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Modern Distributed Rendering Systems

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ABSTRACT

We are living in the big data age: An ever increasing amount of data is being produced by users through data acquisition and simulations. While large scale analysis and simulations have received significant attention for cloud computing and HPC systems, software to efficiently visualize large amounts of data is struggling to keep up.

We propose to research system software to facilitate and accelerate large data visualization through parallel rendering, and to validate the research and development of this system software by the development of new applications for large data visualization.

This research and development will enable domain scientists and large data engineers to better extract meaning from their data, making it feasible to explore more data by accelerating the rendering and allowing the use of high-resolution displays to see more detail.

Due to the nature of this research, we propose an engineering-driven, iterative research process. Based on the foundations of a generic parallel rendering system, individual research questions can be addressed in isolation and optimized through data-driven benchmarking, and integrated in product quality into the parallel rendering system.

KURZFASSUNG

Wir leben im groen Datenzeitalter: Immer mehr Datenmengen werden in den letzten Jahren die von den Anwendern durch Datenerfassung und Simulationen erzeugt werden. Whrend in groem Mastab Analyse und Simulationen haben groe Aufmerksamkeit fr Cloud Computing erhalten. und HPC-Systemen, Software zur effizienten Visualisierung groer Datenmengen ist die kmpfen, um Schritt zu halten.

Wir schlagen vor, Systemsoftware zu erforschen, um groe Datenmengen zu vereinfachen und zu beschleunigen. Visualisierung durch paralleles Rendering, und zur Validierung der Forschung und Entwicklung. Entwicklung dieser Systemsoftware durch die Entwicklung von neuen Anwendungen fr groe Datenvisualisierung.

Diese Forschung und Entwicklung wird es den Wissenschaftlern ermglischen, die sich mit der Erforschung von Domnen und groen Datenmengen beschftigen. Ingenieuren, um die Bedeutung ihrer Daten besser zu extrahieren. mehr Daten zu erforschen, indem Sie das Rendering beschleunigen und die Verwendung von hochauflsende Displays, um mehr Details zu sehen.

Aufgrund des Charakters dieser Forschung schlagen wir eine ingenieurgetriebene, iterative Forschungsprozesses. Basierend auf den Grundlagen eines generischen parallelen Renderings System knnen individuelle Forschungsfragen isoliert bearbeitet werden und optimiert durch datengetriebenes Benchmarking und integriert in die Produktqualitt in das parallele Rendering-System.

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C H A P T E R

1

BACKGROUND

1.1 Motivation

After decades of exponential growth in computational performance, storage and data acquisition, computing is now well in the big data age, where future advances are measured in our capability to extract meaningful information from the available data. Visual analysis based on interactive rendering of three-dimensional data has been proven to be a particularly efficient approach to gain intuitive insight into the spatial structure and relations of very large 3D data sets. These developments create new, unique challenges for applications and system software to enable users to fully exploit the available resources to gain insight from their data.

The quantity of computed, measured or collected data is exponentially growing, fueled by the pervasive diffusion of digitalization in modern life. Moreover, the fields of science, engineering and technology are increasingly defined by a data driven approach to conduct research and development. High-quality and large-scale data is continuously generated at a growing rate from sensor and scanning systems, as well as from data collections and numerical simulations in a number of science and technology domains.

Display technology has made significant progress in the last decade. High-resolution screens and tiled display walls are now affordable for most organizations and are getting deployed at an increasing rate. This increased resolution and display size helps with understanding the data, but with the quadratic increase in pixels to be rendered, it increases the pressure on rendering algorithms to deliver

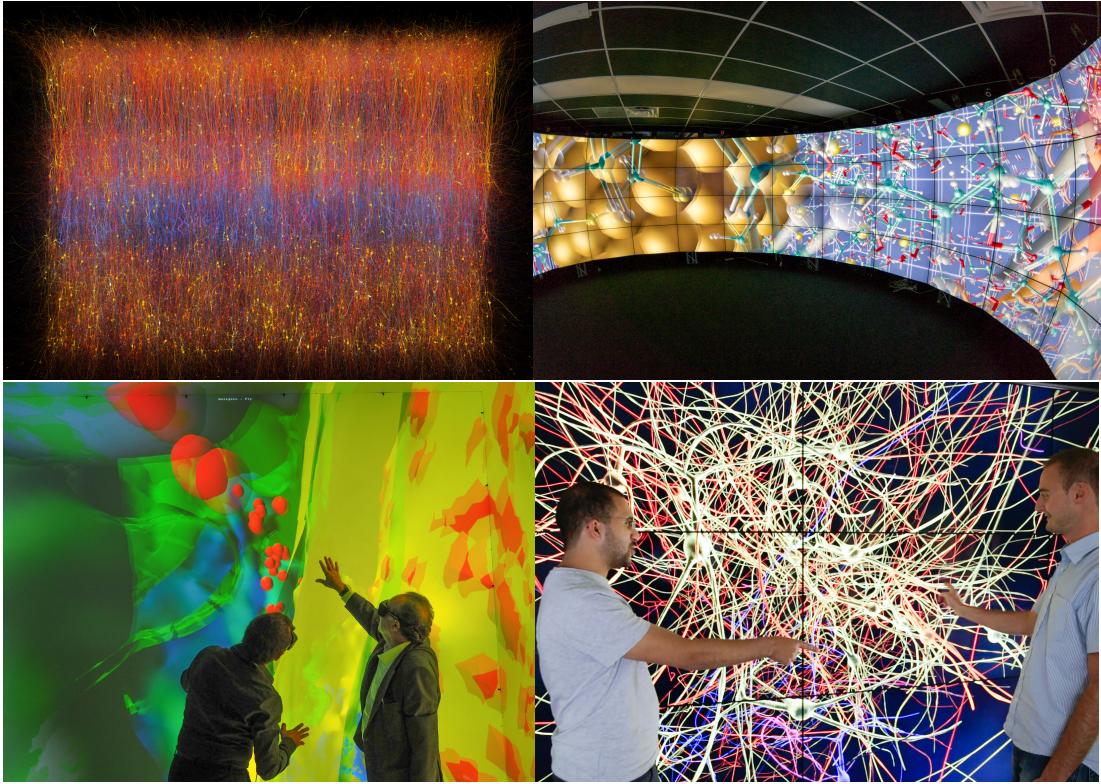


Figure 1.1: *Large Data Visualization: Large data visualization of a brain simulation, molecular visualization in the Cave², exploration of EM stack reconstructions in a Cave, collaborative data analysis on a tiled display wall.*

interactive framerates. Furthermore, for larger system it becomes necessary to develop parallel and distributed applications.

However, not only applications are becoming more and more data-driven, but also the technology used to tackle these kinds of problems is rapidly witnessing a paradigm shift towards massively parallel on-chip and distributed parallel cluster solutions. On one hand, parallelism within a system has increased massively, with tenths of CPU cores, thousands of GPU cores and multiple CPUs and GPUs in a single system. On the other hand, massively parallel distributed systems are easily accessible from various cloud infrastructure providers, and are also affordable for on-site hosting for many organizations.

System software to exploit the available hardware parallelism capable of performing efficient interactive data exploration has not kept up with the pace in hardware developments and data gathering capabilities. On one hand, this is due to an inherent delay between hardware and software capabilities, since develop-

ment typically only starts once the hardware is available. On the other hand, existing software engineered for different design parameters has a significant inertia to change, to the extreme of the necessity to rewrite it from scratch.

In the context of emerging data-intensive knowledge discovery and data analysis, efficient interactive data exploration methodologies have become increasingly important. Visual analysis by means of interactive visualization and inspection of three-dimensional data is a particularly efficient approach to gain intuitive insight into the spatial structure and relations of very large 3D data sets. However, defining visual and interactive methods scalable with problem size and degree of parallelism, as well as generic applicability of high-performance interactive visualization methods and systems are recognized among the major current and future challenges.

