a baseline set of graphics pipeline functionality in this work, but our discussion and analyses do not preclude extensions and changes to the pipeline. For example, some current graphics pipelines, and likely more pipelines in the future, include support in the geometry processor for tessellation of input primitives. While this will change some specific details of the pipeline operation – for example, it will affect the ratio of input bandwidth to the number of rasterization primitives – our fundamental analysis of graphics architectures remains the same.

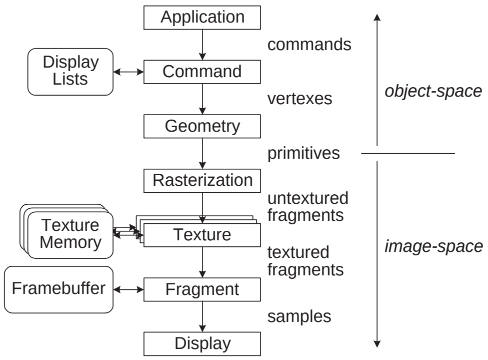


Figure 2.1: Graphics Pipeline Model

2.1 Choices

From an implementation point of view, the OpenGL pipeline is a long sequence of operations, with associated pieces of state that control the operation of various stages. For example, the API call `glBlendFunc` controls how fragments are combined with the framebuffer. As commands are submitted to the hardware, via the OpenGL API, they are executed more or less immediately, without, for example, waiting for an explicit command to cause the scene to be rendered. OpenGL specifies ordered semantics, analogous to those found in most pipelined microprocessor pipelines. Despite any internal use of parallelism to accelerate its computations, the hardware always appears to execute all commands in the order specified by the application.

This thesis is based on an OpenGL-style pipeline, which specifies a stateful immediate-mode interface with ordered semantics. Although OpenGL has made these particular choices, other decisions could have been made. Other options are discussed next.

The graphics interface may either be immediate-mode or retained-mode. An immediate-mode interface allows the application to specify commands directly to the pipeline which are then rendered, more or less immediately. Such an interface provides the greatest flexibility for the application, and readily supports time-varying and dynamic content. A retained-mode interface builds an internal representation of the scene, which is then traversed to generate the output image. Extensive facilities may be provided to allow the application to edit this retained representation. Retained-mode interfaces are typically used to attain performance higher than that which is possible through an immediate-mode interface (due to application limited submission bandwidth) or to avoid addressing the complexities of an immediate-mode interface. Immediate-mode interfaces may also support retained-mode constructs, for convenience and potentially for improved performance. OpenGL supports a retained-mode within its immediate-mode interface via display lists.

A stateful interface has the semantics of a persistent pipeline configuration, which is modified via API calls. A stateless interface bundles the pipeline configuration with each primitive or batch of primitives. The advantage of a stateless interface is that different batches of primitives may be processed independently, as there can be no dependencies between them, except for their effects on the framebuffer. Stateful interfaces have the disadvantage that they may limit the available parallelism, by requiring that the entire command stream be observed to know the value of any particular piece of the state.[1] The advantage of a stateful interface is that the configuration of the pipeline need only be communicated when it is changed, rather than with each batch of primitives. The distinction we have drawn is at the interface, but similar choices may be made within the hardware itself. For example, many software rendering systems maintain a stateful interface for programmer convenience, but internally operate in a stateless fashion, to avoid the difficulties of dealing with state maintenance. Typically immediate-mode interfaces are stateful, as it provides a natural programming model and can greatly lessen the interface bandwidth to the pipeline. Retained-mode interfaces may be either stateful or not.

Ordered semantics have the same meaning for a graphics pipeline as they do for conventional processing: commands appear to execute in the order specified. However, the order of execution of a command is only visible via its effects on the state. Thus the pipeline is free to execute commands in any order, as long as the observed state of the system is the same as if the commands had been performed in exactly the order specified.

There are three main pieces of state in the graphics pipeline: the framebuffer, the texture

[1] In section 8.5 we will discuss vertex arrays, which specifically relax this requirement to allow higher performance implementations.

memory, and the pipeline configuration. The framebuffer is probably the most challenging piece of state to manage.[2] A great deal of parallel graphics architecture has dealt with how to provide parallel access to the framebuffer in a load-balanced fashion, while maintaining semantics desirable to the programmer. Texture memory, although generally larger than the framebuffer, is usually an easier management problem because it is largely read-only, and thus the ordering problems which plague the framebuffer may be avoided by taking some care when textures are modified. Pipeline configuration is the final piece of state to manage. Assuming that the architects have gone to the trouble to support ordering at the framebuffer, which falls at the end of the pipeline, then ordering the commands which modify the pipeline configuration leading up to the framebuffer is straightforward. The same mechanism that maintains the ordering of primitives until the framebuffer can be reused to order the configuration commands. In fact, when these configuration commands are not ordered by the same mechanism, but are instead executed via a sideband path, it is typically a source of lost performance, because the pipeline must be flushed before the commands can be executed.

When ordering is not fully supported it has typically been relaxed or eliminated at the framebuffer, removing the guarantee that fragments are composited in the order their corresponding primitives were submitted. While this relaxation may be acceptable for depth-composited rendering, it practically eliminates the possibility of supporting transparency, and other techniques which rely on program controlled compositing order. Note that the ordering requirements at the framebuffer are in fact fairly relaxed already. In particular, order is only visible on a pixel-by-pixel basis. Thus an architecture with many image parallel fragment processors need not coordinate the processors in general – as long as each does its work in order, the overall set of work is done in order.

Systems with a stateless interface, or those that are stateless internally, may further relax ordering. Such systems can carry the pipeline and texture configuration along with each batch of primitives, and thus batches of primitives can be readily reordered. IRIS Performer, a scene graph library built on top of OpenGL, specifically disallows particular

[2] Interestingly, the OpenGL graphics system specification [Segal and Akeley, 1999] describes operations that are performed on the framebuffer, but the framebuffer is not actually part of the graphics state. Unlike texture and the pipeline configuration, the framebuffer is always shared among all of the graphics contexts, and is thus part of the window system state.

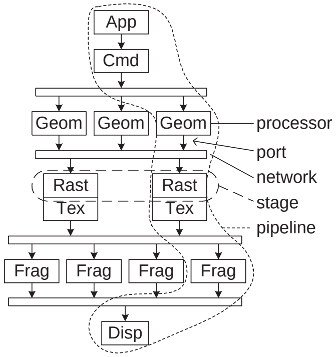


Figure 2.2: A parallel graphics architecture is composed of multiple *pipelines*, each of which is made up of a sequence of *processors*. A horizontal slice across all the pipelines containing all of the instances of a given unit makes up a *stage*. General communication occurs over *networks*, shown as rectangles, and each unit interfaces with the network via a *port*.

forms of state inheritance, which allows them to perform many optimizations when rendering the scene [Rohlf and Helman, 1994]. For example, entire subgraphs may be culled if they are outside of the viewing frustum, and no energy needs to be spent examining the effects of the culled nodes on the state, because by definition they cannot have any effect.[3] Similarly, Performer may sort all of the geometry to be rendered by state configuration, thus minimizing the number of potentially expensive configuration changes in the hardware.

2.2 Terminology

The terminology we will use to describe the parts of a parallel graphics architecture, as well as our style of drawing these architectures, is defined in figure 2.2. The graphics pipeline is made up of a sequence of functional blocks, referred to abstractly as *processors*. A set of identical processors, e.g. all of the rasterizers, are collectively referred to as a *stage*.

[3] Technically, a node in the scene graph saves all of the state it will modify, and restores the state after its execution. Thus state is inherited top-down, but not left-to-right.

We refer to a set of processors that together would form a serial graphics pipeline as a *pipeline*, recognizing that the actual architecture may not consist of simple replications of this pipeline. For example, there may be twice as many fragment processors as there are rasterizers. The stages of the architecture can be interconnected in many ways, which we represent schematically. If two units only communicate with each other, and are located in the same package, they are abutted to show this relationship. For example, the rasterizers and texture processors are paired in the fictitious architecture in figure 2.2. If the two units of a pair are connected by external communication this is shown by an arrow between them, as in the application and command processors which are connected by the host I/O subsystem. Shared communication mechanisms, connecting one or more sources to one or more sinks, are depicted as rectangles. We refer to such shared mechanisms as *networks* and each source and sink has a *port* in to or out of the network.

2.3 Communication Costs

Given our graphics pipeline model, we can now examine the cost of communication at various points in the pipeline. Figure 2.3 summarizes the bandwidth required for a modern graphics pipeline operating at 20 Mvert/sec and 400 Mpixel/sec. A detailed counting of the data communicated in the pipeline is provided in table 2.3. Most architectures will not use communication at all these points in the pipeline. For example, the rasterizer and texture processor may be coupled, in which case untextured fragments are passed internally between the units.

The cost of communication presented here is representative, and may be less (or more) in practice. Texture reads are often blocked, for example a 4×4 texel read, which amortizes the cost of the texture address down to a few bits per texel. When communicating textured or untextured fragments it is common to send a small stamp of fragments, for example a 2×2 fragment quad, reducing the overhead of encoding position and allowing depth to be encoded more compactly as the z of one fragment and z slopes in x and y. Sample masks readily extend such a fragment-encoding scheme to efficiently transmitting super-sampled fragments.

Although we have not yet discussed parallelism, we can already draw some conclusions

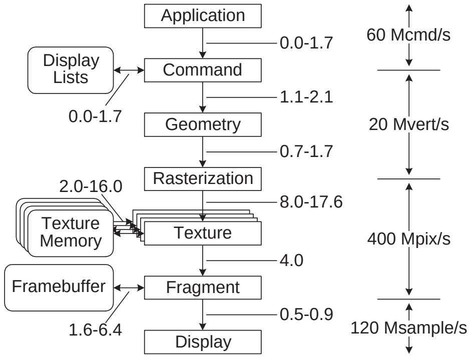


Figure 2.3: Communication bandwidths in gigabytes per second for a 20 Mvert/sec, 400 Mpixel/sec graphics pipeline with a 1600×1200 display. Input bandwidth from the application may be traded off against internal bandwidth from display list memory. The texture memory bandwidth assumes a read of 2 texels per fragment per active texture, 16 or 32-bit textures, and 1 to 4 active textures. The framebuffer memory bandwidth assumes a best case of a depth read and reject, and a worst case of reading and writing depth and color.

about the use of communication. For example, communication before geometry processing, as typified by a sort-first architecture, is comparable in expense to communication between geometry and rasterization, as in a sort-middle architecture. Furthermore, assuming the trend of increasing per-fragment complexity continues (multiple textures, per-fragment lighting, etc.) then the cost of communicating fragments between rasterization and texturing can become quite high, while the cost of communicating fragments after texturing remains relatively fixed.

It is interesting to note that as primitives become smaller and have more parameters (multiple texture coordinates, separate diffuse and specular color, etc.) the cost of communicating textured fragments becomes more and more favorable when compared to communicating primitives, and at approximately 8 pixel triangles they are equal. Thus, in the future, fragment-sorting architectures may be preferable to geometry-sorting architectures

		precision	bits
Commands			
glVertex3f	x, y, z	32	96
glColor4f	r, g, b, a	32	128
glNormal3f	n_x, n_y, n_z	32	96
glTexCoord2f	s, t	32	64
glMultiTexCoord2f (0-3)	tex, s, t	32	0-288
total			**384-672**
Vertexes			
position	x, y, z	32	96
color	r, g, b, a	32	128
normal	n_x, n_y, n_z	32	96
texture (1-4)	s, t, r, q	32	128-512
total			**448-832**
Primitives			
position	x, y	16	32
depth	z, w	32	64
color	r, g, b, a	16	64
texture (1-4)	s, t, r, q	32	128-512
total			**288-672**
Untextured Fragments			
position	x, y	12	24
depth	z	24	24
color	r, g, b, a	12	48
texture (1-4)	s, t, r, q	16	64-256
total			**160-352**
Texels			
address	a	24-32	24-32
color	r, g, b, a	4-8	16-32
total			**40-64**

Table 2.1: Communication cost between pipeline stages. (cont.)

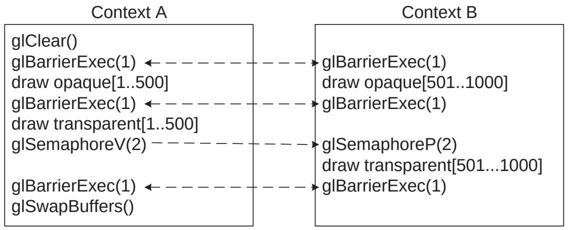
		precision	bits
Textured Fragments			
position	*x*, *y*	12	24
depth	*z*	24	24
color	*r*, *g*, *b*, *a*	8	32
total			**80**
Samples			
color	*r*, *g*, *b*	8	24
depth	*z*	0-24	0-24
total			**36-60**

Table 2.1: Communication cost between pipeline stages. Commands are either written to DMA buffers and prefixed with opcodes, or in some cases written directly to the hardware, with the opcode implicit in the address of the write. Vertices are passed between the command processor and geometry unit, and may be fully expanded, encoding all the vertex properties, or may be passed along incrementally, only transmitting those attributes which have changed since the last vertex. The geometry unit transmits primitives to the rasterization units, and may take advantage of meshing information and send only the new vertices for each primitive, or may send each primitive independently. The rasterizer sends untextured fragments to the texture processor, which then emits textured fragments to the fragment processor. Finally the fragment processor sends samples to the display processor, which include no *x*, *y* position information because the information is typically implicit, as the fragments are sent in raster order, although *z* would be included in a depth-compositing architecture.

purely from a bandwidth perspective. We will show later that there are good reasons to prefer fragment sorting to geometry sorting, even at the cost of increased communication bandwidth.

2.4 Parallel Interface

While building internally parallel graphics hardware is challenging in its own right, modern graphics accelerators often outstrip the ability of the host interface to supply them with data. Igehy, Stoll and Hanrahan introduced a parallel API for graphics to address this bandwidth limitation [Igehy et al., 1998b]. The parallel API extends OpenGL with synchronization primitives that express ordering relationships between two or more graphics contexts that



```
Context A                         Context B
glClear()
glBarrierExec(1)                  glBarrierExec(1)
draw opaque[1..500]               draw opaque[501..1000]
glBarrierExec(1)                  glBarrierExec(1)
draw transparent[1..500]
glSemaphoreV(2)                   glSemaphoreP(2)
                                  draw transparent[501...1000]
glBarrierExec(1)                  glBarrierExec(1)
glSwapBuffers()
```

Figure 2.4: Parallel API Example. The scene to be rendered consists of 1000 opaque primitives and 1000 transparent primitives. The opaque primitives are rendered with depth compositing enabled, and the transparent primitives are rendered in back to front order. The pseudocode uses two contexts to submit this scene in parallel. The first barrier ensures that the clear performed by context A is complete before context B starts drawing. The second barrier ensures that all the opaque primitives are drawn before any transparent primitives. The semaphore pair ensures that context A's half of the transparent primitives are drawn first. The final barrier ensures that all drawing is done before the swapbuffers occurs.

simultaneously submit commands to the hardware. The significance of these primitives is that they do not execute at the application level, which allows the application threads to execute past the synchronization primitives and continue submitting work. These synchronization commands are then later executed by the graphics system. This allows the programmer to order the execution of the various contexts without being reduced to using a serial interface. The primitives we focus our attention on are barriers and semaphores.

A barrier synchronizes the execution of multiple graphics contexts, ensuring that all of the commands executed by any of the contexts previous to the barrier have completed before any of the commands subsequent to the barrier have any effect. A barrier is defined with `glBarrierCreate` (*name*, *count*), which associates a graphics barrier that has *count* contexts participating in it with *name*. A graphics context enters a barrier by calling `glBarrierExec` (*name*). A semaphore provides a point-to-point ordering constraint, and acts as a shared counter. A semaphore "V" (or up) operation atomically increments the counter. A semaphore "P" (or down) operation blocks until the counter is greater than zero, and then atomically decrements the counter. A semaphore is defined with `glSemaphoreCreate` (*name*, *initialCount*), V'd by `glSemaphoreV` (*name*) and P'd by `glSemaphoreP` (*name*). Figure 2.4 provides an example of the use of these primitives.

Chapter 3

Parallelism and Communication

Parallelism and communication are intimately connected. Communication allows us to merge the parallel computation of an image to generate a display, as well as to split a serial input to process it in parallel. We will first discuss the forms of parallelism available in parallel graphics, and then the use of communication to allow this parallelism to be exploited.

3.1 Parallelism

There are two broad forms of parallelism to exploit in parallel graphics:

- **Task Parallelism** performs some or all of the various stages of the graphics pipeline simultaneously.
- **Data Parallelism** duplicates some or all of the stages of the graphics pipeline to process multiple primitives simultaneously.

Task parallelism is the most commonly exploited form of parallelism. Because primitives require varying amounts of work as they progress through the pipeline, exploiting task parallelism requires choosing the ratio of performance between various pipeline stages. One of the choices is the ratio of rasterization to geometry performance. For many modern graphics pipelines the balance is approximately 20:1, in other words there are 20 pixels of rasterization performance for every 1 vertex of geometry performance. Because the computation per primitive varies throughout the pipeline, and depends on characteristics of the input not known a priori (the primitive size), the operation of pipeline will generally be limited by a single stage, rather than taxing all pipeline stages equally. Moreover, most scenes exhibit a skewed input distribution, with almost all of the primitives much smaller than the balanced primitive size, and a few primitives being very large. The result can be that while the rasterizer processes a large primitive the geometry processor sits idle, waiting for the rasterizer to accept subsequent primitives. The affect can be mitigated by introducing buffering between stages, particularly at those points where work may expand. For example, SGI's InfiniteReality includes a 65,536 vertex FIFO between the geometry processors and the rasterization processors to allow the geometry processors to continue to make forward progress while the rasterization processors are rasterizing a large triangle or triangles [Montrym et al., 1997].

Although task parallelism has challenges of its own, we are primarily concerned with the use of data parallelism. Data parallelism allows the combination of multiple graphics pipelines to achieve higher levels of performance, limited only by the efficiency of the resulting combined system. We can further divide data parallelism into two categories, based on the granularity of parallelism:

- **Interframe Parallelism** computes multiple frames in parallel.
- **Intraframe Parallelism** computes a single frame in parallel.

Interframe parallelism increases frame throughput, without decreasing frame latency. For many applications, such as rendering the frames of a movie, it may be acceptable to not address latency. However, interactive computer graphics is generally restricted to operate at human time scales, which limits acceptable latency to a hundred milliseconds or less in many cases. Thus interframe parallel approaches remain limited by the performance of a single pipeline – as soon as the rendering time for the scene on one pipeline exceeds the user's latency tolerance, the system ceases to scale. This generally limits such systems to low degrees of parallelism. Despite its disadvantages, interframe parallelism has the significant advantage of being straightforward to exploit, and in many cases may be readily

I	output image area
T	image parallelism tile size
n	number of pipelines, or processors
d	average depth complexity
O	average overlap factor

Table 3.1: Analysis Notation

retrofitted onto an existing graphics system. For example, SGI's SkyWriter system could compute 2 frames in parallel, and was implemented as a small set of extensions to their VGXT architecture [Silicon Graphics, c 1990a, Silicon Graphics, c 1990b].

Intraframe parallelism can both increase frame throughput and decrease frame latency, by computing a single frame in parallel. Thus, doubling both the size of the input and the size of the graphics system will ideally maintain a constant framerate under both inter- and intra-frame parallelism, but intraframe parallelism may also maintain a constant frame latency. Consequently, the remainder of this thesis will focus on the issues of dealing with intraframe parallelism.

We divide our discussion of intraframe parallelism, referred to hereafter as just parallelism, into two categories:

- **Object Parallelism** partitions the input across parallel processing elements.
- **Image Parallelism** partitions the output across parallel processing elements.

Object parallelism divides the rendering work by distributing objects (primitives, fragments, etc.) among the processors of a pipeline stage, typically in a round-robin or work-balanced fashion. Image parallelism divides the rendering work by partitioning responsibility for the output image over the processors of a stage, and then routing work to those functional units whose partition it overlaps. We refer to the notation defined in table 3.1 for our analysis of parallelism and communication in this chapter, as well as analyses in subsequent chapters.

3.1.1 Object Parallelism

An object parallel pipeline stage partitions the input work across its processors. This partition may be done in a simple round-robin fashion, in a work-balanced fashion, or in many other ways.

The challenge of an object parallel stage, and in general any form of parallelism, is *load imbalance*. The load imbalance is the ratio of the maximum amount of work performed by any processor in the stage, divided by the average amount of work per processor in that stage. The load balance of an object parallel stage can be completely controlled by the choice of work distribution. There are two obstacles to obtaining a good distribution of work. First, it may be difficult to estimate the amount of time required for a particular computation. Second, if the source of the work is also parallel, it may require the multiple work sources to coordinate their distribution, although if each source individually attempts to balance its distribution, that may be adequate.

In an architecture with ordered semantics, the user-specified order of commands must be tracked as those commands are distributed, so the outputs of the stage may be processed in order by subsequent stages. If the work has been distributed in a round-robin fashion, it may be possible to reorder the output by duplicating the round-robin order. With more complicated distribution schemes the ordering information may have to be explicitly passed through the stage. The maintenance of user-specified order has led many architectures which use object parallelism to introduce a point of serialization after an object parallel stage, in order to enforce the ordered semantics. We will see later that this point of serialization can be expensive, although there are systems which distribute this ordering operation.

3.1.2 Image Parallelism

An image parallel stage partitions the output work across its processors. Because the partition is by image coordinates of the work, image parallelism requires that we know, at least conservatively, where each piece of work lies on the screen. Moreover, a piece of parallel work must be routed to all the partitions it overlaps, so, unlike object parallelism, image parallelism can introduce duplicated communication and duplicated computation. The number of partitions that a block of parallel work intersects is the *overlap factor*.

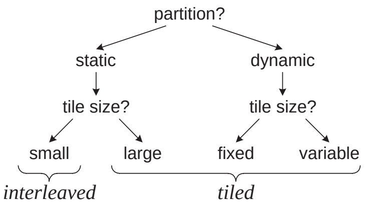


Figure 3.1: Image Parallelism Choices. The screen may be partitioned either statically, with a fixed assignment of pixels to processors, or dynamically, with an assignment determined on a per-frame basis, or even dynamically during the course of a frame. When statically partitioned the tiles can either be made small, insuring an excellent load balance at the cost of a higher overlap factor, or large, for a hopefully lower overlap factor, at the cost of a potentially higher load imbalance. When dynamically partitioned the tiles will typically be large, and may even be variably sized, so that the minimum number of tiles can be assigned to each processor while maintaining a good load balance.

The parallel efficiency of the stage will be determined by the load imbalance of the partitions and the average overlap factor. Both the load imbalance and the overlap factor effectively multiply the input rate seen at a processor, although in slightly different ways. A load imbalance means that each processor gets a different share of the work, and in particular one processor will get more than its fair share of the work. Overlap, which is independent of any load imbalance, means that a given piece of work is processed by more than one processor.

Typically load imbalance is a greater issue for image parallel schemes than object parallel schemes, because the units responsible for a given piece of work are determined solely by that work's screen-space extent. Thus, if the work is not uniformly distributed over the screen, which it generally is not, some partitions will likely have more work than others. This imbalance is exacerbated by temporal effects. The input to a graphics system generally exhibits a large amount of temporal coherence in output space, thus if a piece of work overlaps a partition, subsequent pieces of work are also likely to overlap that partition, which can result in intraframe load imbalances. These effects are typically mitigated by subdividing the output space into more regions than there are processors, and assigning multiple regions to each processor. In the limit, each tile is only a single pixel, and the load balance can be made nearly ideal. Unfortunately, unless the granularity of work is a single pixel as well, the price of an improved load balance is an increased overlap factor, and a balance must be struck between these two effects. Figure 3.1 describes the choices that can be made when partitioning image parallelism.

A detailed discussion of image tiling schemes is outside of the scope of this thesis. We will confine our discussion to the differences in communication between these approaches, which we broadly classify as *interleaved* and *tiled*. Interleaved parallelism uses a fine interleaving of the screen across the stages, and specifically assumes that the tile size is small enough compared to the average piece of parallel work that each piece of work overlaps all the partitions, and consequently all work is broadcast from the previous stage. Tiled parallelism typically uses a coarser tiling than interleaved parallelism, but specifically differs in that it does not assume that each piece of work overlaps all the partitions, but instead sends the work to only those partitions it overlaps. Chen et al. put forth models of the impact of overlap for tiled rendering, and verify their models experimentally [Chen et al., 1998].

In 1977 Fuchs described an architecture for parallel polygon rasterization which was based on a central unit broadcasting primitive descriptions to a set of processing elements with finely interleaved (1 pixel granularity) responsibility for the screen [Fuchs, 1977]. Fuchs and Johnson went on to more fully describe a system based on this architecture in 1979 [Fuchs and Johnson, 1979]. They stressed the near limitless scalability of this system, in which sets of processing boards and associated memory units could be plugged into a backplane bus which distributes the broadcast polygons as well as the output video signal. Although broadcast buses were de rigueur at the time, it is interesting that they made no mention of the bandwidth of this bus, or the accompanying calculation of the maximum rate at which primitives could be broadcast on the bus, which would obviously limit their performance once adequate rasterization parallelism was provided.

In a 1980 paper Parke describes an architecture for tiled rasterization [Parke, 1980]. Unlike Fuchs's use of broadcast communication, Parke uses a dynamic routing network with "splitter" units that build a tree network. Each splitter recursively divides the screen in half, routing input work appropriately. Although Parke's system only had a single source of geometry, it was clearly on the path to a scalable switch interconnect. Parke makes a number of trenchant observations, both about the earlier interleaved proposal of Fuchs and about his own architecture.

Referring to Fuchs's architecture, Parke states:

> "The broadcast approach suffers from the fact that each processor must deal with every polygon and every edge. This results in performance which approaches a polygon-edge overhead value as additional processors are added rather than approaching zero."

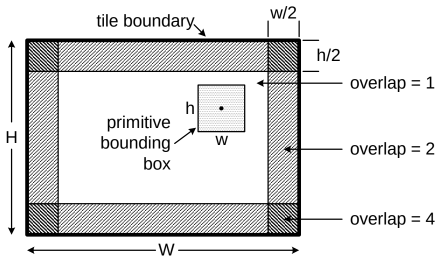
Here Parke has drawn out one of the essential limitations of all schemes which rely on broadcast parallelism. There is a fixed cost to dealing with each piece of work, so increasing parallelism can do no better than this fixed overhead.

Later, referring to his own architecture, Parke says:

> "The splitter architecture depends on a uniformly distributed image environment. If the environment is not uniformly distributed, it is possible to saturate a branch of the splitter tree while the other branches are idle. The worst case is when all the image description primitives lie in a single region. For this case only one single image processor will be active, the rest remaining idle."

Parke identifies that the limitation of an approach with coarse-grained parallelism is sensitivity to the image load balance. He describes a hybrid architecture to merge the strengths of an interleaved and a tiled approach to rasterization. This architecture uses his splitter units for the initial stages of communication, but instead of fully expanding the tree so that each tile is the responsibility of a single processor, he truncates the tree and makes each tile the interleaved responsibility of a number of processors. By choosing the depth of this tree the overhead of broadcasting primitives to multiple processors can be balanced against the potential load imbalance of tiling.

Molnar et al. provide an estimate of the overlap factor O [Molnar et al., 1994]. We define the size of a tile as $W \times H$, and the average primitive bounding box as $w \times h$, as shown in the figure below, after the figure of Molnar et al.



The center of the primitive can fall anywhere with respect to a tile. In particular, it can fall within a corner, in which case it overlaps this region and the three adjacent regions, with probability

$$\frac{4(w/2)(h/2)}{WH}$$

The primitive may fall along an edge, but not in a corner, in which case it overlaps two regions, with probability

$$\frac{2(w/2)(H-h)+2(W-w)(h/2)}{WH}$$

Finally, the primitive may lie within the center of the tile, in which case it overlaps just this tile, with probability

$$\frac{(W-w)(H-h)}{WH}$$

The overlap factor O is the expected number of overlapped tiles, which is simply these probabilities weighted by the resulting overlap of a primitive falling in each of these regions.

$$O = \left(\frac{W+w}{W}\right)\left(\frac{H+h}{H}\right)$$

This equation has the expected behavior that when the tile size is much larger than the primitive bounding box ($W \gg w$ and $H \gg h$) the overlap factor approaches one and when the primitives are large compared to the tile area ($w \gg W$ and $h \gg H$) the overlap factor approaches the ratio of the primitive area to the tile area. Another useful way to view this

equation is as

$$O = \left(1+\frac{w}{W}\right)\left(1+\frac{h}{H}\right)$$

which makes clear that all that is important is the ratio of the primitive edge to the tile edge. If the screen size is doubled, which doubles the primitive size, and the tile size is doubled, then obviously the overlap factor remains unchanged.

3.1.3 Object Parallel to Image Parallel Transition

The input to the graphics systems always provides us with object parallelism, as the application is specifying primitives. Similarly, the output of the graphics system always uses image parallelism, because the final output is a stream of pixels to a display device. Between the input and the output of the graphics system we have the flexibility to use object parallelism and image parallelism as we see fit.

Most architectures transition exactly once from object to image parallelism, and never back to object parallelism. This is most readily explained by the implicit maintenance of order used in image parallel stages of the pipeline. When two image parallel stages are connected and the partition of the output space changes between them, no special effort needs to be made to maintain ordered semantics – as long as all the units in the first stage did their work in order, all the units in the second stage will receive in order work. Any interleaving of the work received by the second stage is acceptable, because the different streams of work affect different sets of pixels, and will have no affect on each other. Although this makes it most natural to use image parallelism for all stages after the sort, we will present two variants of sort-last architectures that break this convention.

3.2 Communication

Communication moves data, in the form of vertices, primitives, textures, fragments, and samples, to computation. To distinguish the purpose of different points of communication, we define four specific types of communication in parallel graphics: sorting, routing, distribution and texturing. *Sorting* communication connects the final object parallel stage with the initial image parallel stage. *Routing* communication interconnects image parallel stages. *Distribution* communication interconnects object parallel stages. *Texture* communication interconnects untextured fragments with texture samples.

Sorting describes the communication stage where an object parallel stage sends parallel work to an image parallel stage and thus sorts the work to the screen. Sorting is characterized by having a deterministic destination for any piece of work – only a single unit is responsible for any given pixel. If the granularity of work being communicated is larger than a single pixel then the communication may have more than a single destination, but the set of destinations remains deterministic.

Routing describes communication between image parallel stages. Although both stages are image parallel, they may use different partitions of the screen. For example, the fragment processing stage may use a fine tiling of the screen, for a good static load balance, while the display processing stage uses a coarse tiling, one monitor per display processor, because it must get all the pixels for a single display to a common point. Because both the source and destination for any particular piece of work are determined solely by image coordinates, we refer to this communication as routing.

Distribution describes communication between object parallel stages. Because both stages are object parallel, the source and destination of any piece of work may be managed by the architecture dynamically to insure a good load balance. The term distribution is meant as a reminder that work is being distributed at these points, presumably in a flexible fashion.

Texture communication describes the communication of untextured fragments and texture data necessary to compute textured fragments. Unlike the other forms of communication, texture communication is disconnected from the particulars of object or image parallelism.

We distinguish the structure of communication as being either broadcast, when each piece of work is transmitted to an entire stage, or one-to-one, when a piece of work is transmitted to a subset of the stage.

Broadcast communication transmits each piece of parallel work to all of the units in the next stage, and thus requires $O(n)$ bandwidth per port to provide scalable performance. Additionally, each unit must be able to accept and process the aggregate command stream of the previous stage. Although the stage will partition the work across the units, there is some fixed cost to each piece of work, which will limit scalability. Using a broadcast protocol typically means that the base units are built to target some maximum degree of parallelism, beyond which the system will not scale well on some performance metrics.

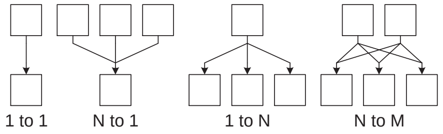


Figure 3.2: Communication Patterns

Point-to-point communication transmits each piece of work to a subset of the units in the next stage, typically only 1, although this will increase with the overlap factor in image parallel stages. Point-to-point communication requires per port bandwidth proportional to the overlap factor. Each functional unit sees a constant rate data stream, which allows point-to-point communication to scale beyond broadcast communication.

3.2.1 Patterns

Communication occurs in four main patterns in graphics architecture, 1 to 1, 1 to N, N to 1, and N to M. These patterns are depicted in figure 3.2. 1 to 1 communication connects stages in the pipeline that are directly coupled. For example, each pipeline's texture processor may only handle the fragments of that pipeline's rasterizer, in which case there is a 1 to 1 connection between them. The next two forms of communication, 1 to N and N to 1, reflect a point of serialization in the system. For example, a system with a serial interface will typically have a single command processor speaking to all the geometry processors. Similarly, a system that supports a single display will typically have all the fragment processors talking to a single display processor. N to M communication occurs where the partitioning of parallel work changes. For example, when the object parallel geometry processors transmit primitives to the image parallel rasterizers in a sort-middle architecture.

The direct connection of 1 to 1 communication is the simplest case to handle. In a multiple chip pipeline implementation, dedicated pins would typically connect the two functional units. If the two units are contained in the same package then the connection is even more straightforward.

The serialization represented by 1 to N or N to 1 communication may have performance ramifications for the architecture (e.g. the system lacks adequate input bandwidth for scalable performance), however, the communication mechanism itself is not the performance limiting factor, but rather the single unit through which all the work is serialized. Because a single point is responsible for either sourcing or sinking all of the communication on the channel, increasing N will further divide the load across the pipelines, but will not increase the per-port cost of the channel. One simple implementation of a 1 to N or N to 1 channel with linear cost is a point-to-point ring.

The challenging pattern is N to M communication. When multiple sources can communicate with multiple destinations, difficult issues arise in building a scalable communication medium. Adding an additional ΔM or ΔN requires that the aggregate bandwidth of the network increase to support the additional units. We now discuss the types of communication used in parallel graphics architecture.

3.2.2 Networks

Communication can be supported on a variety of networks. We will focus on bus, ring and multi-stage indirect networks (MINs). These networks are shown schematically in figure 3.3. Duato, Yalmanchili and Ni are one source for a more detailed examination of these and other networks [Duato et al., 1997].

A bus is a shared communication channel. The bus may only be in use by a single source at a time, and thus requires $O(n)$ bandwidth to support n sources. Moreover, each destination must support the full $O(n)$ bandwidth of the bus. Thus the per-port cost is $O(n)$ and the total bus cost is $O(n^2)$. The primary advantage of a bus is that, although one-to-one communication is very inefficient, broadcast communication is no more expensive. Additionally, arbitration for the bus provides a natural point of serialization, which can provide a convenient mechanism for enforcing the application specified command order. The disadvantage of a bus is that it is difficult to scale, both architecturally and electrically. Buses are architecturally difficult to scale because each source can only fairly occupy the

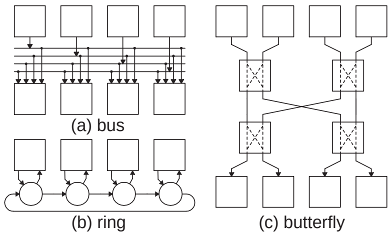

(a) bus
(b) ring
(c) butterfly

Figure 3.3: Communication Interconnects. The bus is depicted as 4 separate lanes to highlight the requirement that the size of the bus be proportional to the number of sources to avoid limiting performance. Ring networks may be employed as a bus interconnect based on point-to-point links, or, as shown here, as a very efficient neighbor-to-neighbor communication mechanism. A butterfly network is one kind of MIN network. It uses external switching elements for communication, and requires a number of stages proportional to the logarithm of the number of sources or destinations.

bus one n^{th} of the time, and therefore the bus width, as well as each source's bus interface, should be proportional to n. Buses are electrically difficult to scale because the distributed load on the wires of bus (the sources and destinations) limits its speed of operation. To address both these problems, buses are typically built to target some maximum degree of parallelism, which limits the scalability of bus-based solutions, and results in the bus being proportionally more expensive when not fully used.

A ring network interconnects multiple units with a series of neighbor-to-neighbor connections. While, for electrical signaling reasons, the speed of operation of a bus actually decreases with an increasing number of sources and destination, a ring network is insensitive to the number of sources and destinations. When used for 1-to-1 communication the average message will travel half way around the network, or one quarter of the way, if the network is bidirectional. Thus, while rings are electrically favorable compared to buses, they are still limited by contention for the link resources. In many architectures, a ring network is used as a broadcast interconnect, with the advantage that all of the wires are point-to-point and as a result may operate much more quickly. A few architectures, most

	cost/port		bandwidth/port			efficiency		
	pins	wires	neighbor	one-to-one	broadcast	neighbor	one-to-one	broadcast
bus	n	n	1	1	1	$1/n$	$1/n$	1
ring	1	1	1	$2/n$	$1/n$	1	$2/n$	1
MIN	1	$\log n$	1	1	$1/n$	$1/\log n$	$1/\log n$	$1/\log n$

Table 3.2: Interconnection Networks. A summary of the cost and performance of bus, ring and multi-stage indirect networks. The cost per port is based on the assumption that each network source requires unit bandwidth, and that one-to-one communication is being performed. The bus network also supports broadcast communication for the same cost, while the ring and MIN would require an n times larger network.

notably those that perform image composition, use the ring network purely for neighbor-to-neighbor communication. In this case there are effectively no scalability limits, because the average message distance is 1, instead of $n/2$. Thus, the addition of a node adds the neighbor-link necessary for it to communicate without increasing the average message distance.

Unlike buses and rings, multi-stage indirect networks, or MINs, use switching elements beyond those provided by the endpoints of the network. Typically the total number of switching elements is $O(n \log n)$, so as the network gets larger the per-port cost of the network is slowly increasing. Thus, while big machines pay for additional switches, small machines do not, so the cost of the network depends on the actual size of the machine, not the maximum size of the machine, as it does with a bus architecture. Indirect networks, as discussed here, are built to support one-to-one communication. That is, a source sends each message to a single destination. In this case, as the number of sources and destinations increases, so does the aggregate traffic handling capacity of the network. We have shown a butterfly network in figure 3.3 as an example of a MIN, other MINs include omega networks, multistage cube networks and fat trees. The primary advantage of a MIN is that it scales readily and its components do not need to be built to target a particular level of parallelism. Unlike a bus however, a MIN is completely distributed, and thus lacks a single point of serialization.

The cost, performance and efficiency of buses, rings and MINs are summarized in table 3.2. We measure the cost of a network as the number of wires it requires per port. This captures both the number of pins it requires, as well as the cost of switching stages incurred in MIN networks. The cost per port assumes the network connects n sources with n destinations. Thus, for example, the cost per port of a bus is $O(n)$, because each source emits unit bandwidth, and they must time-multiplex the bus. The bandwidth per port represents the raw communication capability of each interconnect. The efficiency is the bandwidth per cost, and is probably the most useful measure of a network. The ring network has the best efficiency for neighbor-to-neighbor communication, which is not surprising, given its construction. The bus and ring networks have similar efficiency for broadcast communication, although for the electrical reasons we briefly mentioned, the use of a ring is probably preferable. Finally, the MIN has the best efficiency for one-to-one communication, which we will argue later is the essential communication structure for scalable graphics architectures.

3.2.3 Memory

Communication classically moves data from one place to another over an interconnect. If we consider movement of data from one *time* to another as communication, then memory is just another way to communicate. In fact, the similarity between interconnect and memory as communication is quite strong, particularly in modern architectures. The price determining factor in graphics architectures has shifted from silicon area to package size, or number of pins. Modern high-speed interconnects and high-speed memories have comparable bandwidth per pin (on the order of 1 Gbit/sec), so, at least to first order, the cost of these forms of communication is equivalent. Additionally, both memory and interconnect typically trade increased latency and increased transaction size for increased throughput.

In many cases these two forms of communication, interconnect and memory, are interchangeable. For example, texture can be replicated across the texture processors, providing communication by memory, or the texture can be distributed across the texture processors, and communicated via an interconnect. We consider three broad issues in dealing with memory in graphics systems: tolerating the latency of the memory system, trading replication of memory against communication, and caching memory to avoid more expensive memory accesses.

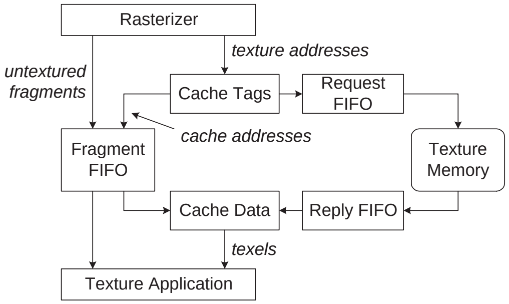


Figure 3.4: Texture Prefetching. The cache tags and cache data are separated temporally by the fragment FIFO. The cache tags are a promise of what will be in the cache when the fragments exit the FIFO.

Tolerating Latency

Although the graphics pipeline is almost exclusively structured as a feed-forward operation, there are a few cases when the pipeline issues a request for information and must wait for a result, in particular at the texture memory system and the framebuffer. Texturing computes the address of a texel or texels in memory, reads those texels, and applies them to the current fragment. The fragment processor typically reads the depth buffer for a fragment, and then conditionally writes the depth and color back to the framebuffer. In both cases the latency of the memory system, the time between the request for data and the receipt of the data, should be hidden to maximize performance.

One well known scheme for hiding memory latency is to temporally separate the generation of the address from the use of the corresponding data, by introducing a FIFO between the appropriate computations. The Talisman architecture uses such a scheme to deal with the very long latency of using compressed textures, which must be decompressed into an on-chip cache before use [Torborg and Kajiya, 1996]. Igehy, Eldridge and Proudfoot describe a texture cache architecture that prefetches texture data before use, completely hiding the latency of the memory system [Igehy et al., 1998a]. Figure 3.4 describes the operation of their architecture. McCormack et al. describe a similar texture read architecture implemented in Neon [McCormack et al., 1998].

It is simpler to tolerate the latency of the texture memory system than that of the framebuffer, because texture accesses are almost exclusively reads. Framebuffer operations are by nature read-modify-writes, and without some care there is a read-after-write hazard in any system that keeps multiple fragments in flight. For example, if two fragments are destined for the same framebuffer location and the depth test is enabled, then the second fragment should only be written to the framebuffer if it passes the depth test *after* the first fragment has either been written to the framebuffer or rejected. If the depth read for the second fragment occurs before the conditional write of the first fragment, then the second fragment may be incorrectly composited. This difficulty is generally addressed with some sort of scoreboard mechanism. McCormack et al. describe Neon's scheduling of 8-fragment batch reads to the memory, with the proviso that none of the fragments in the batch overlap [McCormack et al., 1998]. As soon as a fragment overlaps a fragment already in the batch the entire batch is processed, and a new batch is started with the formerly conflicting fragment. Owens et al. describe a clever scheme that allows them to schedule very large framebuffer reads (hundreds of fragments) efficiently [Owens et al., 2000].

Replication

The choice of whether to structure communication as interconnect or memory is typically an economic one. The cost of replicating memory is that either the replicated resource will not scale in capacity, in which case the cost of the memory is $O(n)$, or if the unique memory does scale with n, the cost of memory is $O(n^2)$. The cost of sharing memory is the engineering effort and expense of providing an interconnect to route memory reads and writes between processors and memories. Of course, this form of communication is often provided – the sort in parallel graphics corresponds to exactly this communication: it routes work to the image parallel processor which owns the corresponding partition of the framebuffer.

The classical use of replicated memory to replace communication is the texture memory subsystem. For example, SGI's RealityEngine [Akeley, 1993] provides a complete copy of the texture memory for each fragment generator (a combined rasterizer and texture processor in our terminology). Each raster memory board consists of 5 fragment generators, and a full-up system with 4 raster memory boards would contain 20 complete copies of the texture memory. While providing ready communication, the downside to this replication is that an increase in the effective texture memory is 20 times more expensive than if the texture memory were shared. InfiniteReality uses a single fragment generator per raster memory board, in large part to reduce the duplication of texture memory [Montrym et al., 1997]. The alternative to replicating texture memory is to share it. Igehy, Eldridge and Hanrahan have studied the practicality of shared texture memory schemes and have found that careful layout of the texture data, so that memory accesses are well distributed over all of the memories, yields excellent results [Igehy et al., 1999]. The disadvantage to sharing texture memory is that it is potentially the highest bandwidth point in the system, and designing an interconnect to handle that bandwidth may be challenging.

Another use of replicated memory is found in sort-last image composition architectures. These architectures replicate the framebuffer per pipeline, transforming the traditional sort in graphics architecture into an image compositing operation. The advantage of this exchange is two-fold. First, in systems where the depth complexity exceeds the number of pipelines, the total communication to generate the output image is $O(nI)$ instead of $O(dI)$. Second, the general communication of sorting commands, primitives or fragments to the appropriate image parallel unit can be replaced by the regular communication of compositing images, which is potentially more easily implemented. For example, PixelFlow uses a pipelined image compositing network, and reduces the majority of the communication in the system to neighbor-to-neighbor communication [Molnar et al., 1992].

Caching

Caching is often combined with memory systems, substituting local memory accesses for remote memory accesses, in much the same way memory can be substituted for interconnect. If we consider the memory as a separate unit from the processor to which it is attached, then they are interconnected by a network (the memory interface), and the cache turns interconnect-based communication (using the memory interface) into memory accesses.

All modern graphics accelerators use caching to minimize texture memory bandwidth. SGI's InfiniteReality graphics system uses a simple request-merging scheme to capture the redundant memory accesses between neighboring fragments, in effect the smallest possible cache [Montrym et al., 1997]. Digital's Neon uses a 2048 byte texel cache, divided into 8 caches, one per memory interface [McCormack et al., 1998]. Although unpublished, numerous consumer graphics accelerators reportedly use multiple kilobyte caches. Data from Igehy et al. demonstrate the effectiveness of reducing texture memory bandwidth with caching in systems which employ serial and parallel rasterization [Igehy et al., 1998a, Igehy et al., 1999]. Hakura and Gupta studied the choice of rasterization algorithm and texture cache organization [Hakura and Gupta, 1997]. Cox, Bhandari and Shantz examined including a second-level cache to capture interframe texture locality [Cox et al., 1998]. Vartanian, Béchennec and Drach-Temam have examined the impact of tiled rasterization patterns in a sort-middle architecture [Vartanian et al., 2000], and the efficiency of parallel texture caching [Vartanian et al., 1998].

While texture caches are dynamically scheduled caches, retained-mode interfaces expose to the programmer a statically schedulable cache. If the application has data which will be rendered multiple times without modification, the programmer can choose to encapsulate that data in a display list, with the advantage that the data may be cached in a display list memory local to the graphics system. Thus display lists can turn communication between the application and the graphics system into local memory references. This has benefit of not only conserving host interface bandwidth, which is often a very limited resource, but also of conserving the host processor's computation.

Chapter 4

Taxonomy and Architectures

Graphics architectures are traditionally classified by the point in the pipeline where they transition from object to image parallelism. This transition is termed the “sort”, because it sorts work based on its screen-space location. The sort can occur between any of the pipeline stages, as shown in figure 4.1. We distinguish four unique sorting architectures: sort-first, sort-middle, sort-last fragment and sort-last image composition.

Sort-first architectures sort before geometry processing. The use of image parallelism for the geometry processing means that the command processor must transform the input vertices, or groups of input vertices, to determine which geometry processors are responsible for their processing. Sort-first architectures typically subdivide the screen into relatively large tiles to reduce the overlap factor of primitive groups. A finely interleaved sort-first architecture would amount to broadcasting the input command stream across all of the pipelines, essentially the simplest possible sort.

Sort-middle architectures sort between geometry processing and rasterization. The geometry processor either transmits individual vertices with meshing information to the rasterizers, or entire primitives, which may already be setup for rasterization. Sort-middle architectures, particularly hardware implementations, typically use interleaved image parallelism (sort-middle interleaved), insuring an excellent static load balance, at the expense of broadcasting primitives between geometry and rasterization. Sort-middle architectures have also been built that use a coarser tiling (sort-middle tiled), which eliminates the broadcast of work between geometry and rasterization, but introduces a potentially difficult load-balancing problem.

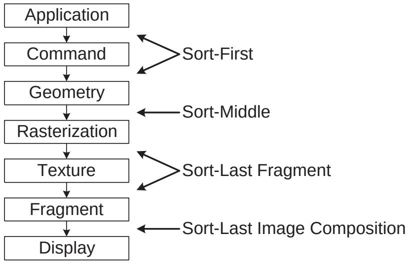


Figure 4.1: Sorting choices.

Sort-last fragment architectures sort after rasterization but before fragment processing. The communication of fragments, which by definition only overlap a single location on the screen, allows the use of a very fine tiling of the screen over fragment processors. This insures an excellent static load balance, without the penalty of a high overlap factor. Sort-last fragment architectures may suffer from geometry and rasterization imbalances, at least in their most straightforward implementations.

Sort-last image composition architectures sort after fragment processing and before display. Image composition architectures, unlike the previous architectures, have communication cost proportional to the output size, instead of the input size. While the image composition network imparts a high initial cost, image composition networks potentially offer better scalability than other architectures because the sorting communication demands on a pipeline are not input dependent. Because the fragment processing stage is object parallel, a given pixel on the screen is the responsibility of each processor which receives a fragment for that location. Thus, any framebuffer operations that are order dependent, including OpenGL features such as blending, stenciling, etc., cannot be supported on an image composition architecture.