1.2 Interactive Visualization

1.3 Parallel Rendering

The main performance indicator for Large Data Interactive Rendering is the performance of the rendering algorithm, that is, the framerate with which the program produces new images. This framerate can be improved by either using faster or more hardware, or by better algorithms exploiting the existing hardware and data. This proposal primarily focuses on the first approach using parallel rendering to exploit the CPU and GPU parallelism available on a single system or a distributed cluster. The early fundamental concepts have been laid down in [Molnar et al., 1994] and [Crockett, 1997]. A number of domain specific parallel rendering algorithms and special-purpose hardware solutions have been proposed in the past, however, only few generic parallel rendering frameworks have been developed (Figure 1.2). We will focus on sort-last and sort-first rendering, since sort-middle architectures are only feasible in a hardware implementation due to the large amount of fragments processed and transferred in the sorting stage.

1.3.1 Domain specific solutions

Cluster-based parallel rendering has been commercialized for off-line rendering (i.e. distributed ray-tracing) for computer generated animated movies or special effects, since the ray-tracing technique is inherently amenable to parallelization for off-line processing. Other special-purpose solutions exist for parallel rendering in specific application domains such as volume rendering [Li et al., 1997; Wittenbrink, 1998; Huang et al., 2000; Schulze and Lang, 2002; Garcia and Shen, 2002; Nie et al., 2005] or geo-visualization [Vezina and Robertson, 1991; Agranov

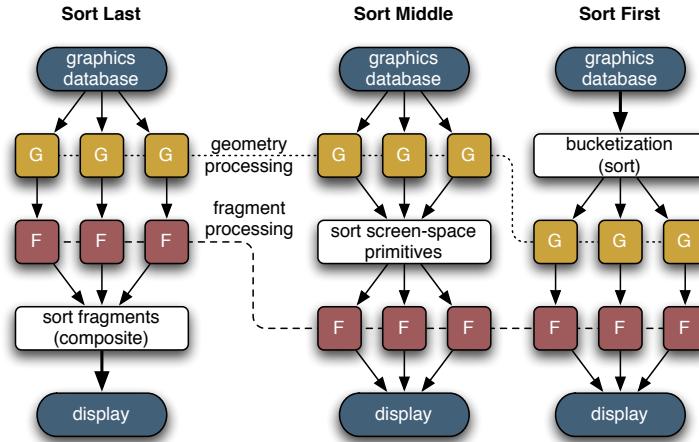


Figure 1.2: Sort-last, sort-middle and sort-first parallel rendering

and Gotsman, 1995; Li et al., 1996; Johnson et al., 2006]. However, such specific solutions are typically not applicable as a generic parallel rendering paradigm and do not translate to arbitrary scientific visualization and distributed graphics problems.

In [Niski and Cohen, 2007], parallel rendering of hierarchical level-of-detail (LOD) data has been addressed and a solution specific to sort-first tile-based parallel rendering has been presented. While the presented approach is not a generic parallel rendering system, basic concepts presented in [Niski and Cohen, 2007] such as load management and adaptive LOD data traversal can be carried over to other sort-first parallel rendering solutions.

1.3.2 Special-purpose architectures

Historically, high-performance real-time rendering systems have relied on an integrated proprietary system architecture, such as the early SGI graphics super computers. These special-purpose solutions have become a niche product as their graphics performance does not keep up with off-the-shelf workstation graphics hardware and scalability of clusters.

Due to its conceptual simplicity, a number of special-purpose image compositing hardware solutions for sort-last parallel rendering have been developed. The proposed hardware architectures include Sepia [Moll et al., 1999; Lever, 2004], Sepia 2 [Lombeyda et al., 2001a; Lombeyda et al., 2001b], Lightning 2 [Stoll et al., 2001], Metabuffer [Blanke et al., 2000; Zhang et al., 2001], MPC Compositor [Muraki et al., 2001] and PixelFlow [Molnar et al., 1992; ?], of which only a few have reached the commercial product stage (i.e. Sepia 2 and MPC

Compositor). However, the inherent inflexibility and setup overhead have limited their distribution and application support. Moreover, with the recent advances in the speed of CPU-GPU interfaces, such as PCI Express, NVLink and other modern interconnects, combinations of software and GPU-based solutions offer more flexibility at comparable performance.

1.3.3 Generic approaches

A number of algorithms and systems for parallel rendering have been developed in the past. On one hand, some general concepts applicable to cluster parallel rendering have been presented in [Mueller, 1995; Mueller, 1997] (sort-first architecture), [Samanta et al., 1999; Samanta et al., 2000] (load balancing), [Samanta et al., 2001] (data replication), or [Cavin et al., 2005; Cavin and Mion, 2006] (scalability). On the other hand, specific algorithms have been developed for cluster based rendering and compositing such as [Ahrens and Painter, 1998], [Correa et al., 2002] and [Yang et al., 2001; Stompel et al., 2003]. However, these approaches do not constitute APIs and libraries that can readily be integrated into existing visualization applications, although the issue of the design of a parallel graphics interface has been addressed in [Igehy et al., 1998].

Only few generic APIs and (cluster-)parallel rendering systems exist which include VR Juggler [Bierbaum et al., 2001] (and its derivatives), Chromium [Humphreys et al., 2002] (an evolution of [Humphreys and Hanrahan, 1999; Humphreys et al., 2000; Humphreys et al., 2001]), ClusterGL [Neal et al., 2011] and OpenGL Multi-pipe SDK [Jones et al., 2004; Bhaniramka et al., 2005; MPK,]. These approaches can be categorized into transparent interception and distribution of the OpenGL command stream and into the parallelization of the application rendering code (Figure 1.3).

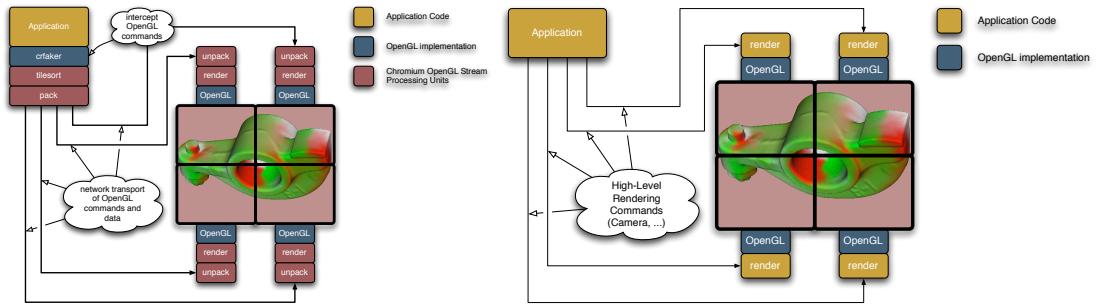


Figure 1.3: Transparent OpenGL interception and parallelization of the rendering code

VR Juggler [Bierbaum et al., 2001; Just et al., 1998] is a graphics framework for virtual reality applications which shields the application developer from the underlying hardware architecture, devices and operating system. Its main aim is

to make virtual reality configurations easy to set up and use without the need to know details about the devices and hardware configuration, but not specifically to provide scalable parallel rendering. Extensions of VR Juggler, such as for example ClusterJuggler [Bierbaum and Cruz-Neira, 2003] and NetJuggler [Allard et al., 2002], are typically based on the replication of application and data on each cluster node and basically take care of synchronization issues, but fail to provide a flexible and powerful configuration mechanism that efficiently supports scalable rendering as also noted in [Staadt et al., 2003]. VR Juggler does not support scalable parallel rendering such as sort-first and sort-last task decomposition and image compositing nor does it provide support for network swap barriers (synchronization), distributed objects, image compression and transmission, or multiple rendering threads per process, important for multi-GPU systems.