While our taxonomy is sufficient to classify most architectures, two particular kinds

Revised	Molnar et al.	Pipeline-Centric	Data-Centric
Sort-First	Sort-First	Geometry-Sorting	Vertex-Sorting
Sort-Middle	Sort-Middle	Rasterization-Sorting	Primitive-Sorting
Sort-Last Fragment	Sort-Last, Sparse	Fragment-Sorting	Fragment-Sorting
Sort-Last Image Comp.	Sort-Last, Full	Display-Sorting	Sample-Sorting

Table 4.1: Revised graphics taxonomy. Our revised taxonomy distinguishes fragment sorting and image composition architectures at the top level, as compared to Molnar et al. which lump them together as varieties of sort-last. We also suggest a pipeline-centric taxonomy, named by the first image-parallel pipeline stage, and a data-centric taxonomy, named by what kind of data is sorted.

of architectures are not immediately classifiable. First, architectures which don't employ image parallelism are not classified under our taxonomy. By definition, the sort is the point where work is sorted based on screen-space location, and in an architecture lacking image parallelism, no such point exists. Of course, even single chip graphics accelerators may employ image parallelism internally, and thus still fall under our taxonomy. Second, and more troublesome, some architectures may actually sort at multiple points. For example, if two sort-middle machines are combined within a sort-last image composition architecture, there is no longer a clear point in the system to identify as the sort. In such cases, our sorting taxonomy classifies machines based on their predominant sort. Thus, such a machine would be termed a sort-last image composition architecture, or, more specifically, a sort-last image composition architecture composed of sort-middle pipelines.

Molnar et al. classified parallel graphics architectures as sort-first, sort-middle or sort-last [Molnar et al., 1994]. In their taxonomy, sort-first architectures sort before the geometry stage, sort-middle architectures sort between geometry and rasterization, and sort-last architectures sort after rasterization. Molnar et al.'s architectural model consisted of a simple two-stage pipeline, comprised of geometry and rasterization. The first stage corresponds to command processing and geometry in our model, and the second stage corresponds to rasterization, texturing and fragment processing. The disadvantage of this model and taxonomy is that it does not distinguish sort-last fragment architectures from image composition architectures, but instead lumps them together as architectures which sort after rasterization. Their taxonomy then subdivides sort-last into "sparse" or "full" varieties, which correspond to sort-last fragment and sort-last image composition in our taxonomy. This implies that fragment sorting architectures and image composition architectures are more closely related than they actually are, and that fragment sorting suffers the disadvantages of image composition architectures. We compare our revised taxonomy with that of Molnar et al., as well as our suggestions for pipeline-centric and data-centric taxonomies, in table 4.1.

For the purposes of the taxonomy, we do not consider where texturing occurs. For many current architectures texturing is coupled with rasterization, although historically it has also been coupled with fragment processing. In some cases the texturing unit was relocated in the pipeline and performed early, as part of geometry processing, or deferred, and performed after fragment processing.

We now examine a number of parallel graphics architectures, from the perspectives of how they employ parallelism and communication, as well as the limits to their parallelism. Of course, in many cases these architectures were constructed as point solutions, and were not intended to be deployed with differing degrees of parallelism. It is still interesting to examine the scalability of these architectures, in order to understand the ultimate limits to their applicability. Table 4.6 on page 67 summarizes the architectures we discuss, along with many architectures not specifically examined in the text.

4.1 Sort-First

Sort-first has historically been the least explored architecture for parallel graphics. One of the principal difficulties of sort-first is partitioning the image over the pipelines. If an interleaved partition of the framebuffer is used, then every geometry processor handles every primitive, and it would have been simpler to construct a sort-middle architecture with a single geometry processor that then fans out to all the rasterizers. Given that sort-first must tile the image, picking an efficient tile size is critical. Smaller tiles will yield a better load balance, but will increase the overlap factor. Larger tiles reduce the overlap factor, but require a good work estimator to insure a balanced distribution of work. Mueller has studied different static and dynamic partitioning schemes for retained-mode sort-first architectures [Mueller, 1995] and determined that a subdivision of the screen which gives each pipeline 10 or more tiles provides a good static load balance. However, as we decrease

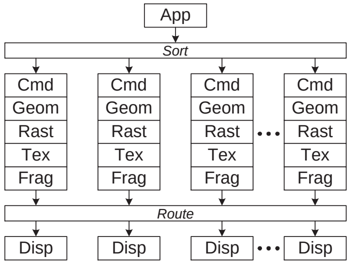


Figure 4.2: Princeton Scalable Display Wall. Princeton's Scalable Display Wall consists of 8 rendering nodes driving a 4 × 2 back-projected display wall. Each node has a complete copy of the retained mode database, and a single master node chooses how to partition the screen and coordinates the renderers. Nodes may render pixels destined for displays other than their own, in which case pixel readback is used to move the pixels to the correct node.

the tile size (increase the number of tiles) to improve the load balance we expect the overlap factor to increase, and no data is presented on this effect.

Interestingly, sort-first has recently reemerged, thanks to the development of high performance consumer graphics accelerators. Combining multiple such accelerators to create a higher-performance graphics systems has been the focus of several recent research projects.

4.1.1 Sort-First Retained-Mode

Sort-first's generally cited advantage is that a retained-mode database may be dynamically migrated among the geometry processors, according to where the geometry currently lies on the screen. Thus the per-frame communication of geometry (the sorting communication) may be minimized, assuming there is significant frame-to-frame coherence. Mueller's results for a software renderer [Mueller, 1997] suggest that this is challenging in practice, and the value is questionable, as the results are very sensitive to the amount of motion in the scene, how quickly the viewer can change their point and direction of view, including simple head rotations, and the amount of instancing in the database.

Samanta et al. [Samanta et al., 1999] describe Princeton's Scalable Display Wall project, one example of a retained-mode sort-first architecture. Their system, depicted in figure 4.2, consists of 8 rendering PCs connected to a single master PC by a gigabit network. Each PC drives a projector, altogether driving a 4 × 2 display wall. Rather than accept the coarse tiling imposed by the physical tiling of the display wall, Samanta's system can decompose the output space along arbitrary boundaries and then use pixel reads and writes to transfer pixels rendered on one node to the node which controls that portion of the output. Frame-to-frame coherence is used to dynamically partition the screen into tiles, with the assumption that the current frame's distribution of work will be very similar to the previous frame. The Princeton system replicates the database on each node, so that geometry never needs to be communicated.

One of the difficulties of retained-mode systems is editing the database. These difficulties may be further exacerbated by systems which migrate the contents of the database around the pipelines, in order to exploit frame-to-frame coherence. Replicating the database further aggravates the editing difficulty, and if the database is substantially edited, the cost of broadcasting the edits may exceed the cost of communicating the primitives instead of replicating the database. Moreover, database replication rapidly limits the scalability of the system. If system size is doubled, in order to render twice as large a scene, then the total memory increases four fold.

4.1.2 Sort-First Immediate-Mode

Although sort-first is generally used with a retained-mode interface, there is no inherent reason why an immediate-mode interface can not be used.

The Stanford WireGL project [Humphreys et al., 2000] uses commercial off-the-shelf graphics accelerators to implement a hardware-accelerated sort-first architecture, depicted in figure 4.3. WireGL exists as a software layer between the application and some number of servers, each with a graphics adapter attached to a display. Typically the server outputs are combined to form a high-resolution tiled display. The primary disadvantage of WireGL is that its partition of the output space, or similarly, the number of pipelines it can use, is determined for it by the number and resolution of output displays. An extension to WireGL

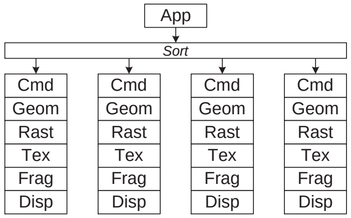


Figure 4.3: WireGL. WireGL is a software layer that sits between the application and one or more unmodified graphics pipelines. By tracking the transformation state of the application WireGL may bucket the command stream and route vertices to only those pipelines which they overlap, as with other sort-first architectures. WireGL uses Myrinet [Boden et al., 1995], a gigabit network technology, to interconnect the computer running the application and the computers hosting the graphics pipelines.

that addresses these issues is discussed in section 4.5.1.

WireGL buckets application commands by their screen extent, transmitting them only to those displays they overlap. WireGL's bucketing applies not only to primitives, but to all state commands [Buck et al., 2000]. When the OpenGL configuration is modified, for example, when the `glBlendFunc` is changed, that information is stored away in a local software copy of the graphics context. The communication of configuration changes to each server is performed lazily, only transmitting the changes to a server when geometry is found to overlap that server. Thus when the configuration is changing frequently, WireGL saves the overhead of transmitting state changes to servers that do not render any primitives with the configuration. This lazy policy extends to all of the state in the system, including textures, and allows WireGL to minimize its use of broadcast communication. The authors present data that demonstrate the efficiency of their immediate-mode interface and lazy state management techniques.

4.2 Sort-Middle

Sort-middle is the most widely implemented and published parallel graphics architecture. Sort-middle architectures can be separated into two distinct categories: interleaved and tiled. Interleaved architectures use interleaved image parallelism, broadcasting each primitive to all rasterizers. Tiled architectures use tiled image parallelism, routing each primitive to only those rasterizers whose partition it overlaps.

4.2.1 Sort-Middle Interleaved

A representative example of a sort-middle interleaved architecture is SGI's InfiniteReality [Montrym et al., 1997], depicted in figure 4.4. InfiniteReality interleaves the screen across the rasterizers in 2-pixel wide vertical stripes, and broadcasts primitives to all the rasterizers. Interestingly, the InfiniteReality only offers scalable rasterization performance – the system always contains 4 geometry processors.[1] Thus, the vertex bus and the rasterizers always need to handle 4 geometry processors, and adding more rasterizers only changes the balance point between geometry and rasterization to correspondingly larger primitives. The authors make a specific point that this interleaving of the rasterizers was chosen to insure load-balanced drawing. However, as a consequence of this choice the vertex bus is a broadcast mechanism, and thus the geometry performance of the system is unscalable – additional geometry units would have no vertex bus bandwidth available.[2]

4.2.2 Sort-Middle Tiled

Unlike sort-middle interleaved architectures, sort-middle tiled architectures to not broadcast primitives between the geometry processors and rasterizers, and thus may scale to higher levels of performance. Tiled architectures have been constructed in two broad

[1] InfiniteReality configurations with only 2 geometry processors were sold, and an 8 geometry processor configuration was demonstrated.

[2] The use of more complicated geometric processing (for example, more lights or more frequent clipping) or image processing operations (which are performed by InfiniteReality's geometry processors) decreases the bandwidth to computation ratio of the geometry processors, and would allow more geometry processors to be effectively utilized. However, the vertex bus bandwidth will still ultimately limit how many triangles per second the system can process.

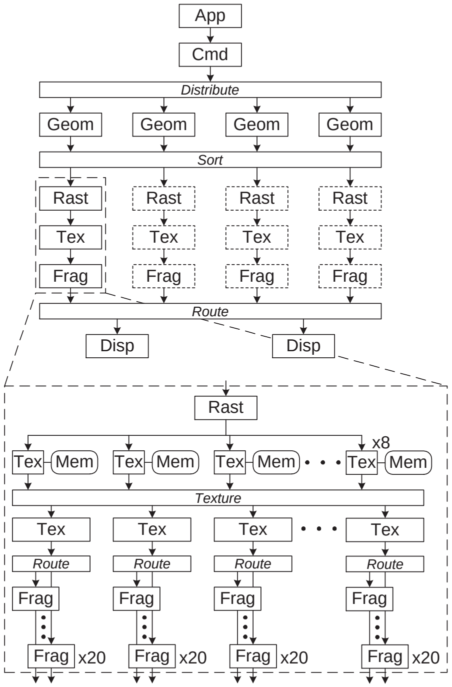


Figure 4.4: SGI InfiniteReality. InfiniteReality consists of 4 geometry processors and 1, 2, or 4 rasterization pipelines, consisting of rasterizer, texture processor and fragment processor. The geometry processors and rasterizers are interconnected by a broadcast vertex bus, which is used as a point of serialization to reorder the object-space parallelism of the geometry stage. A single command processor interfaces the hardware to the system and distributes input primitives over the geometry processors. Each rasterization pipeline makes extensive use of parallelism internally. The texture processor is divided into two stages. The first stage handles the 8-way memory fetch for trilinear mip-mapping. The second stage handles the texture interpolation and application to the untextured fragments. Each of the 4 texture interpolaters in turn fans-out to 20 fragment processors.

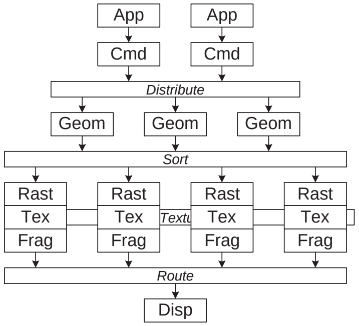


Figure 4.5: Argus. Argus divides the screen into tiles across a set of rasterization threads. Geometry processors enqueue chunks of geometry on only those rasterizers the chunks overlap. Argus supports parallel submission of commands to simultaneous contexts. Ordering constraints between these streams of commands are resolved by the command processors. Argus's communication is implemented via shared memory, although a message passing implementation should be feasible.

classes, those that process their input in primitive order, and those that process their input in tile order.

Primitive Order

Sort-middle tiled architectures that process their input in primitive order have been fairly uncommon. For reasons discussed next, tile order systems have generally been preferred. Argus, a software parallel renderer built at Stanford, is a representative primitive order sort-middle tiled architecture.

Argus, shown in figure 4.5, is organized as a set of multiprocessor aware threads, with one thread per geometry processor and one thread per screen tile. This organization has the interesting property that the tiles are processed as if they were in a work-queue – as soon as a thread is done with its tile it goes to sleep, and another rasterization thread may start executing. Thus the rasterization performance is fairly insensitive to load imbalance across the tiles, as long as the number of tiles is significantly larger than the number of processors. Despite using software rasterization, Argus was limited by the speed of the interface on machines as small as 5 processors. To address this limitation a parallel interface was introduced by Argus's creators.

Tile Order

Sort-middle tiled architecture may choose to process the primitives in tile order rather than primitive order. In such architectures, often referred to as bucketing or chunking architectures, the tiles are processed sequentially, first processing all the primitives that overlap the first tile, then all the primitives that overlap the next tile, etc. The tile processing may also be parallelized, so that multiple tiles are processed simultaneously.

Tile-order sort-middle architectures use memory as communication, sorting the primitives by the tiles they intersect, and storing the primitives away to be processed later, on a per-tile basis. By processing all of the primitives that intersect a particular tile at the same time, only a single tile's worth of the framebuffer needs to be provided. This framebuffer tile may be small enough to fit on chip, saving both the external memory bandwidth and capacity of a complete framebuffer. Moreover, a small on-chip framebuffer may be made much more complicated than would be practical for a framebuffer that must support the entire display.

Microsoft's Talisman architecture [Torborg and Kajiya, 1996] divides the screen into 32×32 tiles for rendering, and supports a high-quality antialiasing algorithm within the on-chip framebuffer. Talisman takes the further step of compressing both the framebuffer and texture store, decompressing them on the fly when pulled into the chip for processing, and recompressing them when written back out. Imagination Technologies's PowerVR architecture [PowerVR Technologies, 2001] is bucket-based, and reportedly GigaPixel's architecture was as well.

Pixel-Planes 5 [Fuchs et al., 1989], shown in figure 4.6, is a hardware implementation of a tile order sort-middle tiled architecture. Although not described, the tile set could be dynamically scheduled on to the rasterization pipelines with a work queue, similar to Argus's scheduling of rasterization threads onto processors, with a resulting relative independence of load-balancing problems. Pixel-Planes 5's ring interconnect is actually a sophisticated point-to-point implementation of a bus. Because communication is not local (geometry processors talk to rasterizers, rasterizers talk to the display) the ring does not provide scalable communication bandwidth. As the size of the ring increases the average message distance increases at the same rate, thus completely consuming any possible increase in aggregate communication bandwidth.

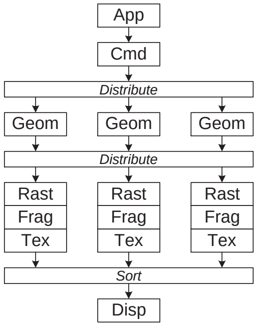


Figure 4.6: UNC Pixel-Planes 5. Pixel-Planes 5 consists of a set of geometry processors and rasterization pipelines interconnected by a ring. Each rasterization pipeline processes all of the primitives for a single 128×128 tile at a time, passing the result to the display processor. Texturing, per-pixel Phong shading and other effects are deferred until after all of the primitives for the tile have been rasterized and composited. This deferred operation omits the possibility of combining primitives with anything other than z-buffered operations, since only the top-most visible surface will be processed.

A disadvantage of tile-order architectures is that the pipeline must be repeatedly configured to process each tile. If the output image is I pixels and the tile area is T pixels, then a system with n rasterizers assigns $k = I/nT$ tiles to each rasterizer. Thus the overhead of configuration, which detracts from the time available for rendering, is increased by the interleave factor k. This may be particularly problematic when dealing with textures, especially if the total amount of texture in use is greater than the texture memory. This may force a tile-order renderer to page the texture memory k times. Similarly, capacity problems may affect the memory used to sort the primitives for tile-order processing. Once that

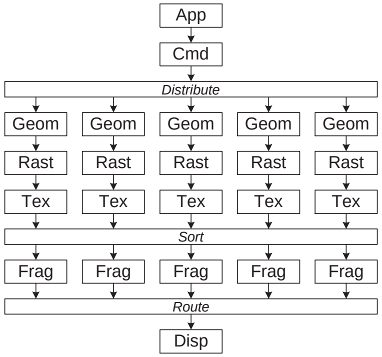


Figure 4.7: Sort-Last Fragment. The architecture shown here is representative of the Kubota Denali and the Evans & Sutherland Freedom Series, although the exact details of those architectures are not known to us.

memory is full it must either be spilled, at potentially large expense, or some of the tiles must be processed, so their primitives can be discarded. This requires that a given tile can be processed multiple times without ill effect, which may preclude or at least complicate the use of tile-based framebuffers.

4.3 Sort-Last Fragment

Sort-last fragment sorts fragments after rasterization and before fragment processing. The primary advantage of this approach is the overlap factor is guaranteed to be 1 – a fragment is always the responsibility of exactly 1 fragment processor. The previous architectures, sort-first and sort-middle, must balance their desire for a small tile size to provide a good load balance with the need to increase the tile size to reduce the overlap factor, or otherwise suffer the performance limitations of an interleaved (broadcast) approach. Sort-last fragment does not have this restriction, and can use a very fine tiling of the screen across the fragment processors to insure an excellent static load balance.

Figure 4.7 depicts an architecture representative of the Evans & Sutherland Freedom

Series [Evans & Sutherland, 1992] and the Kubota Denali [Kubota Pacific, 1993], two sort-last fragment architectures. Although not discussed, both of these architectures likely suffer the Achilles heel of conventional sort-last fragment architectures: geometry processing and rasterization are coupled together. The result is that there is no control over the load balance of rasterization work; if a geometry processor happens to get a large primitive, or a succession of large primitives, they will all be handled by its associated rasterizer. At best this can push the pipelines out of balance, limiting the potential speedup of the hardware. At worst, if the primitives are committed to the framebuffer in order the hardware can become serialized – not only reducing speedup due to load imbalance, but the heavily loaded rasterizer will block other rasterizers from making forward progress.

4.4 Sort-Last Image Composition

Sort-last image composition architectures composite multiple depth-buffered images, the final result of a conventional graphics pipeline, to form their final output. Image composition architectures have no control over the order of framebuffer operations because each pipeline renders its subset of the primitives into its own framebuffer, which may overlap the primitives of other pipelines. As such, they forego support for ordered semantics, and represent a significant departure from the previous architectures. Image composition architectures can suffer from the same load-balancing problems seen in sort-last fragment architectures – the different rasterization processors of each pipeline may have differing amounts of work to do. The load imbalance here is extended to the fragment processors, but assuming their performance is matched to the rasterizers, the performance impact is the same as for sort-last fragment.

Sort-last image composition architectures have the unusual property of requiring a fixed communication bandwidth, dependent on the size of the output. All of the previous architectures require a variable amount of communication, proportional to the size of the input. This fixed communication pattern is often cited as a large advantage of sort-last image composition architectures, but it comes at a high initial price. Compositing a 1280×1024 display at 60Hz with depth compositing requires 450 Mbyte/sec of communication, assuming 24-bit color and 24-bit depth. If we increase the resolution to 1920×1200 at 72Hz, the bandwidth increases to 950 Mbyte/sec. While this is a very manageable amount of communication, particularly when we consider that modern memory interfaces operate at 1 to 2 Gbyte/sec, multisample antialiasing could increase this bandwidth by a factor of 4 to 8, which starts to get significant.

The communication for image compositing may be broadly classified as either pipelined, with each graphics pipeline compositing its local framebuffer with that of its upstream neighbor, or non-pipelined.

4.4.1 Pipelined Image Composition

The promise of pipelined image composition architectures has been their ability to provide linear scalability by connecting the graphics pipelines in a chain. Each graphics pipeline composites its local framebuffer with the stream of framebuffer data arriving from its upstream neighbor, passing the composited result to its downstream neighbor. The compositing may be fully pipelined, so the total delay from the completion of the frame (at which point the output may be start to be composited) to a complete output image need only be the raw time to composite one pipeline's framebuffer with its neighbor, plus the negligible latency of the pipeline-to-pipeline communication times the number of pipelines. If this composition is done at video rates, then the final stage of the image composition pipeline can directly drive the display, with the result that the compositing operation introduces almost no latency.

PixelFlow [Molnar et al., 1992, Eyles et al., 1997], shown in figure 4.8, is one hardware implementation of a pipelined image composition architecture. PixelFlow supports multiple simultaneous interfaces into the hardware, providing the possibility of a parallel interface and application. An additional ring interconnect allows for the distribution of commands over geometry processors, however, as with sort-last fragment, such a distribution can readily fall victim to large primitive effects. This effect is mitigated in PixelFlow by its SIMD rasterization architecture. By processing 32 × 32 pixels simultaneously[3] the effective primitive area becomes 1024 times smaller. PixelFlow defers potentially expensive texture operations, as well as its more general programming shading operations, until

[3] 64 × 128 samples are processed simultaneously, with a resulting pixel stamp of 32 × 32 pixels when using 8-way supersampling.

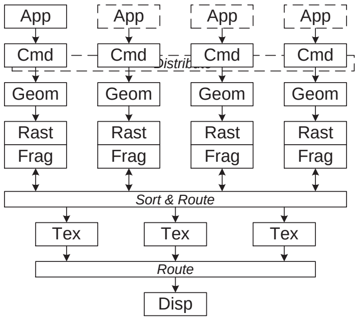


Figure 4.8: UNC PixelFlow. PixelFlow is constructed out of a sequence of nearly complete graphics pipelines, connected on a ring network. Each pipeline consists of a geometry processor, and a combined rasterizer and fragment processor. The rasterizer contains a 64x128 sample framebuffer, and the geometry processor buckets primitives, allowing the screen to be processed in sequential stamps of this framebuffer. The resulting stamps are composited in a pipeline interconnecting the fragment processors. Texturing and other programmable effects are deferred until after the stamps have been merged, to reduce computation at the expense of merging larger samples containing texture coordinates, etc. An additional ring network interconnects the geometry processors to support distribution of commands when a retained-mode interface or serial application is used.

after the final image has been composited. This allows PixelFlow to only shade only the front most visible pixel (or sample in this case) at each location, with the result that the expense of shading and texture is dependent only on the output image size, and not also on the depth complexity of the input.

It is interesting to note that in the time since PixelFlow was described the choice to defer texturing, thus saving computation at the cost of bandwidth, has probably come full circle. The abundance of available computation has made complicated per-fragment shading quite feasible, while the high cost of communicating multiple varying parameters per output sample would probably make a deferred shading approach prohibitively expensive. For example, if we assume each sample has 4 textures to be applied to it, then each sample is approximately 300 bits (see table 2.3), and even a 1280 × 1024 display at 60Hz requires

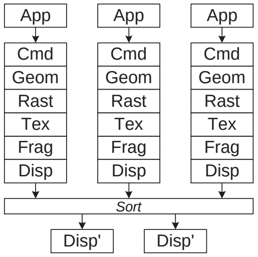


Figure 4.9: Lightning-2. Lightning-2 composites the output digital video streams of unmodified graphics accelerators to form a single output image. The actual Lightning-2 hardware implements the *sort* network. Through significant programmability, Lightning-2 can support screen-space tiling, depth compositing, and other features.

2.8 Gbyte/sec of bandwidth to composite, with supersampling and higher resolution proportionally increasing the bandwidth requirements. PixelFlow provides a 12.5 Gbyte/sec bus to support a 1280×1024 display at 60Hz with 4 samples per pixel.

A sort-last image composition architecture based on commodity graphics accelerators has recently been built on top of a digital video compositing engine called Lightning-2. Lightning-2, developed by Intel and Stanford [Stoll et al., 2001], accepts multiple digital-video outputs from unmodified graphics accelerators, and composites them to form a single image or images. A support library on the graphics accelerators embeds routing information as pixels in the framebuffer, so that each accelerator can place any of its pixels anywhere in the output. One simple use for Lightning-2 is to reassemble the output of a sort-first architecture using tiled rasterization. One such architecture is described in section 4.5.1. With the addition of a copy between the depth buffer and the color buffer, to allow the depth buffer to be scanned out as part of the video signal, Lightning-2 can be used as a sort-last image composition engine, shown in figure 4.9. Lightning-2 has the significant advantage, as with WireGL, of allowing unmodified graphics accelerators to be used. Thus the performance of of a Lightning-2 based architecture can track consumer graphics accelerators, rather than the typically more slowly evolving workstation accelerators.