While Chromium [Humphreys et al., 2002] provides a powerful and transparent abstraction of the OpenGL API, that allows a flexible configuration of display resources, its main limitation with respect to scalable rendering is that it is focused on streaming OpenGL commands through a network of nodes, often initiated from a single source. This has also been observed in [Staadt et al., 2003]. The problem comes in when the OpenGL stream is large in size, due to not only containing OpenGL calls but also the rendered data such as geometry and image data. Only if the geometry and textures are mostly static and can be kept in GPU memory on the graphics card, no significant bottleneck can be expected as then the OpenGL stream is composed of a relatively small number of rendering instructions. However, as it is typical in real-world visualization applications, display and object settings are interactively manipulated, data and parameters may change dynamically, and large data sets do not fit statically in GPU memory but are often dynamically loaded from out-of-core and/or multiresolution data structures. This can lead to frequent updates not only of commands and parameters which have to be distributed but also of the rendered data itself (geometry and texture), thus causing the OpenGL stream to expand dramatically. Furthermore, this stream of function calls and data must be packaged and broadcast in real-time over the network to multiple nodes for each rendered frame. This makes CPU performance and network bandwidth a more likely limiting factor.

The performance experiments in [Humphreys et al., 2002] indicate that Chromium is working quite well when the rendering problem is fill-rate limited. This is due to the fact that the OpenGL commands and a non-critical amount of rendering data can be distributed to multiple nodes without significant problems and since the critical fill-rate work is then performed locally on the graphics hardware.

Chromium also provides some facilities for parallel application development, namely a sort-last, binary-swap compositing SPU and an OpenGL extension providing synchronization primitives, such as a barrier and semaphore. It leaves other problems, such as configuration, task decomposition as well as process and thread

management unaddressed. Parallel Chromium applications tend to be written for one specific parallel rendering use case, such as for example the sort-first distributed memory volume renderer [Bethel et al., 2003] or the sort-last parallel volume renderer raptor [Houston, 2005]. We are not aware of a generic Chromium-based application using many-to-one sort-first or stereo decompositions.

The concept of transparent OpenGL interception popularized by WireGL and Chromium has received some further contributions. While some commercial implementations such as TechViz and MechDyne Conduit continue to exist, on the research side only ClusterGL [Neal et al., 2011] has been presented recently. ClusterGL employs the same approach as Chromium, but delivers a significantly faster implementation of transparent OpenGL interception and distribution for parallel rendering. Transparent OpenGL interception is an appealing approach for some applications since it requires no code changes, but it has inherent limitations due to the fact that eventually the bottleneck becomes the single-threaded application rendering code, the amount of application data the single application instance can load or process, or the size of the OpenGL command stream send over the network.

CGLX [Doerr and Kuester, 2011] tries to bring parallel execution transparently to OpenGL applications, by emulating the GLUT API and intercepting certain OpenGL calls. In contrast to frameworks like Chromium and ClusterGL which distribute OpenGL calls, CGLX follows the distributed application approach. This works transparently for trivial applications, but quickly requires the application developer to address the complexities of a distributed application, when mutable application state needs to be synchronized across processes. For realistic applications, writing parallel applications remains the only viable approach for scalable parallel rendering, as shown by the success of Paraview, Visit and Equalizer-based applications.

OpenGL Multipipe SDK (MPK) [Bhaniramka et al., 2005] implemented an effective parallel rendering API for a shared memory multi-CPU/GPU system. It is similar to IRIS Performer [Rohlf and Helman, 1994] in that it handles multi-GPU rendering by a lean abstraction layer via a conceptual callback mechanism, and that it runs different application tasks in parallel. However, MPK is not designed nor meant for rendering nodes separated by a network. MPK focuses on providing a parallel rendering framework for a single application, parts of which are run in parallel on multiple rendering channels, such as the culling, rendering and final image compositing processes.

Software for driving and interacting with tiled display walls has received significant attention, including Sage [DeFanti et al., 2009] and Sage 2 [Marrinan et al., 2014] in particular. Sage was built entirely around the concept of a shared framebuffer where all content windows are separate applications using pixel streaming but is no longer actively supported. Sage 2 is a complete, browser-centric

reimplementation where each application is a web application distributed across browser instances. DisplayCluster [Johnson et al., 2012], and its continuation Tide [Blue Brain Project, 2016], also implement the shared framebuffer concept of Sage, but provide a few native content applications integrated into the display servers. These solutions implement a scalable display environment and are a target display platform for scalable 3D graphics applications.

1.4 Dissertation Structure

C H A P T E R

2

CONTRIBUTIONS

2.1 Generic Parallel Rendering Framework

2.2 Parallel Rendering Modes

2.3 Load Balancing

2.4 Applications

PARALLEL RENDERING FRAMEWORK ARCHITECTURE

3.1 Overview

A generic parallel rendering framework has to cover a wide range of use cases, target systems, and configurations. This requires on one hand a strong separation between the implementation of an application and its configuration, and on the other hand a careful design to allow the resulting program to scale up to hundreds of nodes, while providing a minimally invasive API for the developer. In this section we present the system architecture of the Equalizer parallel rendering framework, and motivate its design in contrast to related work.

The motivation to use parallel rendering is either driven by the need to drive multiple displays or projectors from multiple GPUs and potentially multiple nodes, or by the need to increase rendering performance to be able to visualize more data or use a more demanding rendering algorithm for higher visual quality. Occasionally both needs coincide, for example for the analysis for large data sets on high fidelity visualization systems.

Fundamentally, there are two approaches to enable applications to use multiple GPUs: transparent interception at the graphics API (typically OpenGL) or extending the application to support parallel rendering natively. The first approach has been extensively explored by Chromium and others, while the second is the foundation for this thesis. The architecture of Equalizer is founded on an in-depth

requirements analysis of typical visualization applications, existing frameworks, and previous work on OpenGL Multipipe SDK.

The task of parallelizing a visualization application boils down to configuring the application’s rendering code differently for each resource, enabling this rendering code to access the correct data, and synchronizing execution. For scalable rendering, when multiple GPUs are used to accelerate a single output, partial results need to be collected from all contributing resources and combined on the output. Equalizer has a strong separation of the rendering code from its runtime configuration. The configuration is laid out in a hierarchical resource description and compound trees configuring the resources for parallel and scalable rendering. The configuration is a dynamic runtime structure, with a serialized configuration file format.

In the following we will first describe the execution model and runtime configurability, followed by the how the generic configuration is used to model the desired visualization setup, and finally introduce specifics of scalable and distributed rendering.

3.2 Asynchronous Execution Model

The core execution model for parallel rendering was pioneered by CAVELib [De-Fanti et al., 1998], refined by OpenGL Multipipe SDK for shared memory systems and scalable rendering, and substantially extended by Equalizer for asynchronous and distributed execution. By analysing the typical architecture of a visualization application we observe an initialization phase, a main rendering loop, and an exit phase. Equalizer decomposes these steps for parallel execution.

The main rendering loop typically consists of four phases: submitting the rendering commands to the graphics subsystem, displaying the rendered image, and retrieving events from the operating system, based on which the application state is updated and a new image is rendered. The configuration of the rendering is largely hard-coded, with a few configurables such as field of view or stereo separation. For parallel execution, we need to separate the rendering code from this main loop, and execute it in parallel with different rendering parameters, as shown in Figure 3.1. Similarly, the initialization and exit phase also needs to be decomposed to allow managing multiple, distributed resources.

Without going into the details at this point, another critical design parameter are synchronization points. Most implementations use a per-frame barrier or similar synchronization to manage parallel execution. In larger installations, this is detrimental for scalability, as even slight load imbalances limit parallel speedup. The Equalizer execution model is fully asynchronous, and only introduces synchronization points when strictly needed. The main synchronization points are:

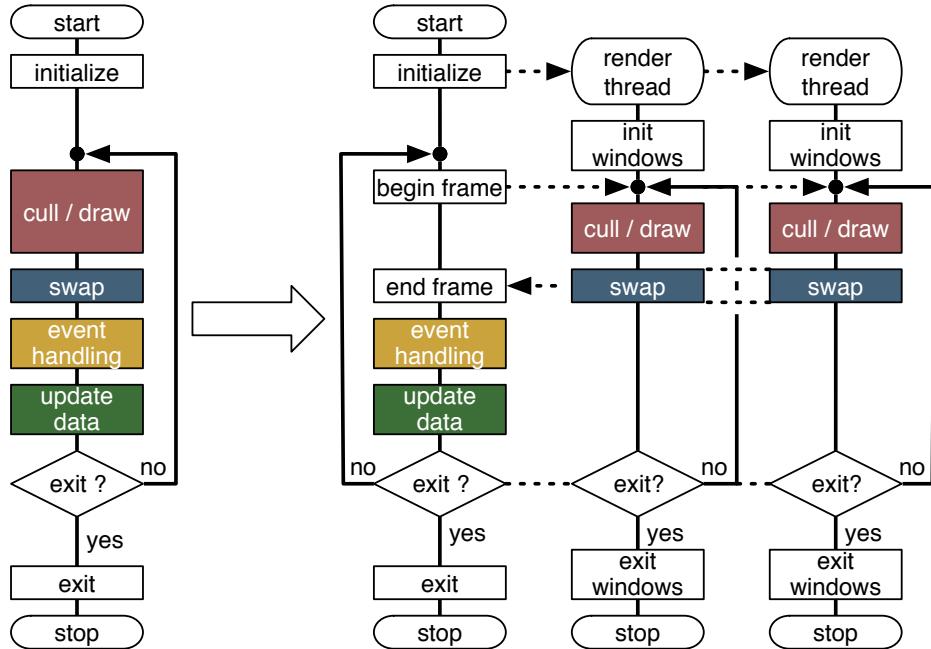


Figure 3.1: Simplified execution flow of a classical visualization application and an Equalizer application.

configured swap barriers between a set of output which have to display simultaneously, the availability of input frames for scalable rendering, and a task synchronization to prevent runaway of the main loop execution. By default, Equalizer keeps up to one frame of latency in execution, that is, some resource might render the next frame while others are still finishing the current. Nonetheless, resources which are ready will immediately display their result. The asynchronous execution architecture, coupled with a frame of latency, allows pipelining of many operations, such as the application event processing, task computation and load balancing, rendering, image readback, compression, network transmission, and compositing.

Figure 3.2 shows the execution of the rendering tasks of a 2-node sort-first compound without latency and with a latency of one frame. The asynchronous execution pipelines rendering operations and hides imbalances in the load distribution, resulting in an improved framerate. For example, we have observed a speedup of 15% on a five-node rendering cluster when using a latency of one frame instead of no latency.

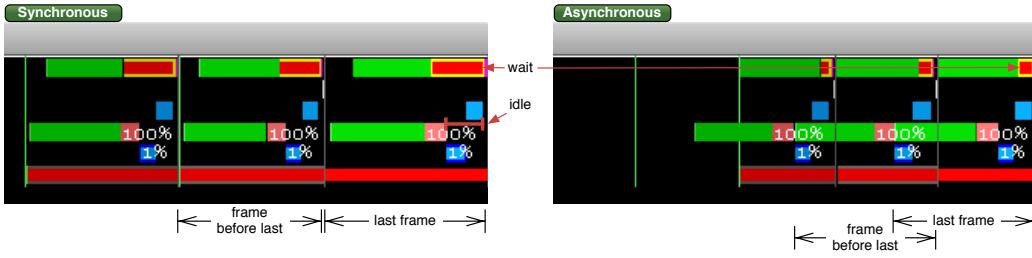


Figure 3.2: Synchronous and Asynchronous Execution

3.2.1 Programming Interface

Equalizer provides a framework to facilitate the development of distributed as well as non-distributed parallel rendering applications. The programming interface is based on a set of C++ classes, modeled closely to the resource hierarchy of a graphics rendering system. The application subclasses these objects and overrides C++ task methods, similar to C callbacks. These task methods will be called in parallel by the framework, depending on the current configuration. This parallel rendering interface is significantly different from Chromium [Humphreys et al., 2002] and more similar to VRJuggler [Bierbaum et al., 2001] or OpenGL Multipipe SDK [Bhaniramka et al., 2005].

To separate the responsibilities in a parallel rendering application, different entities are responsible for different aspects of the runtime system: the application process to drive a rendering session, the server process or thread to control the parallel rendering configuration, render clients to execute the rendering tasks, and an administrative API to reconfigure the rendering session at runtime.

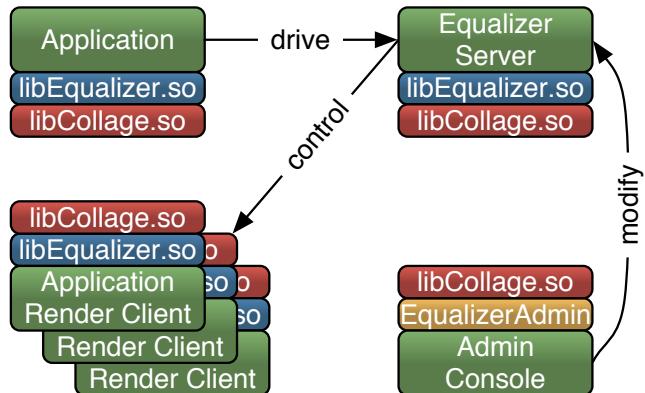


Figure 3.3: Parallel Rendering Entities

3.2.2 Application

The main application thread in Equalizer drives the rendering, that is, it carries out the main rendering loop, but does not actually execute any rendering. Depending on the configuration, the application process often hosts one or more render client

threads. When a configuration has no additional nodes besides the application node, all application code is executed in the same process, and no network data distribution has to be implemented. The main rendering loop is quite simple: The application requests a new frame to be rendered, synchronizes on the completion of a frame and processes events received from the render clients. Figure 3.1 shows a simplified execution model of an Equalizer application.

3.2.3 Server

The Equalizer server manages the parallel rendering session. It is an asynchronous execution thread or process which receives requests from the application and serves these requests using the current configuration, launching and stopping rendering client processes on nodes, determining the rendering tasks for a frame, and synchronizing the completion of tasks.

3.2.4 Render Client

During initialization of the server, the application provides a rendering client executable. The rendering client is often, especially for simple applications, the same executable as the application. However, in more sophisticated implementations the rendering client can be a smaller executable which only contains the application-specific rendering code. The server deploys this rendering client on all nodes specified in the configuration.

In contrast to the application process, the rendering client does not have a main loop and is completely controlled by the Equalizer framework based on application's commands. A render client consists of the following threads: the node main thread, one network receive thread, and one thread for each graphics card (GPU) to execute rendering tasks. If a configuration also uses the application node for rendering, then the application process uses one or more render threads, consistent with render client processes.

The Equalizer client library implements the main loop, which receives network events, processes them, and invokes the necessary task methods provided by the developer.

The task methods clear the frame buffer as necessary, execute the OpenGL rendering commands as well as readback, and assemble partial frame results for scalable rendering. All tasks have default implementations so that only the application specific methods have to be implemented, which at least involves the `frameDraw()` method executing a rendering task. For example, the default callbacks for frame recomposition during scalable rendering implement tile-based assembly for sort-first and stereo decompositions, and *z*-buffer compositing for sort-last rendering.