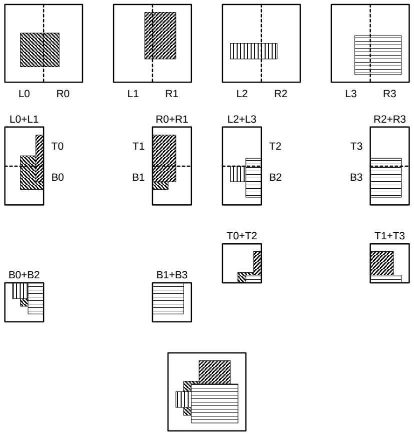


Figure 4.10: Binary-Swap Compositing. Four processors, 0 through 3, have each generated a partial output image, all of which must now be composited. In the first step the images are split into left (L) and right (R) halves and each processor communicates half of its image with its neighbor, compositing the half it receives with its own image. In the second step the resulting half images are split in half again, into top (T) and bottom (B) quarters, and each processor communicates with its 2-away neighbor, compositing the quarter it receives with its own image. After $\log_2 n$ total steps, each processor has one n^{th} of the totally composited image, which may be then reassembled externally, or transmitted to an attached framebuffer. The figure is after figure 3 in [Ma et al., 1994].

4.4.2 Non-Pipelined Image Composition

Special purpose networks, such as the ring interconnect in PixelFlow, allow a pipelined image composition operation to be done very efficiently. More general purpose interconnects, such as those found in multiprocessor computers, may not efficiently support pipelined image composition. If the image composition is performed in a naive tree-based fashion, it will require $O(I \log n)$ time, as opposed to the $O(I)$ time required for a pipelined operation.

Ma et al. describe an algorithm for performing sort-last image composition that they call binary-swap compositing [Ma et al., 1994]. Like the pipelined image composition approach used in PixelFlow, binary-swap compositing merges a variable number of images in time proportional to the size of the image, rather than the number of images. The algorithm is described in figure 4.10. In the simplest case each processor always communicates all of the pixels in its partition, in which case the per processor communication is:

$$I\sum_{i=1}^{\log_2 n}\frac{1}{2^i} = I\left(1-\frac{1}{n}\right)$$

and each processing element has one n^{th} of the final output image after compositing. If the resulting image is then all communicated to a single point for output, then the total communication per processor is I. This is the same result as for the pipelined image composition approach, which we expect, as each pixel must be communicated at least once in order to be merged. Ma et al.'s implementation of binary-swap compositing also tracks the screen-space bounding box of the active pixels in each processor's local framebuffer, and communicates only those pixels. This has the nice effect of reducing the communication bandwidth, particularly in the earliest stages of compositing, when the communicated portions of the framebuffer are the largest, but presumably also the sparsest.

Cox and Hanrahan suggest an alternative algorithm for depth-based image composition based on distributed snooping [Cox and Hanrahan, 1993]. Cox's algorithm uses a broadcast image composition, in which each processor in turn broadcasts the active pixels in its local framebuffer to the global framebuffer. During each processor's broadcast the other processors snoop the broadcast messages, and if any pixel that goes by that occludes a pixel in the processor's local framebuffer, it marks its local pixel as inactive, so it will not be communicated later. Their analysis shows that the expected number of pixels communicated will be $I\log d$, and thus the total communication does not depend on n, the number of images being merged. In reality, the $O(n)$ term is hiding in the implementation of the broadcast communication mechanism, which has $O(n)$ cost. Thus this algorithm is probably most suitable when there is an existing broadcast communication mechanism to be used, as is present in many small scale ($n \leq 8$) multiprocessors.

The chief limitation of image composition architectures arise at their main point of communication – the display. Unlike previous architectures, which typically suffer performance problems that are proportional to the size of the input (i.e. broadcast of triangles, replication of texture), image composition architectures are primarily limited by the size of their output. In a typical implementation, each pipeline must have an entire copy of the output display space. Thus the communication cost (both in framebuffer memory and pipeline interconnect) is $O(nI)$. This rapidly becomes difficult or impossible to support, particularly when driving multiple displays. The Aizu VC-1, described in section 4.5.2, takes a novel approach to avoiding this limitation.

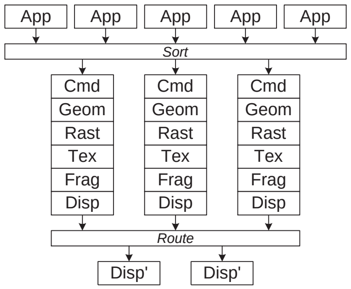


Figure 4.11: WireGL and Lightning-2. In this configuration, Lightning-2 is used to support an arbitrary image parallel decomposition of the output space across the pipelines.

4.5 Hybrid Architectures

The architectures discussed thus far have all exemplified sorting-centric design, with no general (N to M) communication except at the sort. We now examine hybrid architectures which perform distribution and routing communication with general communication.

4.5.1 WireGL + Lightning-2

WireGL, described in section 4.1.2, faces two major difficulties. First, it is a sort-first tiled renderer, which is a significant load-balancing problem to be begin with, but even worse, it has had its tiling chosen for it, with the assignment of a projector per pipeline. Second, serial applications are application and network limited to approximately 7 Mvert/sec, so the WireGL's multiple pipelines only provide improvements in rasterization performance.

WireGL's architects describe the combination of WireGL with Lightning-2 and the Parallel API to address both these problems [Humphreys et al., 2001]. Lightning-2, described in section 4.4.1, is a source-routed digital video compositing engine. Although we have described its use for image composition, it can also be used to perform tiled image reassembly. This allows WireGL to drive a single display with multiple accelerators, rather than being forced to match the display to the accelerators. WireGL divides the screen into tiles, typically 100 × 100, and assigns an interleaved partition of the tiles to each accelerator. Lightning-2 is then used to reassemble the tiled outputs of the multiple accelerators into a single image.

The combination of WireGL with the Parallel API allows multiple application processes to submit commands to the accelerators in parallel. Each accelerator receives bucketed streams of commands that intersect its partition of the output space, one stream per application process. The applications can express ordering constraints between the streams with the parallel API. Parallel API commands are broadcast to avoid the need for a central scheduler, and as a result each pipeline resolves the parallel API commands independently. As an interesting side effect, when the parallel API is only used to impose a partial order, the different pipelines may choose different orders of execution for the command stream.

4.5.2 VC-1

The Aizu VC-1 is a sort-last image composition architecture [Nishimura and Kunii, 1996]. Similar to PixelFlow, the VC-1, shown in figure 4.12, interconnects multiple graphics pipelines with a neighbor-to-neighbor image composition ring. However, rather than providing a complete framebuffer for each pipeline, the VC-1 provides a virtual framebuffer for each

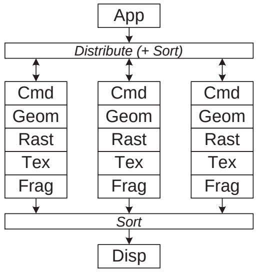


Figure 4.12: Aizu VC-1. The VC-1 interconnects its multiple pipelines with an image composition network. Each pipeline has a small local framebuffer, which is virtualized to act as an entire framebuffer. When the local framebuffer fills it is spilled to the global framebuffer attached to the display. The broadcast bus which connects the geometry processors is used both to load a distributed retained-mode database from the application, and to allow the geometry processors to broadcast large primitives, forcing all of the pipelines to participate in their rasterization.

pipeline, which is only a small fraction (in this case $1/4$) of the size of the global framebuffer, located at the display processor. An indirection table allows the local framebuffer to be dynamically allocated in 4×4 tiles. If the local framebuffer is exhausted then some number of tiles are spilled by merging them with the global framebuffer. Nishimura and Kunii observe that a single large primitive can force a significant number of such spills, and in order to avoid the accompanying performance penalty, large primitives are broadcast to all the pipelines, which then do an image-space decomposition of the primitive, each rendering approximately $1/n$ of the pixels.

One of the most interesting features of the VC-1 is its ability to load-balance large primitives by forcing all pipelines to participate in their rasterization. However, the use of a broadcast mechanism to distribute primitives results in a fairly high threshold for primitive distribution. There is no possibility of deciding that it would be advantageous to simply split this primitive in half and share it with another pipeline. For many scenes the load-balancing difficulty is not that a particular pipeline gets a huge primitive, but instead gets larger primitives on average, because, for example, the object it is rendering is in the foreground.

The VC-1's virtualization of the local framebuffer presents the possibility of addressing one of the main disadvantages of the sort-last image composition architectures. In a conventional sort-last image composition architecture, each pipeline has a complete framebuffer at full output resolution; consequently, increasing the output resolution has a cost linear in both the output size and the number of pipelines. The VC-1 can, within limits, keep the per-pipeline framebuffer size constant while varying the output framebuffer size.

4.6 Observations

We summarize the architectures we have discussed, as well as additional graphics architectures, in table 4.6. We draw a number of observations from these architectures. First, the performance of the hardware is often interface limited. Second, the performance of the system can depend on factors not readily visible to the programmer, such as the screen-space area of primitives. Additionally, the texture subsystem is quickly becoming the most demanding point of communication in the graphics pipeline, both in bandwidth and memory capacity. Finally, temporal locality in the input can result in spatial load imbalances for image parallelism. We will discuss these observed difficulties, and discuss some ways of addressing them.

4.6.1 Interface Limit

Modern graphics hardware can process immediate-mode input commands at a rate greater than they can be generated by an application specifically tuned to do nothing but command submission. The fact that most applications do more work than simply driving the graphics pipeline, sometimes significantly more, only worsens the situation. The result is that the hardware's performance is application-limited in many situations. The problem is not that the interconnect between the processor and the hardware is not fast enough, although that can be an issue, but that the application simply can not generate commands fast enough to keep the hardware busy. We refer to this common problem as *interface limited performance*, where the limitation is due to one or more of the application, the

Sort-First	
Retained-Mode	
Princeton Wall	duplicated database [Samanta et al., 1999]
Mueller	primitive migration [Mueller, 1995, Mueller, 1997]
Immediate-Mode	
WireGL	unmodified commodity pipelines, display per pipeline [Humphreys et al., 2000, Humphreys et al., 2001]
HP Visualize Ascend	[Cunniff, 2000]
Sort-Middle	
Interleaved	
SGI Indigo2	SIMD geometry, scanline-interleaved rasterization [Harrell and Fouladi, 1993]
SGI RealityEngine	MIMD geometry, broadcast triangle bus [Akeley, 1993]
SGI InfiniteReality	broadcast vertex bus, column-interleaved rasterization [Montrym et al., 1997]
Sun Leo	column-interleaved [Deering and Nelson, 1993]
AT&T Pixel Machine	task parallel geometry, data parallel interleaved rasterization [Potmesil and Hoffert, 1989]
Tiled	
Primitive-Order	
Argus	software shared-memory, parallel interface [Igehy et al., 1998b]
Tile-Order	
Pixel-Planes 5	tile-based rasterizers [Fuchs et al., 1989]
Talisman	[Torborg and Kajiya, 1996]
RenderMan	[Cook et al., 1987]
Apple Single-Chip Accelerators	[Kelley et al., 1992, Kelley et al., 1994]
Sort-Last Fragment	
Kubota Denali	[Kubota Pacific, 1993]
E&S Freedom	[Evans & Sutherland, 1992]
Digital Neon	serial through texture processing, 8-way fragment parallel [McCormack et al., 1998]
Pomegranate	distributes work between geometry and rasterization, parallel interface, shared texture [Eldridge et al., 2000]

Table 4.2: Summary of Graphics Architectures (cont.)

Sort-Last Image Composition		
Pipelined		
	PixelFlow	retained-mode, possible parallel immediate mode, bucketed framebuffer [Molnar et al., 1992, Eyles et al., 1997, Molnar, 1995]
	VC-1	tiled framebuffer to minimize duplication, broadcast large primitives [Nishimura and Kunii, 1996]
	Lightning-2	DVI interconnect, unmodified commodity pipelines [Stoll et al., 2001]
	HP Visualize Ascend	[Cunniff, 2000]
	GE NASA II	rasterizer per triangle, depth-sort visibility [Bunker and Economy, 1989, Molnar and Fuchs, 1990]
	Triangle Processor and Normal Vector Shader	rasterizer per triangle, pipelined image composition chain [Deering et al., 1988]
Non-Pipelined		
	Binary-Swap Compositing	[Ma et al., 1994]
	Princeton Sort-Last with Object Partitioning	partitions object work by screen location, reducing compositing communication between pipelines [Samanta et al., 2000]
	Compaq Sepia	gigabit network, unmodified commodity pipelines, color & depth readback [Moll et al., 1999, Heirich and Moll, 1999]

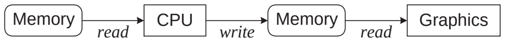
Table 4.2: Summary of Graphics Architectures

device driver, or the processor–graphics interconnect. A number of solutions have been proposed to deal with interface limited performance, including display lists, vertex arrays, higher-order primitives, and a parallel interface.

Display lists, as used in OpenGL, are execution macros that represent a stream of immediate-mode commands. Display lists can be called at any point in the execution of a program, and may even call other display lists recursively. The interface advantage of a display list is that, once specified, the list may be called repeatedly at reduced cost to the application. While display lists may be stored in application memory and submitted by the device driver on behalf of the application, recent hardware includes support for direct evaluation of display lists by the hardware, without host processor intervention. For example, SGI's InfiniteReality includes a large (16 Mbyte) display list memory, specifically to address interface limitations on the Onyx series of machines [Montrym et al., 1997]. A

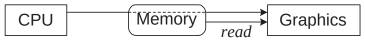
display list may also be optimized into a format more efficient for the hardware to evaluate. This increases the up-front cost of specifying the display list, but is hopefully realized as an improvement in the per-execution cost of the display list. The disadvantage of display lists is that unless they are executed more than once, there is no advantage to using them, and they may decrease performance. Rohlf and Helman cite similar reasons as their motivation to use immediate-mode commands instead of display lists in IRIS Performer [Rohlf and Helman, 1994].

Many applications submit commands to the hardware in an extremely regular pattern – for example, a loop that submits color, normal, and vertex position repeatedly. Moreover, the application is often just traversing memory arrays of color, normal and vertex position information to do this submission. In general, this can result in vertex data passing through the host computer memory system 3 times:



The data is first read by the application, then written by the device driver into a block of commands for the hardware, and finally read by the hardware.

Vertex arrays allow the programmer to specify pointers to application memory which contains vertex attributes, and then with a single call (`glDrawArrays`) have multiple vertices with attributes rendered by the hardware. The vertex and attribute data may be read directly from the host memory system by the graphics pipeline, crossing the memory bus only once.



Vertex arrays also support the specification of arbitrary vertex connectivity with the use of `glDrawElements` call, which allows the programmer to pass an array of vertex indices to the hardware. In this case the hardware may employ a small vertex cache, so as it transfers the user specified vertices over the interface it can skip the transfer of already cached vertices, thus extracting the efficiency of the arbitrary mesh connectivity. The hardware may additionally cache the computation for those vertices, for further performance increases.

The limitation of vertex arrays, as with display lists, is that they must be initially created. If the data are dynamic, and thus must be edited every frame, the performance improvements of vertex arrays may be more negligible, although there is still the advantage of using fewer API commands to specify geometry. Additionally some hardware, particularly PC accelerators, requires that vertex arrays be placed in specially allocated memory for best performance, with the side effect that access to vertex arrays by the application becomes significantly slower.

Instead of optimizing the transfer of the same data to the graphics subsystem, another solution is to change to a higher order representation. For example, the OpenGL interface includes “evaluators,” which allow the programmer to specify the coefficients of a Bézier surface patch, and then evaluate a uniformly sampled mesh of points on that patch, automatically computing normals, texture coordinates, and vertex positions. This can lead to large efficiencies at the interface, as the user can specify many vertices easily, while also transferring computation to the hardware, in this case the evaluation of the basis functions, where it may be parallelized. As with display lists and vertex arrays, evaluators have their limitations. In particular, if the data are not naturally expressed as Bézier patches, the availability of evaluators will be of little use to the application.

Our final solution to the interface limitation is to observe that for many high-performance applications, the application is running on a parallel computer, and the graphics subsystem is a parallel computer as well. The most natural way to connect two such systems is with a parallel interface. Igehy, Stoll and Hanrahan have proposed one such interface [Igehy et al., 1998b]. Igehy et al.’s parallel interface allows multiple graphics contexts to be active in the hardware simultaneously, each with independent, concurrent submission of commands. The parallel API provides parallel programming primitives such as barriers and semaphores to allow the programmer to express ordering constraints between these multiple contexts, thus controlling the final order of what appears on the screen. The advantage of using a parallel interface is that it makes no restrictions whatsoever on the nature of the data submitted, but simply provides additional immediate-mode interface bandwidth into the system. The disadvantage of the parallel interface is that it requires a parallel program, and presumably a parallel computer, to get performance increases over a serial application.

4.6.2 Application Visibility of Work

Ideally the graphics hardware has perfectly predictable performance. The application programmer could, for example, simply count the number of submitted vertices, divide by the vertex rate of the hardware, and determine how long the scene will take to render. While this will work for some applications, in general it is a poor model for the actual system performance. Many factors break this model, two perhaps most significantly. First, overall performance is often fill-limited. Thus the performance will depend on information, the screen-space area of the primitives, which is not readily available to the programmer. Second, new interfaces may adaptively tessellate geometry based on its screen-space projection. Thus the geometry performance may not even be readily predicted by the application.

If we are interested in a parallel interface to the hardware, because it can provide us with greater immediate-mode command bandwidth, then we must be concerned with load-balancing the multiple input command streams across the parallelism internal to the graphics system. Most current applications submit simple primitives (triangles, quadrilaterals, etc.) to the hardware, with the result that the geometry work is proportional to the number of vertices. As a consequence, the programmer is readily aware of how much geometry work is being done per frame, because the submission of vertices is under programmer control. Thus parallel applications, which already must balance their input bandwidth across the interfaces, naturally balance their geometric work across the interfaces.

Unlike geometric work, estimating a primitive’s rasterization work requires significant programmer effort and potential run-time expense. As a consequence, architectures which do not decouple their inputs from rasterization can have large resulting load imbalances. For example, if a parallel application were to divide responsibility for command submission by objects in the scene, then interfaces receiving objects close to the viewpoint will be receiving a proportionally greater share of the rasterization work. Thus it is important to decouple input parallelism from rasterization parallelism.

4.6.3 Texturing

With the extension of the graphics pipeline to include multiple textures per fragment, access to texture memory is rapidly becoming the highest bandwidth point in graphics architecture. In its most straightforward implementation, a mip-mapped texture access requires 8 memory reads to fetch 4-texel neighborhoods in each of two mip-map levels. Assuming 4-byte color, the texture memory bandwidth is 8×4 bytes per pixel, or 12.8 Gbyte/sec assuming a 400 Mpixel/sec fill rate. This bandwidth demand can be greatly reduced by using texture caches, which can reduce texel reads by a factor of 4 or more.

For texture caches to work effectively, the texture processor must have good locality of reference – the texels required to texture one fragment must be likely to be reused on subsequent fragments. Igehy et al. analyzed the efficiency of texture caching under a variety of rasterization schemes, and concluded that either object-parallel rasterization or tiled rasterization provide good texture cache efficiency, while interleaved rasterization has quite poor texture cache efficiency [Igehy et al., 1999]. Their work assumed that rasterization and texture processing were coupled together, and we could consider schemes that change the parallelism used between these two stages. However, examining the cost of communication in table 2.3 and figure 2.3, the path between the rasterizer and the texture processor is potentially the highest bandwidth point in the system, so it quite desirable to couple these stages.

4.6.4 Limits of Image Parallelism

Managing image parallelism is very challenging. If tiled image parallelism is used, then the tile size must be chosen to minimize both load imbalances and the overlap factor, but these two effects are in tension with each other. If interleaved image parallelism is used, then the interconnect must handle expensive broadcast communication, and each processor must handle each piece of work, both of which rapidly limit the scalability of the interleaved approach.

The fundamental problem is that the desirable finely tiled approach conflicts with work that has an extent greater than a single pixel. If we consider a screen of I pixels, a tile area of T pixels, and a pipeline stage with parallelism n, then the relation between these variables is

$$\frac{I}{T} = kn$$

where k is the interleave factor, or the number of tiles per processor. Unfortunately, even at a relatively small tile size of 64×64 and a display resolution of 1280×1024, there are only 320 total tiles, or 10 tiles per processor, with 32-way parallelism. If the model occupies only one tenth of the screen, which is not unreasonable, then only a supreme stroke of luck will result in load-balanced execution. Moreover, the optimal tile size depends on the scale of the model. If the model is twice as far away from the viewer, thus presumably halving its extent in x and y, the optimal tile size is probably one quarter the previous tile area.

Our difficulties with image parallelism are exacerbated by temporal locality in the input. Most graphics applications draw models coherently, and thus the stream of primitives is likely to lie in the same area of the screen for significant portions of the input. Tiled image parallelism can become serialized when all of the primitives are directed to the same processor or processors for too great a period of time. This turns the per-frame load-balancing problem, which has a time scale of tens of milliseconds, into a much finer-grained load-balancing problem, which has a time scale determined by the depth of the buffering present at the inputs to the image parallel stage.

Although much experimentation has been done with coarse-grained tiled parallelism in sort-first and sort-middle renderers, we consider it telling that the most commercially successful parallel graphics systems have been based on sort-middle interleaved architectures. The disadvantage of sort-middle interleaved architectures is that they broadcast work between geometry processing and rasterization. Thus, while they can offer ready scalability of rasterization, because it does not increase the communication bandwidth, it is difficult to scale the geometry performance, because each new source of geometry commands increases the load on the communication infrastructure and rasterizers proportionally.

We feel that the difficulties of coarse-grained tiled image parallelism and sort-middle interleaved approaches indicate that sort-first and sort-middle both sort too early in the pipeline to work well at high degrees of parallelism. We instead advocate sort-last fragment approaches, which have the marked advantage that each fragment is guaranteed to have an overlap factor of exactly 1, and thus an arbitrarily fine-grained tiling of the framebuffer across fragment processors may be used. Sort-last image composition architectures also dodge the challenge of image parallelism, although at the cost of support for ordered framebuffer semantics. Both sort-last fragment and sort-last image composition approaches suffer from potential load imbalances at the rasterizers. We have already shown one architecture that attempts to address this problem. The VC-1, discussed in section 4.5.2, is a sort-last image composition architecture which supports broadcast communication between the geometry processors to parallelize the rasterization of large primitives. The second architecture, Pomegranate, is a novel sort-last fragment architecture whose description makes up the remainder of this thesis.

Chapter 5

Pomegranate: Architecture

Pomegranate is a new, fully scalable graphics architecture. Its design is based on, and motivated by, our observations of the challenges to exploiting parallel graphics architecture. In particular, Pomegranate has an immediate-mode parallel interface, to address the limitations of a serial interface. Pomegranate decouples rasterization parallelism from the input parallelism, so the programmer is not responsible for load-balancing work that is not application visible. Pomegranate uses object parallel rasterization, thus avoiding the difficulties of load-balancing image parallel rasterization without resorting to interleaved parallelism. Pomegranate couples texture processing to rasterization, and the resulting object-parallel texture processing has excellent cache behavior and scalability.

Under our taxonomy, Pomegranate is a sort-last fragment architecture. However, Pomegranate differs from previous sort-last fragment architectures in three important ways. First, Pomegranate introduces a stage of communication between object-parallel geometry and rasterization stages, which allows the rasterization work to be load-balanced independently of the geometry work. Second, Pomegranate uses a shared texture memory, so the total available texture memory scales with the number of pipelines. Finally, Pomegranate has a parallel interface, in order to provide scalable input command bandwidth.

Pomegranate is structured around efficient communication. Pomegranate's multiple pipelines are interconnected with a scalable interconnect, and the structure of Pomegranate's parallelism has been chosen to use one-to-one communication, rather than broadcast communication.

We motivate our discussion of Pomegranate by suggesting two possible implementations: a scalable graphics pipeline and a multi-pipeline chip. A scalable graphics pipeline could be flexibly deployed at many levels of parallelism, from a single pipeline solution with performance comparable to a modern graphics accelerator, up to a 64-pipeline accelerator with "supercomputer" performance. The incremental cost of the Pomegranate pipeline over a traditional graphics pipeline is the area required for approximately 600 KB of buffering, 32 KB for supporting 64 contexts, and the area and pins of a high-speed network interface. We estimate that the incremental cost of the Pomegranate pipeline is an additional 200 pins and 40mm^2 for memory in a modern 0.18μm process. A network chip, replicated as necessary to interconnect all of the pipelines, would weigh in at approximately 1000 pins, which is feasible. Our second possible implementation is a single chip with multiple Pomegranate pipelines. In such a chip the Pomegranate architecture would be leveraged as a practical method for utilizing the hundreds of millions of transistors which will soon be practical in even a consumer-level graphics accelerator. Current graphics accelerators already stretch the capabilities of VLSI tools and engineers with their size and complexity. Pomegranate would enable the design of a comparatively smaller pipeline which could then be replicated to consume the available transistor count, rather than requiring the design of a huge monolithic pipeline.

We will now describe the Pomegranate architecture and the details of its key components, describing how work is distributed in a balanced way at each stage of the pipeline to give scalable performance in each of the five performance metrics. In subsequent chapters we describe the serial ordering algorithm that maintains the serial order mandated by a single OpenGL context, as well as a parallel ordering algorithm that interleaves work according to the order specified by a parallel API. Finally, we present results from a detailed hardware simulation that demonstrates Pomegranate's scalability and compares it to that of traditional parallel graphics architectures.

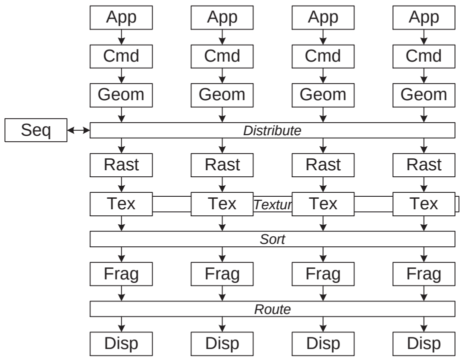


Figure 5.1: Pomegranate Architecture. Each Pomegranate pipeline is composed of six stages: command (Cmd), geometry (Geom), rasterization (Rast), texture (Tex), fragment (Frag) and display (Disp). A network connects the pipelines and a sequencer (Seq) orders their execution of multiple graphics streams submitted by the application threads (App).

5.1 Overview

Pomegranate is composed of *n* graphics pipelines interconnected by a scalable point-to-point network, as depicted in figure 5.1. Each pipeline is composed of six stages: command, geometry, rasterization, texture, fragment and display. The command processor receives commands from an application and passes them to the geometry processor. The geometry processor transforms, lights, and clips the primitives, and sends screen-space primitives to the rasterizer. The rasterizer performs rasterization setup on these primitives, and scan converts them into untextured fragments. The texture processor textures the resultant fragments. The fragment processor receives textured fragments from the texture processor and merges them into the framebuffer. The display processor reads pixels from the framebuffer and sends them to a display. The network allows each stage of each pipeline of the architecture to communicate with all the other pipelines at every stage. For example, each geometry processor can distribute its transformed primitives over *all* the rasterizers.

Each command processor accepts standard, immediate-mode OpenGL commands from a single context, as well as parallel API commands for ordering the drawing commands of the context with the drawing commands of other contexts. As with any parallel system, Pomegranate will operate efficiently only if the load is balanced across its functional units. Because graphics primitives can vary substantially in the amount of processing time they require, and the amount of work a primitive will require is not known a priori, distributing and balancing this workload in a dynamic fashion while minimizing work replication is a key innovation of the Pomegranate architecture and directly contributes to its scalability. Pomegranate performs four main distributions of work: primitives to rasterizers by the geometry processors; remote texture memory accesses by the texture processors; fragments to fragment processors by the texture processors; and pixel requests to the fragment processors by the display engine. Additionally a balanced number of primitives must be provided to each geometry processor, but that is the responsibility of the application programmer.

Two distinct ordering issues arise in Pomegranate. First, the primitives of a single graphics context are distributed twice, first over the rasterizers, and then over the fragment processors. This double distribution results in the work for a single context arriving out of order at the fragment processors, where it must be reordered. Second, each serial graphics context executes its own commands in order, but it must in turn be interleaved with the other graphics contexts to provide parallel execution in accordance with any parallel API commands. A novel serial ordering mechanism is used to maintain the order specified by the OpenGL command stream, and a novel parallel ordering mechanism is used to interleave the work of multiple graphics contexts.

By minimizing the use of broadcast communication in both the distribution of work and the maintenance of order, Pomegranate is able to scale to a high degree of parallelism.

5.2 Scalability and Interface

A fully scalable graphics architecture should provide scalability on the five key metrics discussed in section 1.2: input rate, triangle rate, rasterization rate, texture memory capacity and display bandwidth. Pomegranate provides near-linear scalability in all five metrics. Pomegranate achieves its scalability through a combination of a parallel host interface and multiple types of communication between the functional units.

- Each geometry processor has a host interface that may receive graphics commands simultaneously and independently. Ordering constraints between different graphics contexts may be specified by parallel API commands. This provides scalability of *input rate*. Because each geometry processor is limited by the interface speed, there is no purpose in distributing commands from a single interface across multiple geometry processors. The application must therefore provide a balanced number of triangles to each interface. This provides scalability of *triangle rate*.

- A network port allows each geometry processor to transmit screen-space primitives to any rasterizer. There is no constraint on this mapping, thus allowing the geometry processors to load-balance triangle work among rasterizers. This provides scalability of *triangle rate*.

- The sequencer, shared among all pipelines, determines the interleaving of the execution of the primitives emitted by each geometry processor. It allows multiple contexts to simultaneously submit commands to the hardware and to have their order of execution described by the parallel API. This provides scalability of *input rate*.

- Each rasterizer scan converts screen-space triangles into untextured fragments, and then passes them to the texture processor where they are textured. The geometry processors may load-balance the amount of pixel work sent to each rasterizer in addition to the number of triangles. The geometry processors may also subdivide large triangles so that their work is distributed over all the rasterizers. This provides scalability of *rasterization rate*.

- Textures are distributed in a shared fashion among the pipeline memories, and each texture processor has a network port for reading and writing of remote textures. This provides scalability of *texture memory capacity*.

- Each texture processor has a network port that enables it to route its resultant fragments to the appropriate fragment processor according to screen-space location. This sorting stage performs the object parallel to image parallel sort, and allows the unconstrained distribution of triangles between the geometry and rasterization stages that balances object parallelism. Fine interleaving of the fragment processors load-balances image parallelism and provides scalability in *rasterization rate*.

- Each display processor has a network port that allows it to read pixels from all of the fragment processors and output them to its display. This provides scalability of *display bandwidth*.

In addition to scalability, an equally important characteristic of the Pomegranate architecture is its compatibility with a modern graphics API. OpenGL has strict ordering semantics, meaning that all graphics commands must appear to execute in the order they are specified. For example, two overlapping polygons must appear on the screen in the order they were submitted by the user, and a state change command applies to all subsequent primitives. This constraint forces any parallel OpenGL hardware architecture to be capable of maintaining the serial order specified by the application. This restriction is one of the major obstacles to building a scalable OpenGL hardware renderer. As an analogy, C has become the de facto standard for programming, and as a result microprocessor architects focus the bulk of their efforts addressing the difficulties it introduces — pointer aliasing, limited instruction-level parallelism, strict order of operations, etc. Similarly, we felt it was important to design within the ordering constraints of OpenGL. In addition to specifying ordered semantics, OpenGL is an immediate-mode interface. Commands that are submitted by the application are drawn more or less immediately thereafter. APIs that are built around display lists, scene graphs, or frame semantics all provide the opportunity for the hardware to gather up a large number of commands and partition them among its parallel units. An immediate-mode interface does not enable this approach to extracting parallelism, and thus provides a further challenge.

5.3 Architecture

We now discuss in detail the different stages of the pipeline and their mechanisms for load-balancing, and defer the discussion of maintaining a correct serial and parallel order and the associated sequencer. Figure 5.2 shows the Pomegranate pipeline in detail.

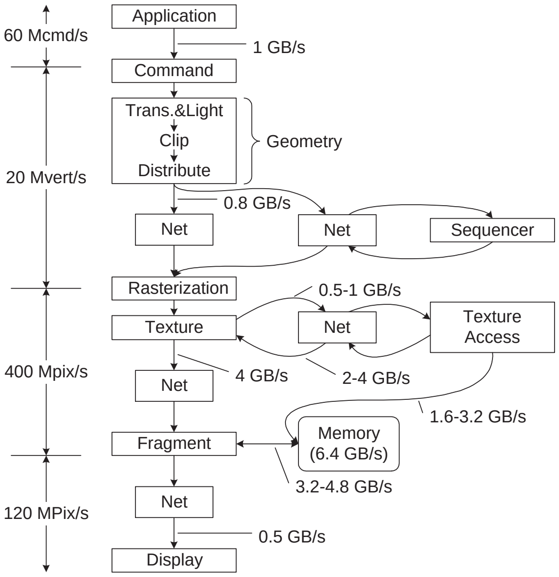


Figure 5.2: The Pomegranate pipeline. The bandwidth requirements of the communication channels are labeled.

Our architectural simulator for Pomegranate takes the functional units largely as black boxes, which accept input commands (vertices, primitives, fragments, etc.), perform the necessary computation, and generate a stream of output commands. The details of the internal processing are largely ignored, our only concern being that we have a reasonable model of the latency and efficiency of each stage. For example, our rasterizer emits 2×2 fragment quads, and consequently its efficiency suffers on small primitives. The implementation of these black boxes is taken as a given, and there are numerous existence proofs in the form of commercially available graphics accelerators.

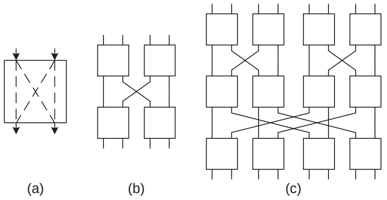


Figure 5.3: Butterfly Network. The butterfly network is composed of a single building block (a) which may be cascaded into a multi-stage network to support an arbitrary number of inputs (b & c), with a number of stages that grows logarithmically with the number of inputs.

5.3.1 Network

Central to the Pomegranate architecture is a scalable network that supports the balanced distribution of work necessary for load-balancing, and the synchronization communication necessary for ordering. We chose to implement the network as a multi-stage butterfly, depicted in figure 5.3. Other networks could have been chosen, the important requirements are support for all-to-all traffic patterns and good scalability. Butterfly networks provide excellent all-to-all communications at a cost of $O(n \log n)$, and thus meet both our requirements.

Networks, and butterflies in particular, are notorious both for suffering severe performance penalties under imbalanced loads, and for incurring increasing latency with increasing utilization. Pomegranate's network usage is engineered to be both uniform and latency tolerant to avoid these problems. For example, in an n-pipeline system, a geometry unit will send one n^{th} of its triangles to each rasterizer. This distribution pattern occurs similarly during texture, fragment and display communication, and is balanced over very fine time scales. Furthermore, the algorithms used in Pomegranate are designed to be able to tolerate latency through the use of buffering.

At the heart of a butterfly network is a $k \times k$ switch ($k = 2$ for figure 5.3). Every cycle, this switch is able to read a single quantum of data (a *flit*) from each of its input channels and write a flit to each of its output channels. Internally, the switch must arbitrate its outputs according to the requests of incoming packets, which are composed of multiple flits. Channels are virtualized to provide multiple virtual channels per physical channel to increase the likelihood that an output channel will have a packet that needs it on every cycle [Dally, 1992]. Virtual channels are critical to large butterfly networks as they increase bandwidth efficiency from approximately 25% to over 75%.

In order to scale a butterfly network beyond the k inputs and outputs of a single switch, an additional stage of switches is introduced. The first stage routes based on the most significant digits of the destination address, and the second stage routes based on the least significant digits. An n-interface network may be constructed using $\log_k n$ stages of n/k switches. As the number of interfaces increases the aggregate bandwidth available increases linearly, while the cost increases as $n \log_k n$.

Pomegranate's multiple networks are actually virtualized ports within a single unified network. Two messages from the same source to the same destination, e.g. geometry processor 0 to rasterizer 3, are guaranteed to arrive in order, but no other ordering guarantees are made by the network. A unified network allows the network to be used efficiently for all types of traffic, rather than having some networks left idle while other networks are overloaded with traffic. In order to support the expected workload and network inefficiencies, each channel runs at 10 Gbyte/sec. Each channel is 32 bits wide and operates at 2.5 GHz. Each 160-bit flit in our system is transferred over 5 32-bit clocks, and thus the switching logic runs at 500 MHz. We use 4×4 switches and 16 virtual channels per physical channel, each capable of buffering 16 flits. Ignoring contention, each hop through a switch imposes 8 flits of latency. Packets are constrained to be an integral number of flits, with a 24 bit header in the first flit, which imposes a small overhead.

5.3.2 Command Processor

The command processor is responsible for the DMA of commands from the application to the geometry processor, including format conversion of the data. Our interface model, which we understand to be typical of modern graphics hardware, is based on the construction of DMA buffers of application commands in host memory. When a buffer fills, or is flushed, the device driver passes a pointer to the data, along with its length, to the command processor, which then pulls the data across the interface.

Our host interface bandwidth is 1 Gbyte/sec. This is representative of AGP4x, a current graphics interface. We model the interface as ideal, with the time to transfer a DMA buffer dependent only on its length and the bus bandwidth. Our own benchmarks suggest it is difficult to achieve even 50% utilization of the AGP bus, however, our objective is to study the scalability and performance of Pomegranate, rather than the host interface.

5.3.3 Geometry Processor

The geometry processor is actually three distinct processors: a transform and lighting engine, a clip processor, and a distribution processor. Each geometry processor supports a single hardware context, although the context may be virtualized.

The transform and lighting (T&L) engine transforms, culls and lights the primitives. The T&L engine is implemented as a vertex-parallel vector processor, processing batches of 16 vertices together. The vertices may all be rejected at multiple points during processing, for example, if they are all outside one of the viewing frustum clip planes, or all of the primitives they describe are backfacing. Clipping is not performed in the T&L engine because it introduces a potentially large number of new vertices and corresponding primitives which must be correctly ordered in the primitive stream. Deferring this generally infrequent operation to a dedicated clip processor greatly simplifies the T&L engine. The T&L engine has a maximum performance of 20 million transformed and lit vertices per pipe per second.

The clip processor performs geometric clipping for any primitives that intersect a clipping plane. After geometric clipping, the clip processor subdivides large primitives into multiple smaller primitives by specifying the primitives multiple times with different rasterization bounding boxes. This subdivision ensures that the work of rasterizing a large triangle can be distributed over all the rasterizers. Large primitives are detected by the signed area computation of back-face culling and subdivided according to a primitive-aligned 64×64 stamp. The stamp area was chosen such that a single application submitting large primitives, such as in a solid-texture application, could keep all of the rasterizers busy. The clip state for each vertex and the signed area of each primitive is computed by the T&L engine, so the clip processor's fast path (no clipping or large primitive subdivision) has almost no computation.

The distribution processor distributes the clipped and subdivided primitives to the rasterizers. This is Pomegranate's first stage of general communication. Because the rasterizers are object parallel, the distribution processor has the freedom to distribute primitives as it sees fit.

The distribution processors transmit individual vertices with meshing information over the network to the rasterizers. A vertex with 3D texture coordinates is 228 bits plus 60 bits for a description of the primitive it is associated with and its rasterization bounding box, resulting in 320 bit (2 flit) vertex packets. At 20 Mvert/sec, each distribution processor generates 0.8 Gbyte/sec of network traffic. A distribution processor generates additional network traffic when large primitives are subdivided to ensure that they present a balanced load to all the rasterizers. In such cases the additional network traffic is unimportant, as the system will be rasterization limited.

The distribution processor governs its distribution of work under conflicting goals. It would like to give the maximum number of sequential triangles to a single rasterizer to minimize the transmission of mesh vertices multiple times and to maximize the texture cache efficiency of the rasterizer's associated texture processor. At the same time it must minimize the number of triangles and fragments given to each rasterizer to load-balance the network and allow the reordering algorithm, which relies on buffering proportional to the granularity of distribution decisions, to be practical.

The distribution processor balances these goals by maintaining a count of the number of primitives and an estimate of the number of fragments sent to the current rasterizer. When either of these counts exceeds a limit, the distribution processor starts sending primitives to a new rasterizer. While the choice of the next rasterizer to use could be based on feedback from the rasterizers, a simple round-robin mechanism with a triangle limit of 16 and a fragment limit of 4096 has proven effective in practice. When triangles are small, and thus each rasterizer gets very few fragments, performance is geometry limited and the resulting inefficiencies at the texture cache are unimportant. Similarly, when triangles are large, and each rasterizer gets few triangles, or perhaps even only a piece of a very large triangle, the performance is rasterization limited and the inefficiency of transmitting each vertex multiple times is inconsequential.

5.3.4 Rasterizer

The rasterizer scan converts triangles, as well as points and lines, into a stream of fragments with color, depth and texture coordinates. The rasterizer emits 2×2 fragment “quads” at 100 MHz and requires 3 cycles for triangle setup, for a peak fill rate of 400 Mpixel/sec. Partially covered quads can reduce the rasterizer’s efficiency to 100 Mpixel/sec in the worst case. We achieve 1.47 to 3.95 fragments per quad for the scenes in this thesis. Each rasterizer receives primitives from all the geometry processors and receives execution order instructions from the sequencer. The fragment quads emitted by the rasterizer are in turn textured by the texture processor.

While the geometry processors are each responsible for a single context, the rasterizers receive primitives from each of the geometry processors, and thus each rasterizer maintains *n* contexts, one per geometry processor. The requirement for multiple hardware contexts per rasterizer and all subsequent stages, as well as the distribution of pipeline configuration commands, is discussed with other state management issues in section 6.2.

5.3.5 Texture Processor

The texture stage, shown in figure 5.4, consists of two units, the texture processor which textures the stream of quads generated by the rasterizer, and the texture access unit which handles texture reads and writes. The input to the rasterization stage has already been load-balanced by the distribution processors in the geometry stage, so each texture processor will receive a balanced number of fragments to texture.

In order to provide a scalable texture memory, the texels of each texture are distributed over all the pipelines in the system. Texture reads, except those that happen to access the local memory system, involve a round-trip over the network: the request must be sent to the appropriate texture access unit, and eventually the data are returned. Thus texture accesses have high latency, in most cases dominated by the network latency. We have previously demonstrated a prefetching texture cache architecture that can tolerate the high and variable amount of latency that a system with remote texture accesses, such as Pomegranate, is likely to incur [Igehy et al., 1998a]. Pomegranate’s texture processor employs this prefetching scheme to hide the latency of texture accesses.

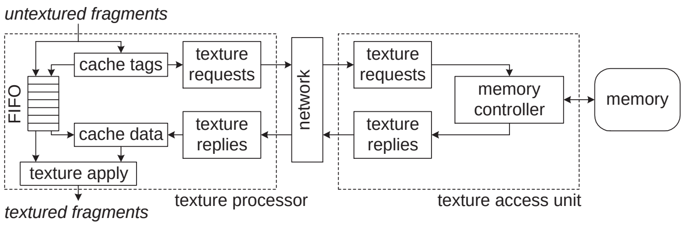


Figure 5.4: Texture Stage. The texture stage is comprised of a texture processor, which makes texture accesses, and applies the texture data to fragments, and a texture access unit, which accepts remote texture accesses and returns the data over the network. The texture processor separates texture requests from texture use with a FIFO to hide the high latency of the networked texture memory.

We subsequently showed that this cache architecture could be used very effectively under many parallel rasterization schemes, including an object-space parallel rasterizer similar to Pomegranate [Igehy et al., 1999]. Based on these results, we use a 4×4 texel cache line size, and round-robin distribution of the 4×4 texel blocks of each texture across the pipelines. The texture processor uses a direct-mapped 16KB texture cache (4096 texels, 256 blocks). A more complete description of the texture memory layout is given in figure 5.5.

A texture cache miss requires that a 160-bit texture request be sent over the network, which will be followed by a 640-bit reply, for a total of 800 bits of network traffic per 16 texels, or 6.25 bytes per texel. If we assume 1–2 texels of memory bandwidth per fragment, our rasterizer requires 4–8 bytes of texture memory bandwidth and 6.25–12.5 bytes of network bandwidth per fragment. At 400 Mpixel/sec, this becomes 1.6–3.2 Gbyte/sec of memory bandwidth and 2.5–5 Gbyte/sec of network bandwidth.

After texturing the fragments, the texture processor routes the fragment quads to the appropriate fragment processors. The fragment processors finely interleave responsibility for pixel quads on the screen. Thus, while the texture engine has no choice in where it

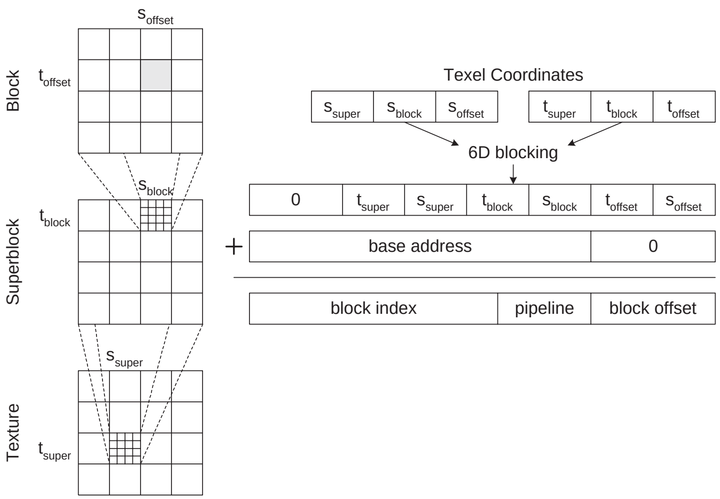
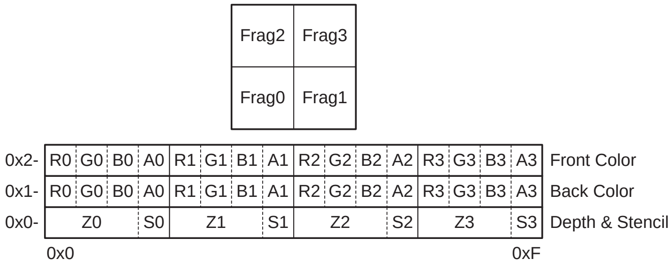

s_offset
t_offset
Block
s_block
t_block
Superblock
s_super
t_super
Texture
Texel Coordinates
s_super | s_block | s_offset
t_super | t_block | t_offset
6D blocking
0 | t_super | s_super | t_block | s_block | t_offset | s_offset
+
base address | 0
block index | pipeline | block offset

Figure 5.5: Texture Memory Organization. Textures are organized into 4 × 4 texel blocks, the smallest granularity of texture access. Blocks are in turn packed into cache-sized superblocks, to minimize the conflict misses of our direct-mapped cache. Finally, superblocks are tiled to cover the texture. The address calculation transforms a texel reference (s,t) into a block offset, pipeline number and block index within that pipeline's local memory.

routes fragment quads, the load it presents to the network and all of the fragment processors will be very well balanced. A quad packet contains 4 fragment colors, 4 corresponding sample masks, the depth of the lower-left fragment, the depth slopes in x and y and the location of the quad on the screen. This representation encodes a quad in 241 bits, or 320 bits (2 flits) on the network. Due to network packet size constraints, this is only twice the size of an individually encoded fragment, which is transmitted as 1 flit. At 100 Mquad/sec, each texture processor sends 4 Gbyte/sec of traffic to the fragment processors.



0x2-	R0	G0	B0	A0	R1	G1	B1	A1	R2	G2	B2	A2	R3	G3	B3	A3	Front Color
0x1-	R0	G0	B0	A0	R1	G1	B1	A1	R2	G2	B2	A2	R3	G3	B3	A3	Back Color
0x0-	Z0			S0	Z1			S1	Z2			S2	Z3			S3	Depth & Stencil
	0x0															0xF	

Figure 5.6: Pixel Quad Memory Layout. Pixel quads (not fragment quads, because these are the final pixels in the framebuffer), are group by component in the framebuffer memory. Efficient block memory transactions that read or write 16 bytes at a time may be used.

5.3.6 Fragment Processor

The fragment stage of the pipeline consists of the fragment processor itself and its attached memory system. The fragment processor receives fragment quads from the texture processor and performs all the per-fragment operations of the OpenGL pipeline, such as the depth test and blending. The memory system attached to each fragment processor is used to store the subset of the framebuffer and the texture data owned by this pipeline.

The use of fragment quads, in addition to reducing network bandwidth, allows efficient access to the memory system by grouping reads and writes into 16-byte transactions. Each pixel quad is organized by pixel component rather than by pixel, so, for example, all of the depth components are contiguous and may be accessed in a single transaction, shown in figure 5.6. This improves Pomegranate's efficiency in the peak performance case of fully covered fragment quads, and when fragment quads are only partially covered Pomegranate is already running beneath peak pixel rates, so the loss of memory efficiency is not as important.

The memory system provides 6.4 Gbyte/sec of memory bandwidth. At 400 Mpixel/sec and 8 to 12 bytes per pixel (a depth read, depth write, and color write), fragment processing utilizes 3.2 to 4.8 Gbyte/sec of this bandwidth. When combined with texture accesses of

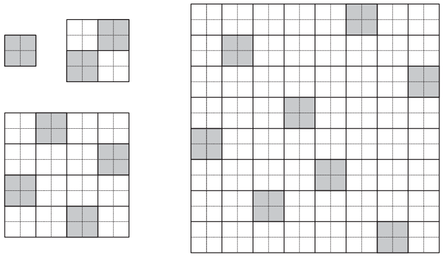


Figure 5.7: Framebuffer Tiling Patterns. The framebuffer tiling patterns for 1, 2, 4, and 8 pipeline systems are shown. The tiling patterns are $n \times n$ quads, and pipeline 0 owns 1 quad in each row and 1 quad in each column. In each case, pipeline 0 owns the shaded pixel quads. Subsequent quads on each row are owned in turn by the remaining pipelines.