Render Context

The render context is the core entity abstracting the application-specific rendering algorithm from the system-specific configuration. It specifies:

Buffer OpenGL-style read and draw buffer as well as color mask. These parameters are influenced by the current eye pass, eye separation and anaglyphic stereo settings.

Viewport Two-dimensional pixel viewport restricting the rendering area. For correct operations, both `glViewport` and `glScissor` have to be used. The pixel viewport is influenced by the destination viewport definition and viewports set for sort-first/2D decompositions.

Frustum Frustum parameters as defined by `glFrustum`. Typically the frustum used to set up the OpenGL projection matrix. The frustum is influenced by the destination's view definition, sort-first decomposition, tracking head matrix and the current eye pass.

Head Transformation A transformation matrix positioning the frustum. For planar views this is an identity matrix and is used in immersive rendering. It is normally used to set up the 'view' part of the modelview matrix, before static light sources are defined.

Range A one-dimensional range with the interval [0..1]. This parameter is optional and should be used by the application to render only the appropriate subset of its data for sort-last rendering.

Event Handling

Event handling routes events from the source (the window in the rendering thread) gradually to the the application main thread for consumption. At each step, events can be observed, transformed or dropped. Events are received from the operating system in the rendering thread, transformed there into a generic representation, and sent over the network to the application. The application processes them in the main loop and modifies its internal state accordingly.

3.3 Configuration

A configuration consists of the declaration of the rendering (hardware) resources, the physical and logical description of the projection system, and the description on how the aforementioned resources are used for parallel and scalable rendering.

The rendering resources are represented in a hierarchical tree structure which corresponds to the physical and logical resources found in a 3D rendering environment: nodes (computers), pipes (graphics cards), windows, and channels.

Physical layouts of display systems are configured using canvases with segments, which represent 2D rendering areas composed of multiple displays or projectors. Logical layouts are applied to canvases and define views on a canvas.

Scalable resource usage is configured using a compound tree, which is a hierarchical representation of the rendering decomposition and recomposition across the resources.

3.3.1 Rendering Resources

The first part of the configuration is a hierarchical structure of nodes-pipes-windows-channels describing the rendering resources. The developer will use instances of these classes to implement application logic and manage data.

The **node** is the representation of a single computer in a cluster. One operating system process of the render client executable will be used for each node. Each configuration might also use an application node, in which case the application process is also used for rendering. All node-specific task methods are executed from the main thread.

The **pipe** is the abstraction of a graphics card (GPU), and uses an operating system thread for rendering. All pipe, window and channel task methods are executed from the pipe thread. The pipe maintains the information about the GPU to be used by the windows for rendering.

The **window** encapsulates a drawable and an OpenGL context. The drawable can be an on-screen window or an off-screen pbuffer or framebuffer object (FBO). Windows on the same pipe share their OpenGL rendering resources. They execute their rendering tasks sequentially on the pipe's execution thread.

The **channel** is the abstraction of an OpenGL viewport within its parent window. It is the entity executing the actual rendering. The channel's viewport is overwritten when it is rendering for another channel during scalable rendering. Multiple channels in application windows may be used to view the model from different viewports. Sometimes, a single window is split across multiple projectors, e.g., by using an external splitter such as the Matrox TripleHead2Go.

3.3.2 Display Resources

Display resources are the second part of a configuration. They describe the physical display setup (canvases-segments), logical display (layouts-views) and head tracking of users within the visualization installation (observers).

A **canvas** represents one physical projection surface, e.g., a PowerWall, a curved screen or an immersive installation. Canvases provide a convenient way to configure projection surfaces. A canvas uses layouts, which describe logical views. Typically, each desktop window uses one canvas, one segment, one layout

and one view. One configuration might drive multiple canvases, for example an immersive installation and an operator station. Planar surfaces, e.g., a display wall, configure a frustum for the respective canvas. For non-planar surfaces, the frustum will be configured on each display segment.

The frustum can be specified as a wall or projection description in the same reference system as used by the head-tracking matrix calculated by the application. A wall is completely defined by the bottom-left, bottom-right and top-left coordinates relative to the origin. A projection is defined by the position and head-pitch-roll orientation of the projector, as well as the horizontal and vertical field-of-view and distance of the projection wall. Figure 3.4 illustrates the wall and projection frustum parameters.

A canvas consists of one or more segments. A planar canvas typically has a frustum description (see Section ??), which is inherited by the segments. Non-planar frusta are configured using the segment frusta. These frusta typically describe a physically correct display setup for Virtual Reality installations.

A canvas has one or more layouts. One of the layouts is the active layout, that is, this set of views is currently used for rendering. It is possible to specify OFF as a layout, which deactivates the canvas. It is possible to use the same layout on different canvases.

A **segment** represents one output channel of the canvas, e.g., a projector or a display. A segment has an output channel, which references the channel to which the display device is connected. To synchronize the video output, a canvas swap barrier or a swap barrier on each segment synchronize the respective window buffer swaps.

A segment covers a part of its parent canvas, which is configured using the segment viewport. The viewport is in normalized coordinates relative to the canvas. Segments might overlap

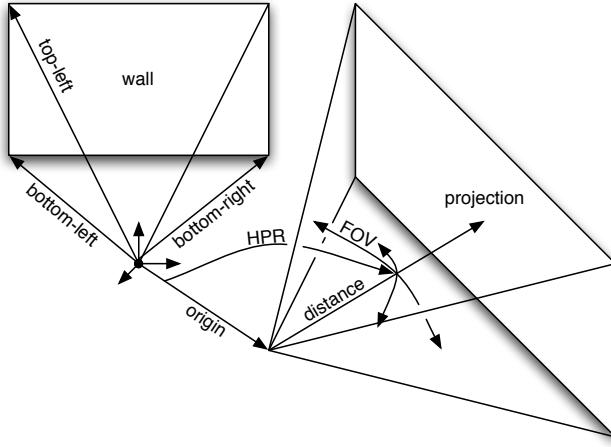


Figure 3.4: Wall and Projection Parameters



Figure 3.5: A Canvas using four Segments

(edge-blended projectors) or have gaps between each other (display walls, Figure 3.5¹). The viewport is used to configure the segment’s default frustum from the canvas frustum description, and to place layout views correctly.

A layout is the grouping of logical views. It is used by one or more canvases. For all given layout/canvas combinations, Equalizer creates destination channels when the configuration file is loaded. These destination channels are later referenced by compounds to configure scalable rendering. Layouts can be switched at runtime by the application. Switching a layout will activate different destination channels for rendering.

A view is a logical view of the application data, in the sense used by the Model-View-Controller pattern. It can be a scene, viewing mode, viewing position, or any other representation of the application’s data. A view has a fractional viewport relative to its layout. A layout is often fully covered by its views, but this is not a requirement. Each view can have a frustum description. The view’s frustum overrides frusta specified at the canvas

or segment level. This is typically used for non-physically correct rendering, e.g., to compare two models side-by-side on a canvas. If the view does not specify a frustum, it will use the sub-frustum resulting from the covered area on the canvas.

A view might have an observer, in which case its frustum is tracked by this observer. Figure 3.6 shows an example layout using four views on a single segment. Figure 3.7 shows a real-world setup of a single canvas with six segments using underlap, with a two-view layout activated. This configuration generates eight destination channels.

An observer represents an actor looking at multiple views. It has a head matrix, defining its position and orientation within the world, an eye separation and focus distance parameters. Typically, a configuration has one observer. Configurations with multiple observers are used if multiple, head-tracked users are in

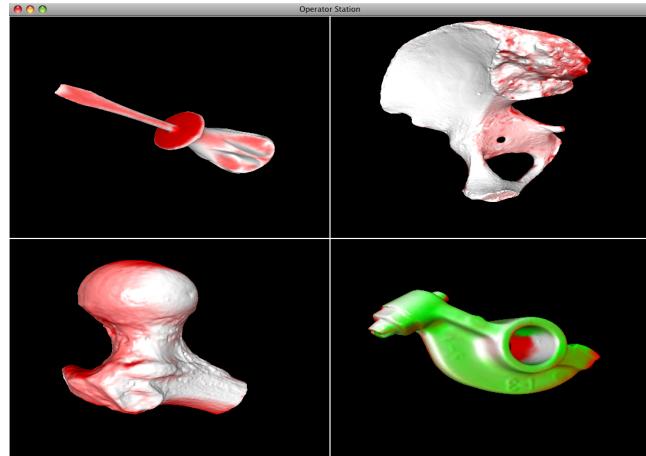


Figure 3.6: Layout with four Views

¹Dataset courtesy of VolVis distribution of SUNY Stony Brook, NY, USA.



Figure 3.7: Display Wall using a six-Segment Canvas with a two-View Layout

the same configuration session, e.g., a non-tracked control host with two tracked head-mounted displays.

3.3.3 Compounds

Compound trees are used to describe how multiple rendering resources are combined to produce the desired output, especially how multiple GPUs are aggregated to increase rendering performance. They are the core contribution enabling a flexible resource configuration.

Compounds are a data structure to describe the parallel execution of rendering tasks in the form of a tree. Each compound corresponds to some rendering tasks (clear, draw, assemble, readback) and references a channel from the resource description which executes the tasks in the given order. A compound may provide output frames from the readback task to others, and can request input frames from others for its own assembly task, and output frames are linked to input frames by name.

Compound trees are a logical description of the rendering pipeline, and only reference the actual physical resources through their channels. This allows mapping a compound tree to different physical configurations by simply replacing the channel IDs. For example, one can test the functionality of a sort-last configuration by using channels of different windows on one local workstation before deploying it to multiple physical GPUs.

A simple leaf compound description for rendering a part of the data set, given by the data *range*, into a particular region of the *viewport* is given in Figure 3.8. The data range is a logical mapping of the data set onto the unit interval and is left to the application to interpret appropriately. Hence the range $[0 \frac{1}{2}]$ indicates that the first half of the data set should be rendered, for example the first $\frac{n}{2}$ triangles of a polygonal mesh with n faces. The viewport is indicated by the parameters [x y width height] as fraction of the parent's viewport, and in the example the data is thus rendered into the left half of the viewport. The resulting framebuffer data – including per-pixel color and depth – of the rendering executed on this channel is read back and made available to other compounds by the name `left_half`.

```
compound {
    channel "draw"
    buffer [ COLOR DEPTH ]
    range [0  $\frac{1}{2}$ ]
    viewport [ 0 0  $\frac{1}{2}$  1 ]
    outputframe {name "left_half" }
}
```

Figure 3.8: Compound executing rendering of a part of the data set into a given region of the viewport.

A non-leaf compound performing some image assembly and compositing task is indicated in Figure 3.9. Framebuffer data is read from two other compounds which supposedly execute rendering for `part_a` and `part_b` of the data set in parallel. The compound itself executes for example *z*-depth visibility compositing of the two input images on its channel and returns the resulting color framebuffer.

```
compound {
    channel "display"
    inputframe { name "part_a" }
    inputframe { name "part_b" }
    outputframe { buffer [ COLOR ] }
}
```

Figure 3.9: Compound performing image compositing.

Leaf compounds execute all tasks by default, but the focus is often on the draw task with a default assemble and standard readback task used to pass the resulting image data on to other compounds for further compositing. Hence while leaf compounds execute the rendering in parallel, non-leaf compounds often correspond to, but are not restricted to the (parallel) image compositing and assembly part. The readback or assemble tasks are only active if output or input frames have

been specified, respectively. Otherwise the rendered image frame is left in-place for further processing in a parent compound sharing the same channel.

Note that non-leaf nodes in the compound tree structure traverse their children first before performing their default assemble and readback tasks. Furthermore, compounds only define the logical task decomposition structure, while its execution is actually performed on the referenced channels. Therefore, since compounds can share channels, as often done between a parent and one of its child compounds, rendered image data can sometimes be left in place, avoiding read-back and transfer to another node.

All attributes as well as the channel are inherited from the parent compound if not specified otherwise. The *viewport*, *data range* and *eye* attributes are used to describe the decomposition of the parent's 2D viewport, database range and eye passes, respectively.

A more formal classification of compound entities is:

Root compound is the top-level compound of a compound tree. It might also be a destination compound, or can be empty (not referencing a channel) when synchronizing multiple destination channels.

Destination compound(s) are the top-most compound referencing a destination channel. This destination channel determines the rendering context for the whole subtree, that is, compounds and their channels lower in the hierarchy contribute to the rendering of the destination channel by executing part of the destination render context and providing output frames which will eventually be composited onto the destination channel.

Source compounds are the leaf nodes in a compound tree. They typically use a different channel from the destination channel and configure scalability by overriding render context parameters. This decomposes the rendering of the destination channel. By adding output and input frames, the partial results are collected and composited:

Decomposition On each child compound the rendering task of that child can be limited by setting the *viewport*, *range*, *period* an *phase*, *pixel*, *subpixel*, *eye* or *zoom* as desired.

Compositing Source compounds define an *output_frame* to read back the result. This output frame is used as an *input_frame* on the destination compound receiving the pixels. The frames are connected with each other by their name, which has to be unique within the root compound tree. For parallel compositing, the algorithm is described by defining multiple input and output frames across all source compounds.

Intermediate compounds may be used to simplify the task decomposition or to configure parallel compositing.

3.4 Compositing

In contrast to most other parallel rendering frameworks, Equalizer decouples the compositing algorithm from the task decomposition. This is a critical component in the architecture, allowing a flexible configuration, often in many unforeseen ways. The compound tree with its task decomposition, input and output frames, is a specialized description “programming” scalable rendering across parallel resources.

Compositing is configured using output frames connected to input frames, compound tasks and eye passes, as well as frame parameters. In its simplest form, a sort-first source compound provides an output frame, which is routed to an input frame using the same name on the destination compound. The source viewport decomposes the task, and the output frame collects this partial result from the source channel and composites it using the correct offset onto the destination channel.

Frame parameters allow the customization of the pixel handling. They include the transferred buffers (color, depth), partial channel viewport, and pixel zooming (upscale and downscale). An output frame may be connected to multiple input frames. These parameters are used in conjunction with compound tasks for parallel compositing, and advanced features such as monitoring and dynamic frame resolution introduced later.

Figure 3.10 shows the pixel flow of direct send compositing for a three-way sort-last decomposition, where the destination channel also contributes to the rendering. In the first step, each channel exchanges two color+depth tiles with its neighbors, and then z -composites its own tile. This yields one complete tile on each channel, of which two color tiles are then assembled on the destination channel.

The corresponding compound tree is shown schematically on the right of Figure 3.10. Each of the three channels has a child compound to execute the rendering and read back to incomplete tiles for sort-last compositing. These three leaf compounds represent the first step in the left-hand diagram. One level up, each channel receives two tiles and assembles them onto its partially rendered result, creating a complete tile. For the two source-only channels, a final color-only output image is connected to the destination channel. The arrows illustrate the pixel flow for one of the tiles.