1.6 to 3.2 Gbyte/sec and display accesses of 0.5 Gbyte/sec, the memory system bandwidth is overcommitted. Memory access is given preferentially to the display processor, since it must always be serviced, then to the fragment processor, because it must make forward progress for the texture processor to continue making forward progress, and finally the texture access unit. The majority of our results are not memory access limited.

Pomegranate statically interleaves the framebuffer at a fragment quad granularity across all of the fragment processors, depicted in figure 5.7. This image parallel approach has the advantage of providing a near perfect load balance for most inputs. As with the rasterizers, the fragment processors maintain the state of *n* hardware contexts. While the rasterizers will see work for a single context from any particular geometry unit, the fragment processor will see work for a single context from all the texture processors because the geometry stage's distribution processor distributes work for a single context over all the rasterizers.

5.3.7 Display

The display processor is responsible for retrieving pixels from the distributed framebuffer memory and outputting them to a display. Each pipeline's display processor is capable of driving a single display. The display processor sends pipelined requests for pixel data to all of the fragment processors, which in turn send back strips of non-adjacent pixels. The display processor reassembles these into horizontal strips for display. Unlike the use of the network everywhere else in Pomegranate, the display system is very sensitive to latency — if pixels arrive late, gaps will appear in the displayed image. We address this issue with a combination of buffering, which enables the display processor to read ahead several scanlines, and a priority channel in the network. Dally has shown that a bounded percentage of the traffic on a network can be made high priority and delivered with guaranteed latency [Dally, 1992]. At a display resolution of 1920 × 1280 and a 72 Hz refresh rate, the display bandwidth is 0.5 Gbyte/sec, 5% of Pomegranate's per-pipeline bandwidth.

Chapter 6

Pomegranate: Ordering and State

Ordered execution of the application command stream must be maintained everywhere its effects are visible to the user. The work distribution algorithms described in the previous chapter explain how the Pomegranate architecture scales performance, but the constraint of ordering was ignored. By far the most prevalent place this constraint is exposed is the OpenGL API itself, which is stateful. For example, a `glBlendFunc` command modifies the blending state for all subsequent primitives and for no previous primitives. Second, many commands (i.e. points, lines, triangles) modify the contents of the framebuffer, and these modifications must occur in order at each pixel. Finally, changes to the texture memory must be ordered.

We first describe the mechanisms used to provide ordered execution of a single context, and the extensions to support the interleaving of multiple contexts subject to the parallel API. We then discuss Pomegranate's state management, which relies upon these ordering mechanisms.

6.1 Ordering

Pomegranate faces two distinct ordering issues. First, the commands for a single context are distributed over the rasterizers, which in turn sort their fragments to the fragment processors. As a result, the original order of execution, while preserved at the rasterizers, is lost at the fragment processors, as shown in figure 6.1. This two-stage communication means that the original order of the command stream must be communicated to the fragment processors to allow them to merge the fragments in the correct order. Second, the operations of different contexts must be interleaved in a manner that observes constraints specified by the parallel API.

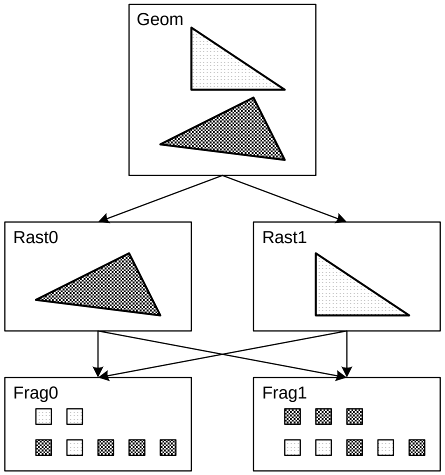


Figure 6.1: Two Stage Communication Loses Serial Ordering. When the triangles are distributed from the geometry processor to the rasterizers, the work is still in order – it has just been distributed. However, as each rasterizer emits fragments they are sorted to the appropriate fragment processor, and will arrive interleaved with the fragments of the other rasterizers.

6.1.1 Serial Ordering

The key observation to implementing ordering within a single context is that every place work is communicated, the ordering of that work must be communicated as well. The first stage of communication is managed by the distribution processor, which distributes blocks of primitives over the rasterizers. Every time it stops sending primitives to the current

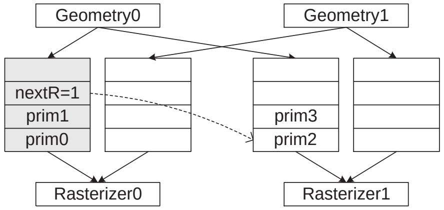


Figure 6.2: `NextR` operation. Geometry processor 0 distributes its first 2 primitives to rasterizer 0, and its second two primitives to rasterizer 1. It expresses the ordering constraint between them with a `NextR` command. Shading denotes primitives and commands processed by rasterizer 0.

rasterizer and starts sending primitives to a new rasterizer it emits a `NextR` command to the current rasterizer, announcing where it will send subsequent primitives. Figure 6.2 shows the operation of this mechanism. These `NextR` commands provide a linked list of the primitive order across the rasterizers. The rasterizers in turn broadcast the `NextR` commands to all the fragment processors. Each rasterizer has dedicated command buffering for each geometry processor, so that the commands from different geometry processors may be distinguished.

The fragment processors each have dedicated buffering for receiving commands from each of the rasterizers, as illustrated in figure 6.3. Each fragment processor executes commands from a single rasterizer at a time. When a fragment processor executes a `NextR` command, it ceases listening to the current rasterizer and starts listening to the specified next rasterizer. This is analogous to following the linked list of `NextR` commands emitted by the distribution processor. While a fragment processor processes commands from only a single rasterizer at any point in time, all of the rasterizers can continue to make forward progress and to transmit fragments to the fragment processors where they will be buffered.

One concern that arises with this mechanism is the overhead of communicating the `NextR` commands. The amount of traffic generated by `NextR` commands from a geometry unit to a rasterizer is limited. When the scene is rasterization limited the distribution processor will switch rasterizers quite frequently, but the overhead of the `NextR` commands

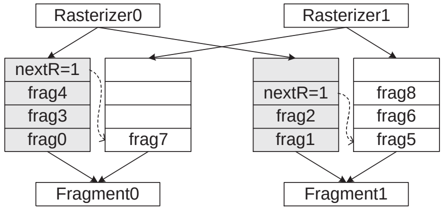


Figure 6.3: `NextR` operation continued. Rasterizer 0 and rasterizer 1 simultaneously process the primitives distributed to them by geometry processor 0. After rasterizing primitive 1, rasterizer 0 broadcast a `NextR` to all the fragment processors, announcing that they should now process fragments from rasterizer 1. The texture processors have been omitted for clarity. Shading denotes fragments and commands emitted by rasterizer 0.

sent to the rasterizers will be very small compared to the number of fragments being communicated between the texture processors and the fragment processors. When the scene is geometry limited the distribution processor will switch rasterizers every 16 vertices, and thus one single-flit `NextR` packet is sent to a rasterizer for every 16 two-flit vertex packets sent to a rasterizer. This represents an overhead of approximately 3%, which remains constant as the system scales. The `NextR` messages from the rasterizers to the fragment processors, on the other hand, represent a potential broadcast in the system because each rasterizer must broadcast each `NextR` it receives to all the fragment processors. Fortunately, this broadcast may be avoided by employing a lazy algorithm. Because `NextR` commands take only a few bits to encode, we can include space for a potential `NextR` command in every fragment quad without increasing its size in network flits. Because the fragment processors have very finely interleaved responsibility for quads on the screen, chances are good that a fragment quad will be sent to the fragment processor shortly after the `NextR` command is observed by the rasterizer. A timeout ensures that a `NextR` command that is waiting to piggyback on a fragment quad is not excessively delayed, prompting the rasterizer to send as many outstanding `NextR` commands as possible in a single network packet.

In general, the fragment processors operate independently, each processing fragments at its own rate. The exception is when a command observes or modifies shared state beyond that on a single fragment processor, in which case the fragment processors must be synchronized. Pomegranate uses an internal fragment barrier command, BarrierF, to support this synchronization. For example, glFinish has an implementation similar to this pseudocode:

```
glFinish( ) {
   BarrierF
   hardware writeback to device driver
}
```

The BarrierF ensures that all previous operations by this context are complete on all fragment processors before the writeback signaling completion of the glFinish occurs.

A similar issue arises at the rasterizers. If a command modifies the current texture state, which is shared among the multiple rasterizers, it must be executed in the correct serial order with respect to the other commands from that context. Pomegranate enforces this constraint with an internal BarrierR command which forces all of the rasterizers to synchronize. A texture modification command can be bracketed between BarrierR commands and thus be made atomic within the hardware. For example, glTexImage2D has an implementation similar to this pseudocode:

```
glTexImage2D( ) {
  BarrierR
  texture download
  cache flush
  BarrierR
}
```

The initial BarrierR ensures that all previous commands for this context are complete on all rasterizers before the texture download starts so that the new texture does not appear on any previous primitives. The final BarrierR ensures no subsequent commands for this context are executed on any rasterizer before the texture download completes, so that the old texture does not appear on any subsequent primitives.

	entries	bytes/entry	bytes
Primitive	4096	120	480K
Texture	256	72	18K
Fragment	4096	32	128K

Table 6.1: Total FIFO sizes for each of functional unit. The FIFO size is listed as the total number of commands it can contain. The primitive FIFO is the FIFO at the input to the rasterizer, and determines how many primitives a geometry unit can buffer before stalling. The texture FIFO is the FIFO that receives texture memory requests and replies and determines how many outstanding texture memory requests the texture system can have. The final major FIFO is the fragment FIFO, which is where the fragment processors receive their commands from the texture processors. The *n* pipeline architecture uses the same FIFOs as the 1 pipeline architecture, but divides them into *n* pieces. The FIFO sizes have been empirically determined.

The Pomegranate architecture is designed with the expectation that the same parts which construct the base processors are repeated to create larger, more powerful systems. As part of this assumption, the amount of buffering at the input of each fragment processor is fixed. This buffering is always divided evenly among all the rasterizers, so as the number of pipelines increases the buffering available per rasterizer at each fragment processor shrinks. However, the increase in the number of pipelines matches this decrease, and the total amount of buffering per rasterizer across all fragment processors remains constant.

The total amount of buffering available per rasterizer determines the fragment limit used by the distribution processor. In an *n*-pipeline system, each rasterizer only has the attention of the fragment processors one n^{th} of the time on average. To maintain good efficiency, it must be the case that the other $1-1/n$ fraction of the time the rasterizer's fragments will be absorbed by the buffering at the fragment processors. If the distribution processor assigns f fragments per rasterizer before emitting a NextR, then on average a rasterizer will emit $f\frac{n-1}{n} \approx f$ fragments while the fragment processors service the other $n-1$ rasterizers. To avoid blocking, f should be less than the total per rasterizer buffering available at the fragment processors. Pomegranate sets the distribution processor fragment limit f to 4096 fragments, and the per fragment processor buffering is 4096 quads, or 16384 fragments. Table 6.1 summarizes the sizes of Pomegranate's FIFOs.

Although we have not examined the cost of the BarrierR command in our experiments, it clearly may be an expensive operation, because it forces all of the rasterizers to synchronize. Because a geometry processor gives at most $f = 4096$ fragments to a rasterizer before switching to a new rasterizer, in the simple case of serial operation the cost of this synchronization is f, the maximum number of fragments assigned to a rasterizer by a geometry processor, divided by the rasterization rate of 400 Mpixel/sec, or 10μS. This analysis is complicated by parallel applications, in which the rasterizers are receiving work from multiple geometry processors, but because the geometry processors are balancing their work distribution we expect the rasterizers to all encounter the `BarrierR` command at approximately the same time, as in the serial case. The potential performance lost to synchronizing at `BarrierF` commands is likely much smaller than for `BarrierR` commands because the distribution of work over the fragment processors is balanced over very short time scales, and thus the fragment processors are likely to encounter the `BarrierF` command at very nearly the same time.

6.1.2 Parallel Ordering

The internal hardware commands `NextR`, `BarrierR` and `BarrierF` suffice to support serial ordering semantics. The extension of the hardware interface to a parallel API requires additional support. The parallel API requires that some or all of the graphics resources be virtualized, and more importantly, subject to preemption and context switching. Imagine an application of $n+1$ graphics contexts running on a system that supports only n simultaneous contexts. If a graphics barrier is executed by these $n+1$ contexts, at least one of the n running contexts must be swapped out to allow the $n+1^{\text{th}}$ context to run. Furthermore, the parallel API introduces the possibility of deadlock. Imagine an incorrectly written graphics application that executes a `glSemaphoreP` that never receives a corresponding `glSemaphoreV`. At the very least, the system should be able to preempt the deadlocked graphics context and reclaim those resources. Resolving the preemption problem was one of the most difficult challenges of the Pomegranate architecture.

One solution to the preemption problem is the ability to read back all of the state of a hardware context and then restart the context at a later time. Although this may seem straightforward, it is a daunting task. Because a context may block at any time, the preempted state of the hardware is complicated by partially processed commands and large partially-filled FIFOs. As a point of comparison, microprocessor preemption, which has a much more coherent architecture compared to a graphics system, is generally viewed by computer architects as a great complication in high-performance microprocessors.

A second approach to the preemption problem is to resolve the API commands in software, using the preemption resources of the microprocessor. With this approach, even though ordering constraints may be specified to the hardware, every piece of work specified has been guaranteed by the software to eventually execute. Figure 6.4 illustrates this approach. Each graphics context has an associated submit thread that is responsible for resolving the parallel API commands. The application thread communicates with the submit thread via a FIFO, passing pointers to blocks of OpenGL commands and directly passing synchronization primitives. If the submit thread sees a pointer to a block of OpenGL commands, it passes this directly to the hardware. If the submit thread sees a parallel API command, it actually executes the command, possibly blocking until the synchronization is resolved. This allows the application thread to continue submitting OpenGL commands to the FIFO beyond a blocked parallel API command. In addition to executing the parallel API command, the submit thread passes the hardware a sequencing command that maintains the order resolved by the execution of the parallel API command. The important part of this hardware sequencing command is that even though an ordering is specified, the commands are guaranteed to be able to drain: the hardware sequencing command for a `glSemaphoreP` will not be submitted until the hardware sequencing command for the corresponding `glSemaphoreV` is submitted. Thus, a blocked context is blocked entirely in software, and software context switching and resource reclamation may occur.

In order to keep hardware from constraining the total number of barriers and semaphores available to a programmer, the internal hardware sequencing mechanism is based on a single sequence number per hardware context. Upon executing a `glSemaphoreV` operation, the submit thread increments the hardware context's sequence number by one to indicate a new ordering boundary, annotates the semaphore with a (*ctx*, *seq*) pair and issues an `AdvanceContext` (*ctx*, *seq*) command to the hardware. Upon completing the `glSemaphoreP` operation, the signaled submit thread removes the corresponding (*ctx* , *seq*)

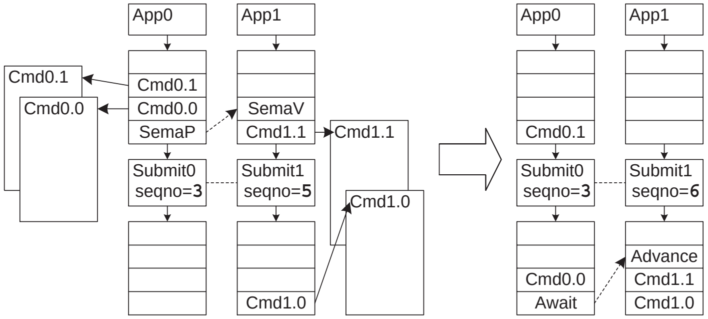


Figure 6.4: Submit Threads. Each graphics context has an associated submit thread which is responsible for resolving the parallel API primitives. On the left, submit thread 0 is blocked waiting to resolve a semaphore P that will be released by context 1. Both application threads are continuing to submit work, and the hardware is continuing to consume work. On the right, submit thread 1 has processed the semaphore V, which caused it to increment its sequence number, and release submit thread 0, which in turn submitted a dependency on that sequence number.

annotation from the semaphore and issues a `AwaitContext` (*ctx*, *seq*) command to the hardware.

An extended version of the semaphore mechanism is used to implement barriers. The first $n-1$ submit threads to arrive at the barrier execute an `AdvanceContext` to create a sequence point and block. The last context to arrive at the barrier executes an `AwaitContext` on the previous $n-1$ contexts, an `AdvanceContext` to create its own sequence point and then unblocks the waiting contexts. The $n-1$ waiting contexts then each execute an `AwaitContext` on the nth context's just created sequence point, for a total of n `AdvanceContexts` and n `AwaitContexts`. Figure 6.5 shows an example execution of a 4 context barrier.

A sequence number is associated with a particular hardware context, not with a virtual graphics context, and when a context switch occurs, it is not reset. This allows us to express dependencies for contexts that have been switched out of the hardware, and thus execute an $n+1$ context barrier on n context hardware.

context A	contextB	context C	context D
Advance(A, seqA)	Advance(B, seqB)	Advance(C, seqC)	
			Await(A, seqA)
			Await(B, seqB)
			Await(C, seqC)
			Advance(D, seqD)
Await(D, seqD)	Await(D, seqD)	Await(D, seqD)	

Figure 6.5: Example `glBarrierExec` Resolution. This figure depicts the resolution of a parallel API barrier across 4 contexts. The first 3 contexts to arrive at the barrier generate sequence points. The last context to arrive at the barrier, D, waits for all of those sequence points, ensuring that every context has reached the barrier. Context D, once it success completes its 3 wait operations, has passed the barrier and emits a sequence point. Context A, B and C wait for the D's sequence point, because when D passes the barrier, by extension all contexts pass the barrier. Alternatively, each context could wait on all the other contexts, but that requires order $O(n^2)$ communication, while this solution is $O(n)$.

Given the `AdvanceContext` and `AwaitContext` commands for expressing ordering constraints among contexts, Pomegranate now needs a way of acting on these constraints. The sequencer unit provides a central point for resolving these ordering constraints and scheduling the hardware. The distribution processors at the end of the geometry stage, each of which is dedicated to a single hardware context, inform the sequencer when they have work available to be run and what ordering constraints apply to that work. The sequencer then chooses a particular order in which to process work from the various contexts and broadcasts this sequence to all of the rasterizers, which, along with all the subsequent stages of the pipeline, are shared among all the contexts.

The sequencer processes three distinct commands. Whenever a distribution processor starts emitting primitives, it sends a `Start` command to the sequencer to indicate that it has work available to be scheduled. In addition, distribution processors transmit all `AdvanceContext` and `AwaitContext` commands for their associated context to the sequencer, which in turn enforces the ordering relationships expressed by these commands when making its scheduling decisions. The sequencer receives these commands from all of the distribution processors, and as elsewhere, distinguishes them by buffering them all separately.

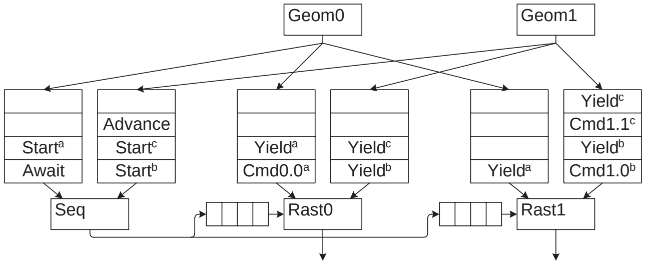


Figure 6.6: Sequencer Operation. This figure continues the execution of the contexts shown in figure 6.4. The superscripts on FIFO entries mark related commands. For example, geometry processor 0 sends Start^a to the sequencer to announce it has work available to schedule. It then sends the work, Cmd0.0^a, to rasterizer 0, and follows it with a Yield^a, which is broadcast to all the rasterizers. In this case the sequencer would be forced to choose the order of execution 1, 1, 0. The blocks of commands are shown as if they are single primitives in this example, although in reality they could be multiple commands, and can involve the use of NextR commands to thread their execution across the rasterizers.

An AdvanceContext command causes the sequencer to increment the sequence number tracked for the corresponding context. An AwaitContext command blocks further processing of commands for that context until the context waited on has reached the specified sequence number. When the sequencer processes a Start command it broadcasts an Execute instruction to all of the rasterizers, instructing them to execute instructions from the corresponding context. Each rasterizer maintains a queue of Execute instructions, and processes them in order. The sequencer processes commands as quickly as it can, subject to the constraints imposed on it by the AwaitContext commands and the available buffering for execution commands at the rasterizers.

The counterpart of the Start command is the Yield command. When a distribution processor starts emitting work, it sends a Start to the sequencer to announce the availability of work to schedule, and when it ceases emitting work it broadcasts a Yield to all the rasterizers. When a rasterizer encounters a Yield it reads the next Execute command

from the sequencer and starts executing that context. The Yield command provides context switching points to support ordering and to allow the pipelines to be shared. First, if a context waits on another context, it must also yield to allow the rasterizers to work on other contexts, which will eventually allow this context to run again. Second, a context must occasionally yield voluntarily, to allow the hardware to be shared among all the contexts so that a single context does not unfairly monopolize the machine. The frequency of these yields is determined by the relationship of the triangle rate of the geometry units to the command buffering provided at each rasterizer. In our implementation, a context yields once it has sent one NextR command to each rasterizer, or has exceeded a fixed timeout since the last primitive it transmitted, chosen such that it is likely the geometry processor is idle. Figure 6.6 illustrates the relationship between the sequencer, the geometry (distribution) processors, and the rasterizers.

The use of a central scheduler, the sequencer, to resolve ordering imposes two limitations on the architecture. First, it limits the minimum efficient amount of work between Start and Yield commands. Second, it limits the maximum efficient granularity of parallelism.

If too small a granularity of work is used the system is limited by the rate at which the sequencer can make scheduling decisions and transmit them to the rasterizers. Our system can make 125 million scheduling decisions a second, which in a full 64-pipeline system operating at 20 Mtri/sec per pipeline corresponds to approximately a 10-triangle granularity of work, which is quite small. In reality, the sequencer becomes limited by the bandwidth of transmitting Execute commands to the rasterizers in this case. Because the Execute commands are always broadcast, and there are at most 125 million of them a second, one solution to this limitation would be to introduce a dedicated ring network that connects the sequencer to all the rasterizers, to allow it to efficiently broadcast Execute commands.

If too large a granularity of work is chosen by the application, and there is not an adequate amount of available parallelism (for example, the application uses the parallel API to enforce a total order), then the execution will become serialized, as all of the rasterizers wait for the primitives being emitted by one geometry processor. This is analogous to choosing the correct granularity of NextR commands, as discussed in section 6.1.1. In this case, the application should use a granularity of parallelism smaller than the amount of primitive buffering available at the inputs to the rasterizers. We rely on the programmer to chose an appropriate granularity of parallelism. If the parallel API constrains the hardware to process a large number of primitives from one context before it processes the next context, nothing can be done to change this.

6.2 State Management

The most difficult issue in state management is maintaining the ordered semantics of the interface. In the previous section we explained our ordering mechanisms for serial and parallel contexts. Given those mechanisms, ordering the execution of the state commands with respect to the primitives they affect is straightforward. Our second issue to deal with is support for context switching, so the hardware's physical contexts may be virtualized.

6.2.1 State Commands

State commands modify the configuration of the pipeline, and are ordered with respect to all other commands. Thus setting the `glBlendFunc`, for example, affects the compositing of all subsequent primitives with the framebuffer, but no previous primitives. We maintain this ordering constraint in Pomegranate by treating state commands just as we treat vertices, primitives, fragments, and other forms of work that flow through the pipelines. The state commands are buffered in the input FIFOs to each stage, and executed in order as a result.

A slight complication is introduced by the duplication of contexts in the rasterizers, texture processors, and fragment processors. Because each rasterizer executes commands from all of the geometry processors, it must maintain a copy of every context in the system. Thus, state commands that affect rasterizer or texture processor state must be broadcast by the geometry processor to all of the rasterizers. Similarly, fragment processor state changes must be broadcast. However, in this case the broadcast is performed by a texture processor – there is no need for all of the rasterizers to observe fragment processor state commands. The geometry processor simply emits fragment processor state commands just like any other primitive, and whatever rasterizer/texture processor pair happens to receive the command will then broadcast it to the fragment processors. Figure 6.7 shows the communication paths for various state commands.

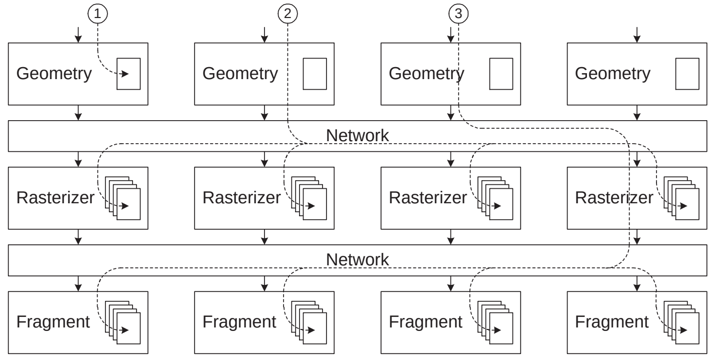


Figure 6.7: Communication of State Commands. Commands that update the command processor or geometry processor context are handled directly, as there is only a single copy of the state (1). Commands which update the rasterizer, texture processor or fragment processor context must be broadcast from the previous stage, to update each copy of the duplicated contexts. (2,3).