For most rendering applications even a relatively complex setup such as this example requires very little programmer involvement. The abstractions provided by the resource description, render context and compounds enable Equalizer to reconfigure the application almost transparently. For polygonal rendering, it suffices that the application honors the `range` parameter of the render context to decompose its rendering. All other tasks, in particular the parallel compositing

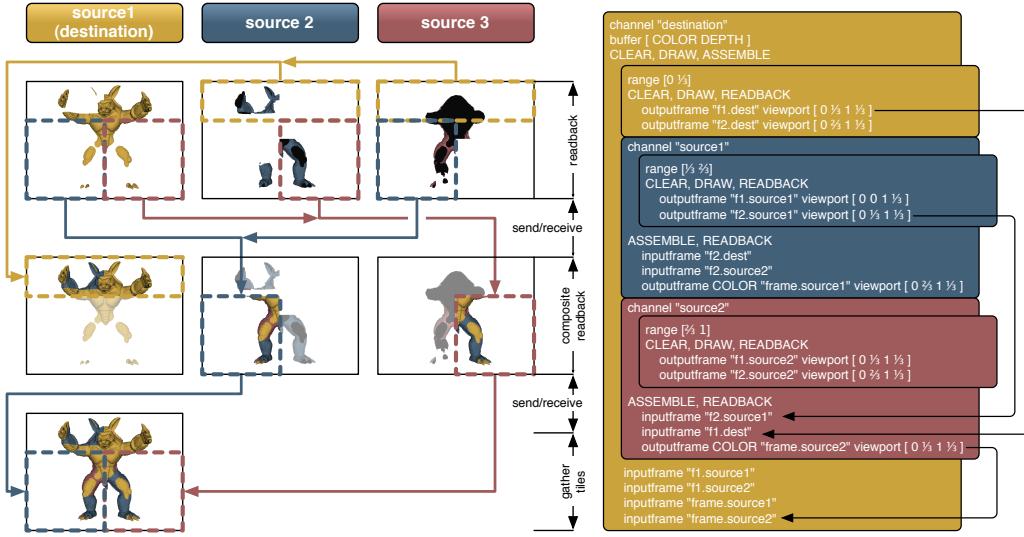


Figure 3.10: Direct Send Compositing

and pixel transfers, are fully handled by Equalizer. Applications which require ordered compositing, for example volume rendering, overwrite the assemble callback to reorder the input frames correctly.

The abstraction through frames is flexible, but still allows many architectural optimizations:

Unordered Compositing: Unless overwritten by the application, Equalizer will composite all input frames in the order they become available, not in the order they are configured. In the example from Figure 3.10, the destination channel will assemble its four input frames one by one as the output frame is received. Due to the asynchronous execution and resulting pipelining of operations, this availability changes each frame depending on the runtime of other tasks.

Asynchronous Compression, GPU and Network Transfers: Compressing, transmitting and receiving frames between nodes is handled by threads independent from the render thread. GPU transfers are handled by asynchronous PBO transfers. Pipelining all these operations with the actual rendering significantly minimizes the compositing overhead.

On-GPU Transfers: Occasionally, the source and destination channel are on the same GPU. Using textures as pixel buffers allows minimal overhead for the output to input frame transfer.

3.5 Load Balancing

Compounds in itself only provide a static configuration of the parallel rendering setup. Equalizers are algorithms which hook into a compound and modify parameters of their respective subtree at runtime to dynamically optimize the resource usage, by each tuning one aspect of the decomposition. Due to their nature, they are transparent to application developers, but might have application-accessible parameters to tune their behavior. Resource equalization is the critical component for scalable parallel rendering, and therefore the eponym for the Equalizer project name.

Compounds are a static snapshot of a configuration, and equalizers provide dynamic configuration on top. This separation of responsibilities is an important architectural component of our parallel rendering framework. Load balancing is one use case for equalizers, where the algorithm analysis runtime statistics to change the task decomposition each frame to equalize rendering times between all resources.

3.6 Distributed Execution Layer

An important part of writing a parallel rendering application is the communication layer between the individual processes. Equalizer relies on the Collage network library for its internal operation. Collage provides networking functionality of different abstraction layers, gradually providing higher level functionality for the programmer. The main primitives in Collage and their relations are shown in Figure 3.11 and provide:

Connection A stream-oriented point-to-point communication line. Connections transmit raw data reliably between two endpoints for unicast connections, and between a set of endpoints for multicast connections. For unicast, process-local pipes, TCP and Infiniband RDMA are implemented. For multicast, a reliable, UDP-based protocol is discussed in Section 7.1.1.

DataI/OStream Abstracts the marshalling of C++ classes from or to a set of connections by implementing output stream operators. Uses buffering to aggregate data for network transmission. Performs byte swapping during input if the endianness differs between the remote and local node.

Node and LocalNode The abstraction of a process in the cluster. Nodes communicate with each other using connections. A LocalNode listens on various connections and processes requests for a given process. Received data is wrapped in ICommands and dispatched to command handler methods. A Node is a proxy for a remote LocalNode.

Object Provides object-oriented, versioned data distribution of C++ objects between nodes. Objects are registered or mapped on a LocalNode.

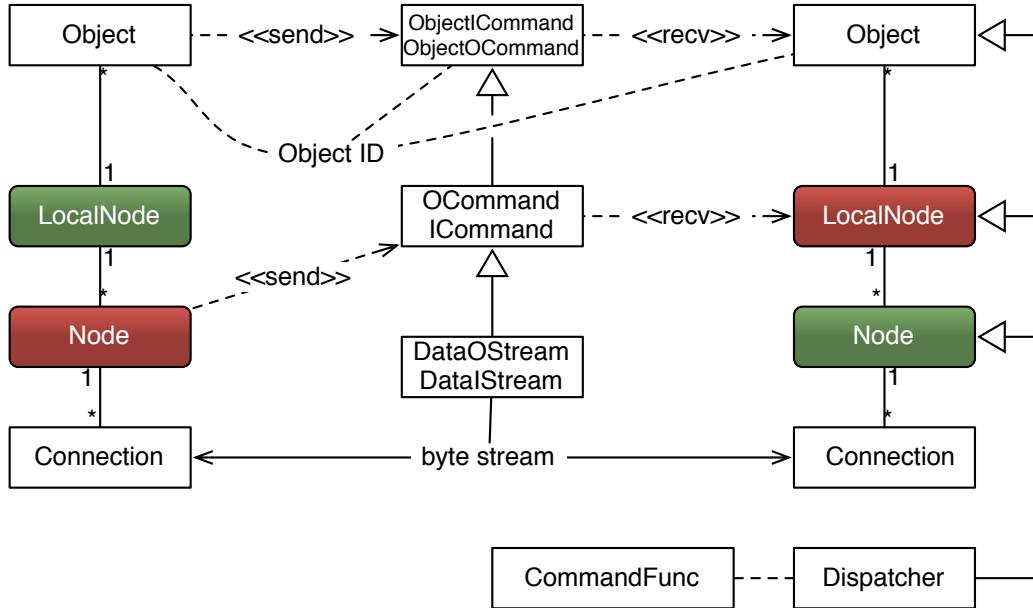


Figure 3.11: Communication between two *Collage* objects

Collage implements a few generic distributed objects which are used by Equalizer and other applications. A barrier is a distributed barrier primitive used for software swap synchronization. Its implementation follows a simple master-slave approach, which has shown to be sufficient for this use case. Queues are distributed, single producer, multiple consumer FIFO queues. To hide network latencies, consumers prefetch items into a local queue. Queues are used for tile and chunk compounds (Section ??).

An object map facilitates distribution and synchronization of a collection of distributed objects. Master versions can be registered on a central node, e.g., the application node in Equalizer. Consumers, e.g., Equalizer render clients, can selectively map the objects they are interested in. Committing the object map will commit all registered objects and sync their new version to the slaves. Syncing the map on the slaves will synchronize all mapped instances to the new version recorded in the object map. This effective design allows data distribution with minimal application logic.

C H A P T E R

4

PARALLEL RENDERING MODES

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5

COMPOSITING OPTIMISATIONS

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6

LOAD BALANCING ALGORITHMS

C H A P T E R

7

DATA DISTRIBUTION AND SYNCHRONIZATION

7.1 Distributed, Versioned Objects

Adapting an existing application for parallel rendering requires the synchronization of application data across the processes in the parallel rendering setup. Existing parallel rendering frameworks address this often poorly, at best they rely on MPI to distribute data. Real-world, interactive visualization applications are typically written in C++ and have complex data models and class hierarchies to represent their application state. As outlined in [Eilemann et al., 2009], the parallel rendering code in an `Equalizer` application only needs access to the data needed for rendering, as all application logic is centralized in the application main thread. We have encountered two main approaches to address this distribution: Using a shared filesystem for static data, or using data distribution for static and dynamic data. Distributed objects are not required to build `Equalizer` applications. While most developers choose to use this abstraction for convenience, we have seen applications using other means for data distribution, e.g., MPI.

Distributed objects in Collage provide powerful, object-oriented data distribution for C++ objects. They facilitate the implementation of data distribution in a cluster environment. Distributed objects are created by subclassing from `co::Serializable` or `co::Object`. The application programmer implements serialization and deserialization. Distributed objects can be static (immutable) or

dynamic. Objects have a universally unique identifier (UUID) as cluster-wide address. A master-slave model is used to establish mapping and data synchronization across processes. Typically, the application main loop registers a master instance and communicates the UUID to the render clients, which map their instance to the given identifier. The following object types are available:

Static The object is not versioned nor buffered. The instance data is serialized whenever a new slave instance is mapped. No additional data is stored.

Instance The object is versioned and buffered. The instance and delta data are identical; that is, only instance data is serialized. Previous instance data is saved to be able to map old versions.

Delta The object is versioned and buffered. The delta data is typically smaller than the instance data. The delta data is transmitted to slave instances for synchronization. Previous instance and delta data is saved to be able to map and sync old versions.

Unbuffered The object is versioned and unbuffered. No data is stored, and no previous versions can be mapped.

Serialization is facilitated using output or input streams, which abstract the data transmission and are used like a `std::stream`. The data streams implement efficient buffering and compression, and automatically select the best connection for data transport. Custom data type serializers can be implemented by providing the appropriate serialization functions. No pointers should be directly transmitted through the data streams. For pointers, the corresponding object is typically a distributed object as well, and its UUID and version are transmitted in place of a pointer.

Dynamic objects are versioned, and on commit the delta data from the previous version is sent, if available using multicast, to all mapped slave instances. The data is queued on the remote node, and is applied when the application calls `sync` to synchronize the object to a new version. The `sync` method might block if a version has not yet been committed or is still in transmission. All versioned objects have the following characteristics:

- The master instance of the object generates new versions for all slaves. These versions are continuous. It is possible to commit on slave instances, but special care has to be taken to handle possible conflicts.
- Slave instance versions can only be advanced; that is, `sync(version)` with a version smaller than the current version will fail.
- Newly mapped slave instances are mapped to the oldest available version by default, or to the version specified when calling `mapObject`.

The `Collage Serializable` implements one convenient usage pattern for object data distribution. The `co::Serializable` data distribution is based on the concept of dirty bits, allowing inheritance with data distribution. Dirty bits form a 64-bit mask which marks the parts of the object to be distributed during the next commit.

For serialization, the application developer implements `serialize` or `deserialize`, which are called with the bit mask specifying which data has to be transmitted or received. During a commit or sync, the current dirty bits are given, whereas during object mapping all dirty bits are passed to the serialization methods.

Blocking commits allow to limit the number of outstanding, queued versions on the slave nodes. A token-based protocol will block the commit on the master instance if too many unsynchronized versions exist.

Optimizations

The API presented in the previous section provides sufficient abstraction to implement various optimizations for faster mapping and synchronization of data: compression, chunking, caching, preloading and multicast. The results section evaluates some of these optimizations.

The most obvious one is compression. Recently, many new compression algorithms have been developed which exploit modern CPU architectures and deliver compression rates well above one gigabyte per second. **Collage** uses the Pression library [GmbH and Project, 2016], which provides a unified interface for a number of compression libraries, such as FastLZ [Jesper et al.,], Snappy [open-source@google.com, 2016] and ZStandard [Facebook, 2016]. It also contains a custom, virtually zero-cost RLE compressor. Pression parallelizes the compression and decompression using data decomposition. This compression is generic, and implemented transparently for the application. Applications can also use data-specific compression.

The data streaming interface implements chunking, which pipelines the serialization code with the network transmission. After a configurable number of bytes has been serialized to the internal buffer, it is transmitted and serialization continues. This is used both for the initial mapping data and for commit data.

Caching retains instance data of objects in a client-side cache, and reuses this data to accelerate mapping of objects. The instance cache is either filled by “snooping” on multicast transmissions or by an explicit preloading when the master objects are registered. The preloading sends instance data of recently registered master objects to all connected nodes, while the corresponding node is idle. These nodes simply enter the received data to their cache. Preloading uses multicast when available.

Due to the master-slave model of data distribution, multicast is used to optimize the transmission time of data. If the contributing nodes share a multicast session, and more than one slave instance is mapped, **Collage** automatically uses the multicast connection to send the new version information.

7.1.1 Reliable Stream Protocol

RSP is an implementation of a reliable multicast protocol over unreliable UDP transport. RSP behaves similarly to TCP; it provides full reliability and ordering of the data, and slow receivers will eventually throttle the sender through a sliding window algorithm. This behavior is needed to guarantee delivery of data in all situations. Pragmatic generic multicast (PGM [Gemmell et al., 2003]) provides full ordering, but slow clients will disconnect from the multicast session instead of throttling the send rate.

RSP combines various established algorithms [Adamson et al., 2004; ?] for multicast in an open source implementation capable of delivering wire speed transmission rates on high-speed LAN interfaces. In the following we will outline the RSP protocol and implementation as well as motivate the design decisions. Any defaults given below are for Linux or OS X, the Windows UDP stack requires different default values which can be found in the implementation.

Our RSP implementation uses a separate protocol thread for each RSP group, which handles all reads and writes on the multicast socket. It implements the protocol handling and communicates with the application threads through thread-safe queues. The queues contain datagrams of the application byte stream, prefixed by a header of at most eight bytes. Each connection has a configurable number of buffers (1024 by default) of a configurable MTU (1470 bytes default), which are either free or in transmission.

Handling a smooth packet flow is critical for performance. RSP uses active flow control to advance the byte stream buffered by the implementation. Each incoming connection actively acknowledges every n (17 by default) packets fully received. The incoming connections offset this acknowledgment by their connection identifier to avoid bursts of acks. Any missed datagram is actively nack'ed as soon as detected. Write connections continuously retransmit packets for nack datagrams, and advance their window upon reception of all acks from the group. The writer will explicitly request an ack or nack when it runs out of empty buffers or finishes its write queue. Nack datagrams may contain multiple ranges of missed datagrams, which is motivated by the observation that UDP implementations often drop multiple contiguous packets.

Congestion control is necessary to optimize bandwidth usage. While TCP uses the well-known additive increase, multiplicative decrease algorithm, we have chosen a more aggressive congestion control algorithm of additive increase and additive decrease. This has proven experimentally to be more optimal: UDP is often rate-limited by switches; that is, packets are discarded regularly and not exceptionally. Only slowly backing off the current send rate helps to stay close to this limit. Furthermore, our RSP traffic is limited to the local subnet, making cooperation between multiple data stream less of an issue. Send rate limiting uses

a bucket algorithm, where over time the bucket fills with send credits, from which sends are subtracted. If there are no available credits, the sender sleeps until sufficient credits are available.

C H A P T E R

8

CONCLUSION

8.1 Future Work

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