There are two potential issues with Pomegranate's duplication of contexts. First, it sets an absolute limit on the number of pipelines which Pomegranate can support. Second, the use of broadcast communication to update the contexts may result in in a lack of scalability.

In practice, duplication of the hardware contexts in the rasterizers and subsequent stages is not a major issue, as the size of the contexts is relatively small. The size of the various contexts is summarized in table 6.2. As shown, the cost of supporting 64 hardware contexts is a modest 28.1 KB of memory.

Broadcast of state changes is potentially a more troublesome issue. If, for example, each application context changes its rasterization state every 64 primitives, then in a 64 pipeline system half of the commands processed by the rasterizers will be state commands, instead of primitives. We believe this should not be a serious issue for several reasons.

	bits/context	64-pipeline
Command	6,425	6,425
Geometry	86,351	86,351
Rasterizer	1,214	77,696
Texture	856	54,784
Fragment	80	5,120
Total		230,376

Table 6.2: Context Size. The size in bits of the context associated with each functional unit, and the total per-pipeline storage for a Pomegranate with support for 64 pipelines. The command processor and geometry processor are dedicated to a single interface and only require a single context, while the subsequent pipelines stages must support *n* contexts. The total storage requirements are 230,376 bits, or 28.1 KB.

First, the majority of state commands modify vertex attributes (texture coordinates, geometric normal, color, etc.) and are thus part of the command processor context, which is maintained in a single location and not broadcast. Second, programmers already structure their submission of commands to the hardware to deliberately sort by mode, minimizing potentially expensive state changes. Finally, we expect that the applications which can make use of a large, parallel, graphics accelerator will typically be of the style of scientific visualization applications – large amounts of geometry, but comparatively few mode changes.

All of that being said, if broadcast state changes do prove to have a significant performance impact, we propose the adoption of lazy state updates at each point in the pipeline where a broadcast state update is currently performed. For example, if the blend function is updated the texture processor would note the new value of the blend function, and only transmit it to fragment processors when it sends them a fragment, thus avoiding broadcasting the blend function when it is changing frequently. In the likely common case of the blend function changing infrequently, the complete broadcast of the state change still occurs, it is simply performed lazily. Thus the incremental cost of lazy state updates is just the additional cost of replicating context information (such as the blend function) at all of the earlier stages of the pipeline. As shown in table 6.2, the size of the individual contexts after the geometry processor are comparitively small, so this duplication is readily affordable.

6.2.2 Context Switching

Context switching has historically been a sticking point in graphics architecture, although its importance has long been recognized. Voorhies, Kirk and Lathrop discuss the advantages of providing graphics as a “virtual system resource”, and stress that the key to virtualizing the graphics system is to “switch low-level contexts rapidly” [Voorhies et al., 1988].

Context switching can be implemented in a number of fashions. One approach is to shadow all of the graphics state in software, in which case context switching is as simple as submitting state commands to make the hardware reflect the new context. Shadowing the state of every graphics command in software would be very expensive however, particularly since some state, notably the vertex attributes, is expected to change very frequently. Because the hardware must maintain the context, another possible approach is to read back the context from the hardware. Thus, while context switches are now somewhat more expensive (as they require a round-trip to the hardware), the common case of command submission is significantly faster. Many architectures directly use the second approach, but unfortunately things are not quite that simple for Pomegranate.

Pomegranate’s implementation of the parallel API has major ramifications for context switching. Unlike a graphics system with a serial interface, application commands may not be able to complete without a context switch. For example, a barrier of $n+1$ contexts executing on *n* context hardware requires context switching. Thus context switching can not be executed simply by allowing all previous commands to complete execution and then reading back the hardware state, because those commands may be blocked from completion. Part of our motivation for introducing the submit threads was to insure that commands submitted to the hardware (versus those buffered, but waiting for submission by the submit threads) are guaranteed to drain, so we will never deadlock the hardware.

We propose the following solution to address context switching on Pomegranate. Each application process with a bound graphics context (and thus a potential user of a hardware graphics context) has its own independent submit thread. Each hardware context has an associated lock, and when the submit thread wishes to submit a block of work to the hardware, it must first acquire the appropriate hardware lock. The lock guards both access to the hardware and to a shared variable which indicates what submit thread currently owns this context. A submit thread which does not currently own a hardware context may context switch by acquiring the lock for a hardware context, and then, while holding the lock, reading back the hardware state of the context and saving it away for the previous submit thread owner, and finally updating the shared variable to indicate it owns the context. The preempting submit thread then updates the hardware with its context, which was saved away the last time it was context switched, and resumes submission of application commands.

In this scheme every time the hardware is touched a lock must be acquired, but we believe this will not have any significant performance impact, because the lock needs to be acquired only per command block, which greatly amortizes the cost of lock acquisition. Furthermore, with an appropriate choice of mechanism, the acquisition of the lock by the thread which currently owns the hardware context can be made very fast. Additionally, we can reduce the cost of the context switch by hiding the readback. The preempting thread does not need to wait for the readback of the previous thread's context. As long as the readback is performed in order, before the commands which set the state for the preempting context, the readback may happen asynchronously. Whether the state is read back synchronously or asynchronously, some care must be taken to insure that the preempted submit thread does not preempt another context and start executing again before its state has been returned. Similarly, a sequence point must be created to insure that when the preempted context does start executing again the commands it submits on the new hardware context remain ordered behind the commands it submitted on its previous hardware context.

Given this mechanism, an appropriate policy must also be chosen for context switching the hardware. Without some care, two submit threads could spend all of their time passing a hardware context back and forth, neither of them making any progress. One possible solution is to include a timer, so that a submit thread will always preempt the submit thread which has owned its hardware context the longest. Alternatively, simply preempting a random context, as long as it has owned the hardware for some minimum number of milliseconds, would likely work well.

Chapter 7

Simulation and Results

We have implemented an OpenGL software device driver and hardware simulator to verify our architecture. Our system supports all of the major functionality of OpenGL.

The Pomegranate hardware is modeled under an event-driven simulator. The simulator is composed of multiple independent threads of execution which communicate with each other via events. Threads advance events and await on events to coordinate their execution. The simulator provides a shared global knowledge of time, so threads may both wait for other threads to complete a task, as well as simply wait for time to pass to model clock cycles, etc. The simulator is non-preemptive and a particular thread of execution ceases execution only when it explicitly waits for time to pass or waits on an event.

Our simulator masquerades as the system OpenGL dynamic library on Microsoft Windows NT and SGI IRIX operating systems. Application parallelism is supported through additional functions exported by our OpenGL library that allow the creation of user threads within our simulator. This simulation methodology allows us to deterministically simulate Pomegranate, which aids both debugging and analysis of performance. In particular, performance problems can be iteratively analyzed by enabling more and more instrumentation in different areas of the hardware, with the confidence that subsequent runs will behave identically.

We analyzed Pomegranate's performance with three applications, shown in table 7.1. The first, March, is a parallel implementation of marching cubes [Lorensen and Cline, 1987].

scene	March	Nurbs	Tex3D
input	400^3 volume	1632 patches, 8 passes	256^3 volume
output	2.5K × 2K	2.5K × 2K	1K × 1K
triangles	1.53M	6.68M	512
fragments	10.4M	8.83M	92.5M

Table 7.1: Benchmark Scenes.

The second, Nurbs, is a parallel patch evaluator and renderer. The final, Tex3D, is a 3D texture volume renderer.

- March extracts and draws an isosurface from a volume data set. The volume is subdivided into 12^3 voxel subcubes that are processed in parallel by multiple application threads. The subcubes are drawn in back to front order, allowing the use of transparency to reveal the internal structure of the volume. The parallel API is used to order the subcubes generated by each thread in back to front order. Note that while March requires a back to front ordering, there are no constraints between cubes which do not occlude each other, so substantial inter-context parallelism remains for the hardware.

- Nurbs uses multiple application threads to subdivide a set of patches and submit them to the hardware. We have artificially chosen to make Nurbs a totally ordered application in order to stress the parallel API. Such a total order could be used to support transparency. Each patch is preceded by a semaphore P and followed by a semaphore V to totally order it within the work submitted by all the threads. Multiple passes over the data simulate a multipass rendering algorithm.

- Tex3D is a 3D texture volume renderer. Tex3D draws a set of back to front slices through the volume perpendicular to the viewing axis. Tex3D represents a serial application with very high fill rate demands and low geometry demands, and is an example of a serial application that can successfully drive the hardware at a high degree of parallelism.

We measure Pomegranate's performance on these scenes in four ways. First we examine Pomegranate's raw scalability, the speedup we achieved as a function of the number of pipelines. Next we examine the load imbalance across the functional units, which will determine the best achievable speedup for our parallel system. Then we quantify the network bandwidth demanded by the different stages of the pipeline and analyze the lost performance due to network imbalance. Finally we compare Pomegranate's performance to simulations of sort-first, sort-middle and sort-last architectures.

7.1 Scalability

Our first measure of parallel performance is speedup, presented for our scenes in figure 7.1. Nurbs exhibits excellent scalability, despite presenting a totally ordered set of commands to the hardware. At 64 processors the hardware is operating at 99% parallel efficiency, with a triangle rate of 1.10 Gtri/sec and a fill rate of 1.46 Gpixel/sec. The only application tuning necessary to achieve this level of performance is picking an appropriate granularity of synchronization. Because Nurbs submits all of its primitives in a total order, the sequencer has no available parallel work to schedule, and is always completely constrained by the API. This results in only 1 geometry unit being schedulable at any point in time, and the other geometry units will make forward progress only while there is adequate buffering at the rasterizers and fragment processors to receive their commands.

March runs at a peak of 595 Mtri/sec and 4.05 Gpixel/sec in a 64-pipeline architecture, a 57× speedup over a single pipeline architecture. While this scalability is excellent, it is substantially less than that of Nurbs. If we examine the granularity of synchronization, the problem becomes apparent. Nurbs executes a semaphore pair for every patch of the model, which corresponds to every 512 triangles. March, on the other hand, executes 3 semaphore pairs for every 12^3 voxel subcube of the volume, and the average subcube only contains

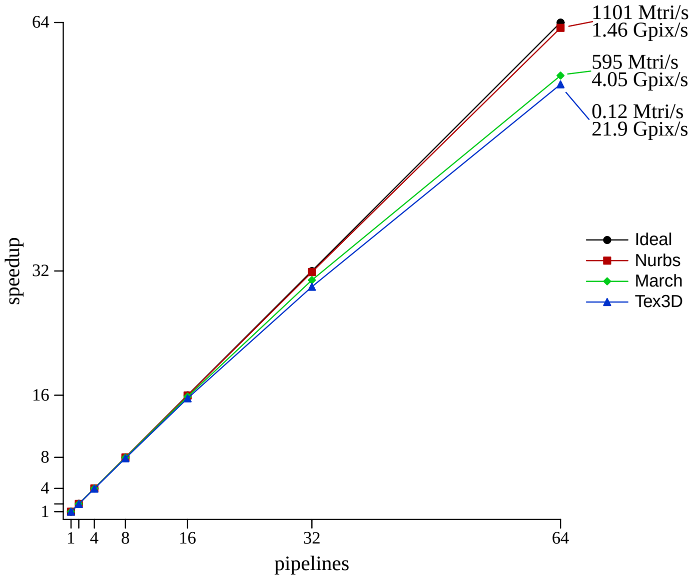


Figure 7.1: Pomegranate speedup vs. number of pipelines.

38.8 triangles. Thus, the number of synchronization primitives executed per triangle is more than an order of magnitude greater than that of Nurbs. Furthermore, there is high variance in the number of triangles submitted between semaphores. These effects cause March to encounter scalability limitations much sooner than Nurbs, despite its much weaker ordering constraints.

Tex3D runs at 21.9 Gpixel/sec on a 64-pipeline Pomegranate, with a tiny 0.12 Mtri/sec triangle rate, a 56× speedup over a single pipeline architecture. Tex3D scales very well, considering that it is a serial application. If Tex3D's input primitives were skewed towards smaller triangles it would rapidly become limited by the geometry rate of a single interface and execution time would cease improving as we add pipelines.

	pipelines		
	4	16	64
Geometry	1.00/1.00	1.00/1.00	1.00/1.00
Rasterizer	1.00/1.00	1.00/1.00	0.98/1.02
Fragment	1.00/1.00	1.00/1.01	0.99/1.01
Network	0.99/1.03	0.98/1.22	0.96/2.52

Table 7.2: Load balance for Nurbs. Each entry in the table presents the minimum/maximum work done by any functional unit as a fraction of the average work per functional unit. Geometry work is measured in triangles; rasterization and composition work is measured in fragment quads. The network imbalance is measured in bytes of traffic per pipeline. The large imbalance at 64 pipelines is because the sequencer is broadcasting commands to all of the rasterizers, and as a result pipeline 0 has significantly higher network usage than the other pipelines. This does not affect Nurbs because its performance is geometry limited and the substantial network bandwidth provided for rasterization is largely unused, allowing the imbalanced used of the network by the sequencer to be absorbed.

7.2 Load Balance

In order to achieve high parallel efficiency, the work performed by the hardware must be balanced across the functional units and the communication must be balanced across the network. Table 7.2 presents the load imbalance for Nurbs on our architecture with 4, 16, and 64 pipelines. The load balance is within a few percent for all the functional units. This indicates that Pomegranate's methodology for distributing work is providing us with an excellent load balance. By the time Nurbs reaches 64 pipelines the network is significantly out of balance. This is an artifact of Nurbs's relatively low network usage, as it is geometry limited, and the asymmetry of the network traffic generated by the sequence processor, as discussed in section 7.3. The results for March, shown in table 7.3, are qualitatively similar.

Table 7.4 shows the load imbalance for Tex3D. Despite all of the application commands arriving through a single interface, the subsequent rasterization and fragment stages still receive an extremely balanced load. The texture load imbalance is the ratio of the most texture requests handled by a pipeline to the average. Numbers close to 1 indicate that the shared texture memory is working effectively, because all of the texture requests are well distributed over the pipelines. Tex3D's network imbalance is becoming significant by

	pipelines		
	4	16	64
Geometry	1.00/1.00	1.00/1.00	0.99/1.02
Rasterizer	1.00/1.00	1.00/1.01	0.98/1.02
Fragment	1.00/1.00	1.00/1.00	0.99/1.01
Network	0.99/1.02	0.99/1.08	0.99/1.39

Table 7.3: Load balance for March.

	pipelines		
	4	16	64
Geometry	0.00/4.00	0.00/16.0	0.00/64.0
Rasterization	1.00/1.00	1.00/1.00	1.00/1.00
Texture	1.00/1.00	1.00/1.00	1.00/1.01
Fragment	1.00/1.00	1.00/1.00	0.99/1.00
Network	1.00/1.01	1.00/1.04	0.99/1.15

Table 7.4: Load balance for Tex3D.

the time we reach 64 pipelines. This large asymmetry is the result of all of the primitives entering through a single interface and being distributed from a single geometry unit. As Pomegranate is scaled, the total rasterization speed increases, but the entire geometry traffic is still borne by a single pipeline.

7.3 Network Utilization

There are five main types of network traffic in Pomegranate: geometry, sequencer, texture, fragment and display. Geometry traffic comprises vertices transmitted from the geometry processor to the rasterizers and the `NextR` ordering commands, as well as any state commands, textures, etc. for the subsequent stages. Sequencer traffic is the communication between the distribution processors and the sequencer as well as the sequencer and the rasterizers, and encapsulates all the traffic which allows the hardware to be shared among multiple contexts. Texture traffic is made up of the texture request and texture reply traffic generated by each texture processor. Fragment traffic is composed of the quads emitted by the texture processors and sent to the fragment processors. Display traffic is the pixel read requests and replies between the display processors and the fragment processors.

	March	Nurbs	Tex3D
Geometry	0.84/0.85	0.54/0.58	0.01/0.93
Sequencer	0.02/1.06	0.05/2.95	0.00/0.14
Texture	0/ 0	0/ 0	3.00/3.01
Fragment	1.82/1.84	1.19/1.20	3.31/3.32
Total	2.68/3.71	1.78/4.67	6.33/7.26

Table 7.5: Network traffic by type for each of our scenes on a 64-pipeline Pomegranate. Each row corresponds to a particular type of traffic and each pair of numbers is the average/maximum amount of traffic per pipeline of that type in gigabytes per second. These simulations do not include a display processor.

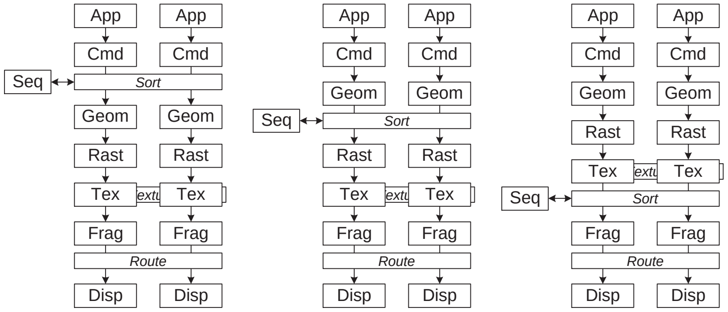
The network bandwidth for each traffic type across our scenes on a 64-pipeline Pomegranate is presented in table 7.5. The sequencer numbers are extremely skewed because there is a single sequencer in the system, so all sequencing information from the distribution processors flows into a single point, and all sequencing decisions for the rasterizers flow back out of that point, which introduces a broadcast into the system. In section 6.1.2 on page 102 we discuss the maximum overhead of the sequencer, and the possibility of using a ring network for the communication of the sequencing information. This would eliminate both a source of broadcast communication from Pomegranate's network, and the unbalanced use of the network by the sequencer.

7.4 Comparison

We compare Pomegranate's performance to 4 other parallel graphics architectures:

Sort-First sorts between the command processor and the geometry processor. The screen is statically partitioned in 32 × 32 tiles among the pipelines. The command processor transforms the screen-space bounding boxes of blocks of 16 vertices to route primitives to pipelines.

Sort-Middle Tiled is a sort-middle architecture with the screen statically partitioned in 32 × 32 tiles among the rasterizers. Individual primitives are only transmitted to the rasterizers whose tiles they overlap.



(a) Sort-First (b) Sort-Middle (c) Sort-Last Fragment

Figure 7.2: Sort-First, Sort-Middle and Sort-Last Fragment Architectures implemented on the Pomegranate simulator. Sort-middle tiled and sort-middle interleaved are both implemented as (b), the only difference being the granularity of the framebuffer tiling, and the use of broadcast vs. one-to-one communication between the geometry processors and the rasterizers.

Sort-Middle Interleaved partitions the screen in 2 × 2 tiles to ensure rasterization and fragment load-balancing. Each geometry processor broadcasts its primitives to all rasterizers.

Sort-Last Fragment partitions the screen in 2 × 2 tiles among the fragment processors. Each rasterizer is responsible for all the primitives transformed by its corresponding geometry processor.

These architectures, depicted in figure 7.2, are all built on top of the Pomegranate simulator, and differ only in how the network is deployed to interconnect the various components. We provide each of these architectures, although not Pomegranate, with an ideal network — zero latency and infinite bandwidth — to illustrate fundamental differences in the work distribution. Each of these architectures has been built to support the parallel API and a shared texture memory. The ordering mechanisms necessary to support the parallel

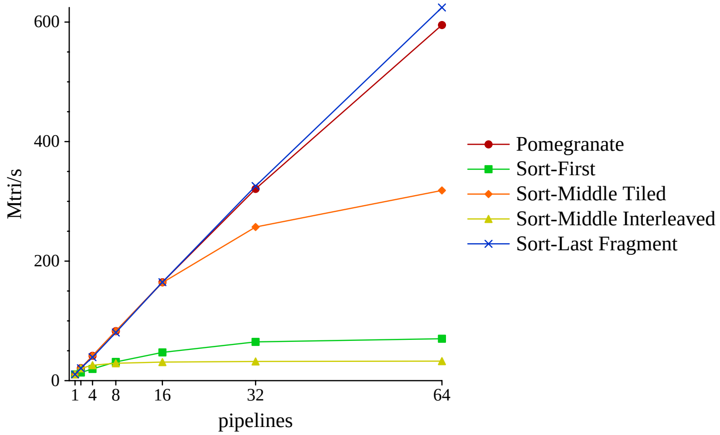


Figure 7.3: Millions of triangles per second vs. number of pipelines for each of the architectures on March.

API are borrowed from Pomegranate, although they are deployed in different places in the pipeline.

Figure 7.3 shows the performance of all of these architectures for the March data set. As March runs, all of the primitives are clustered along the isosurface, which results in high screen-space temporal locality. Sort-first, which uses coarse-grained image parallelism for both geometry and rasterization, is most severely impacted because temporal locality causes spatial load imbalances over short periods of time, the lengths of which are determined by the amount of FIFOing available. Sort-middle tiled employs object parallelism for the geometry stage, and, because this scene is not rasterization limited, exhibits substantially more scalability than sort-first, although its limitations are exposed at higher levels of parallelism. Sort-middle interleaved behaves much more poorly than sort-middle tiled because it broadcasts triangle work to every rasterizer, and each rasterizer can process a limited number of triangles per second. Sort-last fragment and Pomegranate both scale very well because they rasterize each triangle only once (eliminating redundant work) and

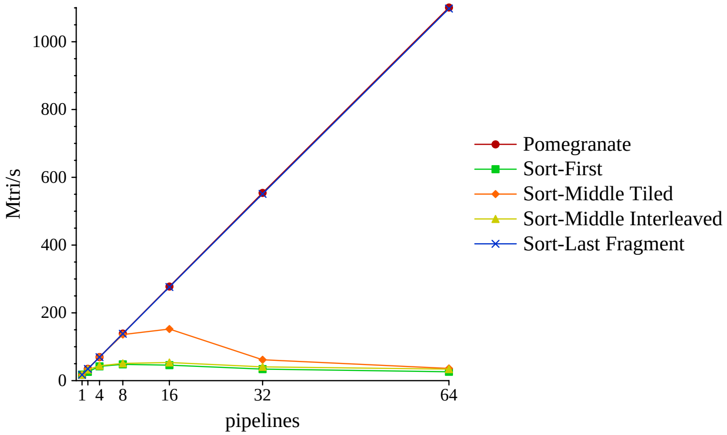


Figure 7.4: Millions of triangles per second vs. number of pipelines for each of the architectures on Nurbs.

use object parallelism for rasterization (eliminating any issues with temporal locality). The main difference between Pomegranate and sort-last fragment, the balancing of fragment work across rasterizers by the geometry processors, does not matter here because the triangles are relatively uniform in size.

Nurbs, shown in figure 7.4, exhibits much worse scalability for sort-first and sort-middle than March, and in fact even slows down at high degrees of parallelism. The granularity of work for Nurbs is a patch, which exhibits a great degree of temporal locality in screen-space, even greater than March, which explains the performance at low degrees of parallelism. However, unlike March, Nurbs is a totally ordered application, and when combined with architectures that use image parallelism for geometry or rasterization, the result is hardware that performs almost no better than the serial case. As the number of pipelines increases, the system is capable of processing more work. However, the amount of FIFOing available from each pipeline for each tile decreases, reducing the window over which temporal load imbalance may be absorbed. The hump in performance at moderate numbers

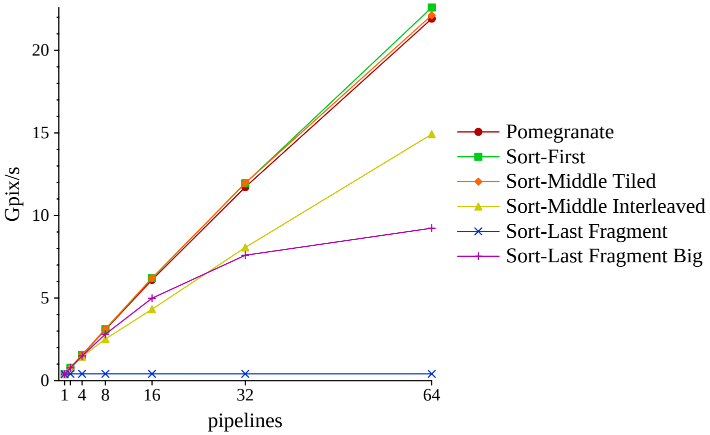


Figure 7.5: Billions of pixels per second vs. number of pipelines for each of the architectures on Tex3D. Sort-last fragment big is the same architecture as sort-last fragment, with the buffering at the fragment processors increased sufficiently to avoid serializing the rasterizers on large triangles.

of pipelines is a result of these effects. As with March, sort-last fragment and Pomegranate exhibit excellent scalability.

Unlike March and Nurbs, Tex3D, shown in figure 7.5, is a completely rasterization limited application. The speedup for sort-first and sort-middle tiled here is limited purely by the rasterization load balance of the entire frame, illustrating that even scenes which appear very well balanced in screen-space may suffer large load imbalances due to tiling patterns at high degrees of parallelism. Sort-middle interleaved, which was previously limited by its reliance on broadcast communication, is now limited by texture cache performance, which is severely compromised by the use of extremely fine-grained rasterization. Each triangle is so large in this application that it serializes sort-last fragment at the fragment processor stage: the fragment FIFOs provide elasticity for the rasterizers to continue ordered rasterization on subsequent triangles while the current triangle is merged with the framebuffer, but when a single large triangle fills up the entire FIFO this elasticity is lost and the rasterizers are serialized. If we greatly increase the buffering at the fragment processors, shown by the “sort-last fragment big” curve, so that sort-last fragment is no longer serialized by the large primitives, the fundamental problem with sort-last fragment is exposed: imbalances in triangle size cause load imbalances across the rasterizers. In Tex3D at 64 pipelines, the worst rasterizer has almost twice the work of an average rasterizer. Many applications (e.g. architectural walkthroughs) have a few very large polygons and exhibit much more severe imbalance in rasterization work than the relatively innocuous Tex3D. Pomegranate addresses this fundamental problem by load-balancing both the number of triangles and the number of fragments across the rasterizers, and exhibits excellent scalability on Tex3D.

Chapter 8

Discussion

Pomegranate was designed to support an immediate-mode parallel graphics interface and uses high-speed point-to-point communication to load-balance work across its pipelines. Our results have demonstrated the quantitative impact of these choices, and we will now revisit their qualitative benefits and costs. We also discuss the consistency model Pomegranate provides, which specifies how the commands of the various graphics contexts may be interleaved.

While the architecture we have developed is complete, Pomegranate presents interesting areas for further study. We consider possible future work in shared state management, automatic parallelization, and a revision of the Pomegranate architecture.

8.1 OpenGL and the Parallel API

The decision to support OpenGL, a strict serial API, has proven somewhat complicated to implement, but has not resulted in a performance impact. In fact, Nurbs, which totally orders the submission of its work across all contexts, achieves almost perfectly linear speedup, despite its very strong ordering constraints. The expense of supporting ordering is FIFOs which allow the various pipeline stages to execute commands in application order.

While it may be necessary for the application programmer to choose an appropriate granularity of parallelism, particularly in a strongly ordered scene, it is not required that the application balance fragment work, only primitive work. This is a desirable feature, as, in general, application programmers have little knowledge of the amount of fragment work that will be generated by a primitive, but they are well aware of the number of primitives being submitted.

8.2 Communication

Pomegranate uses a network to interconnect all the pipeline stages. This approach to interconnecting a graphics system has become much more practical recently due to the advent of high-speed point-to-point signaling, which reduces the cost of providing the multiple high bandwidth links necessary in such a network. Nonetheless, we expect the cost of the network to dominate the cost of implementing an architecture like Pomegranate.

Pomegranate achieves its high scalability only when it is able to use the network as a point-to-point communication mechanism. Every time broadcast communication is performed, scalability will be lost. However, some commands must be broadcast. Commands that modify the state of a particular context (e.g. `glBlendFunc`) must be broadcast to all of the units using that state. The command distribution could potentially be implemented lazily, but is still fundamentally a broadcast communication, which will impose a scalability limit. Most high performance applications already try to minimize the frequency of state changes to maximize performance. It remains to be seen how the potentially greater cost of state changes in Pomegranate would impact its scalability.

8.3 Consistency Model

Igehy, Stoll and Hanrahan introduced the notion of a *consistency model* for parallel graphics, as a way to describe the possible interleaving of the fragments of multiple primitives at the framebuffer [Igehy et al., 1998b]. Their discussion pertained to systems with a parallel interface, although if we relax the ordered semantics of the interface, by choice or by necessity, the same issues arise in any graphics architecture.

If we have a parallel graphics system, then the initial serial command stream from the application will be processed with some degree of parallelism internally before being committed to the framebuffer, which may itself be parallel. If ordering is not maintained within the system, then any point in the system where parallel computations are merged has an implied consistency model. We consider the two extreme models proposed by Igehy et al. In the first model, command-sequential consistency, entire commands (i.e. primitives) are considered atomic, and the hardware will interleave their execution. In the second model, fragment-sequential consistency, the only atomic operation is a framebuffer read-modify-write update. Without fragment sequential consistency, conventional operations such as depth compositing will not operate properly, because the compositing of one fragment may be interposed in the read-modify-write cycle of another fragment at the same screen location, leading to incorrect operation. Often systems which provide command-sequential consistency do so at a granularity greater than a single command. For example, the granularity of parallel work could be several primitives, in which case the resulting consistency model is “several-command-sequential consistency”. However, because the interleaving may happen on any arbitrary command boundary, this model is still just command-sequentially consistent.

If we introduce the parallel API, then even a graphics system with ordered semantics *per context* will still have a sequential consistency model which describes how the different contexts may be interleaved. Systems such as Argus and Pomegranate rely on a central scheduler to choose the interleaving of the various contexts, and then communicate that ordering throughout the system, which results in command-sequential consistency. Parallel WireGL takes a different approach, and chooses an ordering independently on each rendering server, with the result that primitives which overlap the partitions of different rendering nodes may be interleaved differently on the two servers. Thus WireGL provides fragment-sequential consistency. The authors of the parallel WireGL system suggest that any application which generates deterministic images, either through depth-buffering or through expressing a total order with the parallel API, will operate correctly with just fragment-sequential consistency.

8.4 Shared State Management

One of the driving forces behind Pomegranate was to provide full support for ordered semantics, including inter-context ordering constraints expressed via the parallel API. Ordered semantics require that operations occur, or appear to occur, in the order specified. We have extensively described how we order the operations of a single graphics context. In most cases, computations for a single context may be performed independently of any other contexts, as the operations are not based on shared state. For example, the transformation of vertices by the geometry processor depends only on the particular graphics context (matrices, etc.). The exception to this rule is operations on shared state. The most visible piece of the shared state is the framebuffer, and we have already described how we support the ordering of the various graphics contexts operations upon it.

There are two other kinds of state that may be shared: texture objects and display lists. The idea of sharing texture and display list state is already present in GLX and wgl, the X11 and Microsoft Windows mechanisms for dealing with OpenGL contexts. Both of these interfaces allow a context to be specified to share display lists and texture objects with another context. The sharing is transitive, and thus multiple contexts may all share the same set of texture objects and display lists. The current Pomegranate architecture supports the sharing of texture objects between multiple contexts, in addition to the use of shared texture memory.[1]

8.4.1 Texture Objects

Shared texture objects (and display lists) introduce the complication that they may be created, modified or destroyed by one context while other context is using them. The potential for simultaneous modification introduces a new semantic issue. For example, if a context updates a texture object, when should those changes be visible? Certainly the modifications, as well as creation and deletion of shared objects, must be ordered by the parallel API. In Pomegranate, individual texture updates are made atomic, using the `BarrierR` mechanism discussed in section 6.1.1, to provide the correct API semantics for a serial application. But specifying the complete mipmap hierarchy of a texture requires multiple texture updates, during which the texture may be in an invalid state. What are the correct semantics if another context is using such a texture object? One reasonable possibility is to specify that the semantics are undefined. As the programmer did not order the operations on the shared object, it apparently would have been equally reasonable for the pre-mutation or post-mutation value of the object to be used. Would the value of the texture object during mutation be reasonable to use?

[1] The meaning of "shared" is unfortunately overloaded here. Until this section, shared texture specifically referred to remote reads and writes of memory over a network, as opposed to its replication. Now shared has the additional meaning of shared between contexts – thus multiple contexts are sharing the same texture object. In fact, the two meanings of sharing are completely independent.

In our current implementation, the state describing texture objects (their filtering modes, how the texture is repeated, etc.) is maintained by the device driver. When a context binds a texture object, commands are embedded in the command stream to update the texture processor context. Contexts that share texture objects use a shared namespace for the texture object state, thereby observing each other's changes. The difficulty arises when one context modifies a texture object that a second context is currently using. Because the device driver maintains the state, it does not respect any ordering constraints between the graphics contexts. Moreover, the second context has no reason to notice that the texture object has been modified, and may continue using old texture object state. We see two possible solutions to these problems.

Our first solution is to delegate processing of commands that deal with texture objects to the submit threads. Thus these commands could be processed in an order guaranteed to be consistent with the parallel API. In this case, each submit thread would have to check the validity of its currently bound texture object, most likely every time it resolves a parallel API command, and update its context's configuration in the texture processor if appropriate. This has the advantage that texture object management is still virtualized, and avoids the complexity of implementing it in hardware. The disadvantage of this scheme is its uncertain complexity, and semantics which are vague at best.

Our second solution is to push the management of shared texture objects all the way into the hardware, and make it the responsibility of the texture processors. This has the marked advantage of completely ordering texture commands and providing very clear semantics. It has the potentially large disadvantage of exposing a virtualization problem to the hardware.

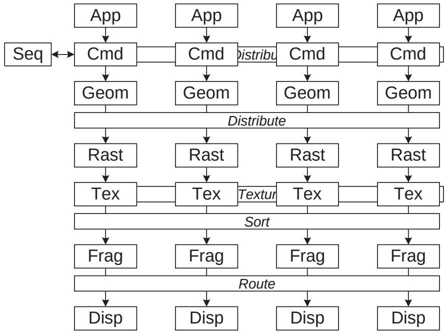


Figure 8.1: Pomegranate architecture, revised to share display lists. The command processors are connected by a network, allowing each to read and write the shared display list memory. The sequencer is also moved earlier and connected to the command processors.

8.4.2 Display Lists

One of the potentially large advantages of display lists is that they may reside in the graphics hardware, thereby saving precious interface bandwidth. We heavily stressed an immediate-mode interface for Pomegranate, and in fact never implemented display list support in our simulator, although it could be trivially implemented by saving away command buffers in host memory, and instructing the command processor to DMA them. If we wished to devote more resources to display lists, a logical step would be to support their execution out of graphics memory, instead of host memory. In this case we would presumably also share the display list memory, rather than replicating it across the pipelines.

Pomegranate could be modified to support shared display lists as shown in figure 8.1. An additional network port allows all of the command processors to read and write the shared display list memory. As before, this is really just an additional port on a shared network, so there is little additional cost to this connection. Because display lists are shared state in the hardware (that is, a given display list occupies the same memory for all interfaces instead of being replicated), operations on the display lists must be ordered. The

sequencer is therefore connected to the command processors, and the partial order specified by the submit threads is immediately resolved. It is still advantageous to defer the determination of a total order to the hardware, as it means the submit threads only have to communicate between each other to resolve the parallel API, rather than on every block of application work. Deferring determination of a total order to the hardware also allows for differences in the speed of execution of the geometry processors, due to differing command streams. Although we have not measured the effects of placing Pomegranate's sequencer at the command processor, we expect that it would perform comparably to the current architecture.

8.4.3 Virtual Memory

Texture objects and display lists are largely unbounded in size and number. Both objects are referred to by integer names, allowing, at least in theory, millions of them to be defined. Each individual object may additionally be quite large. To deal with the resulting potential problem of storage, we would like to virtualize texture objects and display lists.

Virtualization is readily dealt with in a conventional graphics architecture with a serial interface. Because only a single graphics context may be executing in the hardware at any point in time, it may have free reign to use the hardware resources as it sees fit, including paging display lists and texture objects out of the memory system to make space for other objects. When a different context is granted the hardware, either through programmer action or operating system intervention, the device driver can then restore the new context's display list and texture object state as necessary.

In an architecture with a parallel interface, such as Pomegranate, multiple contexts may be simultaneously creating, modifying and deleting objects. Thus, what had been a straightforward single-threaded memory management problem, becomes a parallel memory management problem. Pomegranate simplifies this problem somewhat by insuring that the are no deadlock issues in the hardware – the submit thread mechanism insures that work submitted to the hardware is guaranteed to drain. But if it becomes necessary to page the graphics hardware memory, the paging itself must be correctly serialized, to insure that memory in use (i.e. currently bound textures, executing display lists) is not paged out.

Presumably work on multiprocessor virtual memory management would be relevant to this problem.

One interesting way to address the difficulties of virtualizing the graphics memory is to provide hardware support for virtual memory, so that the graphics memory may be demand-paged. While not removing the need for a parallel memory management scheme (to support multiple simultaneous contexts creating and destroying textures and display lists), this would neatly solve the difficult problem of paging potentially in-use state in and out of the graphics system. If the graphics system memory is virtual, then the host computer's virtual memory can be used as its backing store. When a graphics page fault occurs, the device driver is notified and arranges for the transfer of the appropriate page of memory into the graphics system.

8.5 Automatic Parallelization

When designing Pomegranate, we focused our energies on providing a parallel immediate-mode interface to the graphics hardware, because for applications with dynamic data it may be the only way to provide adequate input bandwidth. Without a parallel interface, such an application may not be able to effectively use more than a single graphics pipeline, unless the application is rasterization limited. However, for applications that can use interfaces which reduce the application command bandwidth into the hardware, it would be desirable if a serial application could effectively utilize multiple pipelines. One attractive solution is to put support for the parallel API into a scene graph library, such as IRIS Performer or Java 3D. Thus any application which uses these libraries could use the parallel API automatically, which little or no programmer effort. Another interesting possibility, with possibly wider applicability, is to automatically parallelize the serial command stream of an application.

A simple way to parallelize a serial command stream is to allocate multiple hardware contexts to the single graphics context, and then distribute the application's commands around the contexts, submitting some of the commands through each context. Two issues must be addressed. First, commands that configure the context (`glBlendFunc`, `glColor`, etc.) must be broadcast, because OpenGL has a stateful interface, and second, the ordered

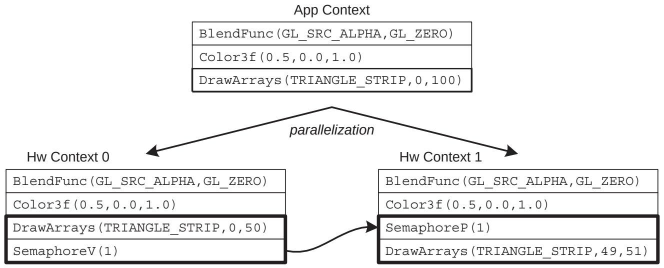

App Context
BlendFunc(GL_SRC_ALPHA,GL_ZERO)
Color3f(0.5,0.0,1.0)
DrawArrays(TRIANGLE_STRIP,0,100)
parallelization
Hw Context 0
BlendFunc(GL_SRC_ALPHA,GL_ZERO)
Color3f(0.5,0.0,1.0)
DrawArrays(TRIANGLE_STRIP,0,50)
SemaphoreV(1)
Hw Context 1
BlendFunc(GL_SRC_ALPHA,GL_ZERO)
Color3f(0.5,0.0,1.0)
SemaphoreP(1)
DrawArrays(TRIANGLE_STRIP,49,51)

Figure 8.2: Automatic parallelization of vertex array execution. The bold boxes are commands inserted or modified by the parallelization.

semantics of the original command stream must be maintained. The expense of broadcasting state commands could possibly be mitigated through lazy updates, in the style of WireGL [Buck et al., 2000]. The ordered semantics can be maintained with the ordering mechanism already provided for parallel contexts: the parallel API. In this case, we could use semaphores to express a total order across all the contexts – precisely the order in which the work was distributed. The real obstacle to such a scheme is the limited performance of a serial command stream – if the application is just submitting immediate-mode primitives through the traditional `glBegin`-`glVertex`-`glEnd` pattern, then the system's performance will be wholly application limited. Several interface mechanisms exist that amplify the application's command bandwidth, by allowing relatively small commands to specify a large amount of work. We will focus on display lists and vertex arrays.

Vertex arrays allow the application to specify pointers to arrays of data containing color, normal, position and other vertex attributes. A single API call, `glDrawArrays` for example, can then be used to direct the hardware to render all the primitives defined by those arrays. Vertex arrays specify only vertices and their attributes, so their parallelization is more straightforward than display lists. One possible approach is shown in figure 8.2. The `glDrawArrays` command is decomposed into multiple smaller `glDrawArrays` commands. A semaphore is used to sequence the sub-commands, maintaining the ordered semantics specified by the application. The splitting of the `glDrawArrays` command overlaps the

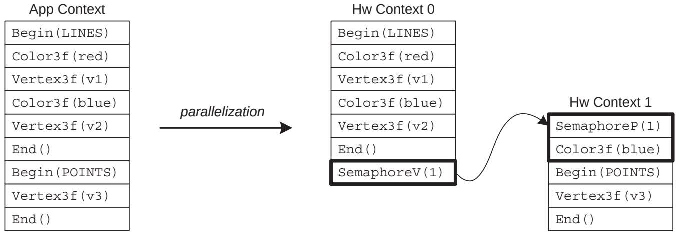


Figure 8.3: Automatic parallelization of display list execution. The bold boxes are commands inserted by the parallelization.

two sub-arrays, because the primitives are not independent. Commands that configure the context, such as `glBlendFunc` and `glColor` in the example, are broadcast to all the contexts. Commands that modify shared state, such as `glTexImage2D` or `glVertex`, should also be sequenced, but are processed only by a single context.

For both display lists and vertex arrays, the difficulty of automatic parallelization is OpenGL's stateful interface. Any command, in particular a vertex, potentially depends on all the previous commands. For example, a vertex has the last specified texture coordinates, no matter how long ago they were specified. Not coincidentally, vertex arrays mitigate this difficulty by specifying that after calling `glDrawArrays` the vertex attributes (normal, color, etc.) that are enabled have indeterminate values. Similarly, the attributes that are not enabled are held constant from before the `glDrawArrays` call. Thus all of the state for a vertex is determined entirely by state before the `glDrawArrays` call and the enabled vertex attribute arrays, and we can safely split the execution of a `glDrawArrays` command in any fashion we choose.

The problem of state management is exacerbated by display lists, because, unlike vertex arrays, they can encapsulate arbitrary commands. However, display lists are expected to be reused after creation, and some effort could be spent in analyzing and optimizing their execution as it will be amortized over hopefully multiple executions. Figure 8.3 shows an example of one possible optimization. Here lazy state evaluation is used so that each context is sent only the commands necessary to bring its context up to date for the primitives it is assigned to render. Thus the stream of colors, normals, etc. specified for primitives rendered by other contexts will not be needlessly broadcast. Our example is simpler than the more general display list case, which can include calls to other display lists, which could also be parallelized, etc. One possible way to address the added complexity of display lists calling display list would be to make leaf display lists (those that don't in turn invoke other display lists) the basic unit of parallelism. A leaf display list could be factored into two parts, the list itself, and the list's effects on the state (current color, etc.). Then one context would be chosen to execute any particular leaf display list, while all the other contexts only execute the state differences.

8.6 Pomegranate-2

The current Pomegranate architecture is based in part on the assumption that the geometry work is application visible, because the amount of geometry work is in fixed proportion to the kind and number of commands submitted by the application. This is not necessarily always the case. For example, a display list command can generate a great deal of work for the hardware, while requiring almost no application work. Granted, the programmer may be aware of how much work it will require, since he constructed the display list, but that does not mean he necessarily wishes to specify the parallelization of its execution, or its distribution across pipelines. Similarly, the use of higher order primitives which are adaptively tessellated by the hardware, such as Bézier surface patches, may result in input geometry that creates an amount of work proportional to screen-space area.

These situations, in which the amount of geometry work is not visible to the programmer, motivate us to consider schemes in which the geometry processors are decoupled from the inputs. Such an architecture, which we refer to as Pomegranate-2, could be built as shown in figure 8.4. Pomegranate-2 introduces an additional stage of communication between the command processors and geometry processors, allowing each command processor to distribute and load-balance its work across all the geometry processors. In the architecture shown here, the sequencer is adjacent to the command processors, and geometry processors receive `Execute` commands, specifying the sequence in which they should process work from the command processors. The disadvantage of this approach is that it does

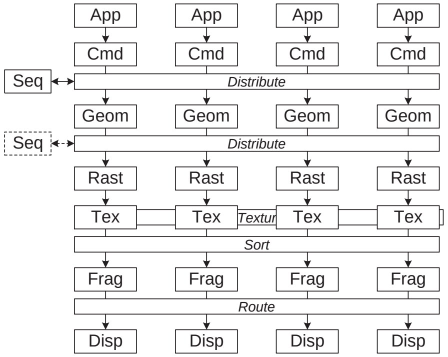


Figure 8.4: Pomegranate-2. The inputs are decoupled from the geometry processors, allowing the per-input work to be balanced across the pipelines in the system.

not expose the amount of rasterization work emitted by the context when communicating with the sequencer, as the command processors do not have that information available to them. Thus, while Pomegranate's geometry processors can yield (`Yield`) before they emit too much rasterization work, and thereby avoid serializing the rasterizers, Pomegranate-2 would not have that option.

One possible way to avoid this difficulty would be to leave the sequencer in its current location between the geometry processors and rasterizers, and then use an additional ordering mechanism between the command processors and geometry processors to maintain the order of the submitted work. This mechanism could likely be similar to the `NextR` commands the geometry processors transmits to the rasterizers, to track the thread of execution of a single context. It remains to be seen how an architecture such as Pomegranate-2 would perform, and what other difficulties its implementors might encounter.

Chapter 9

Conclusions

This thesis has examined parallel graphics architectures from a joint perspective of scalability and communication, and synthesized a new architecture, Pomegranate, optimized for efficient communication and high scalability.

Parallel graphics architecture is fundamentally a problem in efficiently managing object and image parallelism, and the transition between them. This transition between object and image parallelism is the "sort" in parallel graphics architecture, and creates the necessity for communication in any such architecture. We have made two extensions to the parallel graphics sorting taxonomy. First, we more carefully distinguish the location of the sort within the graphics pipeline. This provides a clearer picture of specific architectures, and also allows us to draw a clearer distinction between architectures which sort fragments, and those which composite images. Second, we consider more forms of communication than just the sort. Most parallel graphics architectures also include distribution (object-parallel), routing (image-parallel) and texture communication. Examining a number of architectures under this communication-centric taxonomy leads to two broad conclusions for creating a scalable graphics architecture. First, broadcast communication must be avoided. It requires a broadcast interconnect, which scales only at high cost, and broadcast computation, which does not scale at all. Second, image parallelism must be carefully managed. Tiled image parallelism provides limited available parallelism, and requires a careful balance between a reduced overlap factor and increasing load imbalance. Moreover, the difficulties of tiled image parallelism are worsened by strong scene dependencies and temporal effects. In contrast, interleaved image parallelism achieves an excellent load balance, at the cost of requiring broadcast communication if used any earlier than texture processing.

With a grounding in our observations from this revised parallel graphics taxonomy, we developed Pomegranate, a new fully scalable graphics architecture. Our observations led us to a sort-last fragment architecture, which uses interleaved image parallelism for the fragment processors, and object parallelism for previous stages. In order to provide Pomegranate with sufficient input bandwidth, we provide a parallel interface to the hardware, allowing multiple graphics contexts to be submitting commands simultaneously over independent interfaces.

Load-balancing the many object parallel stages of a sort-last fragment architecture presents a potential stumbling block. In particular, rasterization work is proportional to primitive area, which is not known a priori. In sort-first and sort-middle architectures this load-balancing problem is addressed by partitioning the screen across the rasterizers. In a sort-last fragment architecture another solution must be found. Our solution is to include a stage of communication after the geometry processors, allowing each geometry processor to distribute its rasterization work in a load-balanced fashion across the rasterizers. Texture processing suffers the same load-balancing problems as rasterization, which we address by coupling rasterization and texture processing, thus load-balancing them together. This also meets our requirement for a bandwidth-efficient texture system. Good texture caching behavior can be guaranteed by assigning groups of primitives to rasterizers, while avoiding the need to communicate large untextured fragments or independently load-balance the texture processing stage.

Our choice of a sort-last fragment architecture for Pomegranate was driven by our desire for a scalable architecture. We have shown that scalability requires that broadcast communication be avoided. Pomegranate avoids the use of broadcast communication for the distribution of primitives as well as the sorting of fragments. As a direct consequence, we can use a scalable point-to-point interconnect within Pomegranate, which has excellent efficiency and scalability. Previous architectures that have stressed communication efficiency, and the avoidance of broadcast, most notably image composition architectures, have done so at the expense of supporting ordered execution or an immediate mode interface. Pomegranate demonstrates that through the use of buffering and a lightweight ordering mechanism, ordered semantics and an immediate mode interface can be maintained, while still providing excellent scalability.

While much of our discussion has focused on externally parallel graphics architectures – those constructed of multiple chips and boards – we expect architectures such as Pomegranate to be increasingly important for single-chip designs. The increasing complexity of designing a single chip, which will soon exceed one billion transistors, makes the implementation of a single deep pipeline more and more difficult. Architectures such as Pomegranate provide a way to construct a single, simpler, graphics pipeline and replicate it to provide increased performance in an efficient fashion. The availability of enormous on-chip interconnect bandwidth will make architectures such as Pomegranate not only efficient at the single-chip level, but extremely practical as well.

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