



**University of
Zurich**^{UZH}

Department of Informatics

Parallel Rendering and Large Data Visualization

A dissertation submitted to the Faculty
of Economics, Business Administration
and Information Technology of the
University of Zürich

for the degree of
Doctor of Science (Ph. D.)

by
Stefan Eilemann

Accepted on the recommendation of

Prof. Dr. Renato Pajarola
Prof. Dr. Markus Hadwiger

September 20, 2018

The Faculty of Economics, Business Administration and Information Technology
of the University of Zurich herewith permits the publication of the aforementioned
dissertation without expressing any opinion on the views contained therein.

Zurich, September 20, 2018

The head of the Ph. D. program in Informatics: Prof. Abraham Bernstein, Ph.D.

ABSTRACT

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

Visualization has proven to be an efficient tool for understanding data, in particular visual analysis as a powerful tool to gain intuitive insight into the spatial structure and relations of 3D data sets. Large-scale visualization setups are becoming ever more affordable. High-resolution tiled display walls are in reach even for small institutions, and can often be driven by a single multi-GPU workstation. Virtual reality has arrived in the consumer space, making it accessible for a large audience.

This thesis advances the field of parallel rendering by formalizing the design and implementation of system software for large data visualization through parallel rendering, novel algorithms to accelerate the rendering of large amounts of data, and validates this research and development with new applications for large data visualization. Our research and development enables 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-fidelity displays to see more detail.

KURZFASSUNG

Wir leben im großen Datenzeitalter: Immer mehr Datenmengen werden in den letzten Jahren die von den Anwendern durch Datenerfassung und Simulationen erzeugt werden. Während in großem Maßstab Analyse und Simulationen haben große Aufmerksamkeit für Cloud Computing erhalten. und HPC-Systemen, Software zur effizienten Visualisierung großer Datenmengen ist die kämpfen, um Schritt zu halten.

Wir schlagen vor, Systemsoftware zu erforschen, um große 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 für große Datenvi-sualisierung.

Diese Forschung und Entwicklung wird es den Wissenschaftlern ermöglichen, die sich mit der Erforschung von Domänen und großen Datenmengen beschäftigen. Ingenieuren, um die Bedeutung ihrer Daten besser zu extrahieren. mehr Daten zu erforschen, indem Sie das Rendering beschleunigen und die Verwendung von hochauflösende 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 können individuelle Forschungsfragen isoliert bearbeitet werden und optimiert durch datengetriebenes Benchmarking und integriert in die Produktqualität in das parallele Rendering-System.

ACKNOWLEDGMENTS

The research leading to this proposal was supported in part by the Blue Brain Project, the Swiss National Science Foundation under Grant 200020-129525, the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 604102 (Human Brain Project), the Hasler Stiftung grant (project number 12097), and the King Abdullah University of Science and Technology (KAUST) through the KAUST-EPFL alliance for Neuro-Inspired High Performance Computing.

I would like to take the opportunity to thank the Blue Brain Project and its visualization team, RTT AG (now part of Dassault Systems), KAUST, University of Siegen, the Electronic Visualization Laboratory at the University of Illinois Chicago, and all the other contributors for their support in the research and development leading to this thesis.

I would like to thank Prof. Renato Pajarola and the VMML for his long-term commitment to my research work and Patrick Bouchaud for putting me onto the path taken by this thesis. Last, but not least, I'd like to thank all collaborators who worked with me on this endeavour: Daniel Nachbaur, Cedric Stalder, Maxim Makhinya, Dardo D. Kleiner, Carsten Rohn, Daniel Pfeifer, Sarah Amsellem, Juan Hernando , Marwan Abdellah, Raphael Dumusc, Lucas Peetz Dulley, Jafet Villafranca, Philippe Robert, Ahmet Bilgili, Tobias Wolf, Dustin Wueest, and Martin Lambers.

CONTENTS

Abstract	i
Kurzfassung	iii
Acknowledgments	v
1 Background	1
1.1 Motivation	1
1.2 Challenges	3
1.3 Parallel Rendering	4
1.3.1 Domain Specific solutions	5
1.3.2 Special Purpose Architectures	6
1.3.3 Generic Approaches	6
1.4 Thesis Structure	10
2 Contributions	11
2.1 Parallel Rendering Architecture	11
2.2 Scalable Rendering	13
2.3 Load Balancing	13
3 Parallel Rendering Architecture	15
3.1 Overview	15
3.2 Asynchronous Execution Model	16

3.2.1	Programming Interface	19
3.2.2	Application	20
3.2.3	Server	20
3.2.4	Render Client	20
3.2.5	NUMA Aware Thread Scheduling	22
3.3	Configuration	24
3.3.1	Rendering Resources	24
3.3.2	Display Resources	25
3.3.3	Compounds	28
3.4	Virtual Reality	30
3.4.1	Head Tracking	31
3.4.2	Dynamic Focus Distance	31
3.4.3	Asymmetric Eye Position	32
3.4.4	Model Unit	32
3.4.5	Runtime Stereo Switch	32
3.5	Tiled Display Walls	32
3.6	Compositing	34
3.7	Load Balancing	37
3.8	Runtime Reconfiguration	37
3.9	Distributed Execution Layer	38
4	Scalable Rendering	41
4.1	Overview	41
4.2	Sort-First	42
4.2.1	Stereo	42
4.2.2	Pixel	43
4.2.3	Subpixel	44
4.2.4	Tiles	44
4.3	Sort-Last	44
4.4	Time-Multiplex	45
4.5	Mixed Mode Compounds	46
4.6	Stereo-Selective Compounds	47
5	Compositing	49
5.1	Overview	49
5.2	Parallel Compositing	49
5.3	Region of Interest	53
5.4	Asynchronous Compositing	54
5.5	Compression for Image Compositing	55
5.5.1	Enhanced RLE Compression	56
5.5.2	GPU Transfer and CPU Compression Plugins	58

5.6	Out-of-Order Assembly	59
6	Load Balancing	61
6.1	Overview	61
6.2	Sort-First and Sort-Last Load Balancing	62
6.2.1	Dynamic Work Packages	64
6.2.2	Benchmarks	65
6.3	Cross-Segment Load Balancing	67
6.4	Dynamic Frame Resolution	71
6.5	Frame Rate Equalizer	72
6.6	Monitoring	72
7	Data Distribution and synchronisation	73
7.1	Overview	73
7.2	Architecture	75
7.2.1	Connection	75
7.2.2	Data Streams	76
7.2.3	Thread-aware Command Dispatch	77
7.2.4	Nodes	77
7.3	Distributed, Versioned Objects	78
7.3.1	Reliable Stream Protocol	85
8	Applications	89
8.1	Livre	89
8.2	RTT Deltagen	90
8.3	RTNeuron	91
8.4	RASTeR	91
8.5	Bino	92
8.6	Omegalib	92
9	Conclusion	95
9.1	Summary	95
9.2	Future Work	96

LIST OF FIGURES

1.1	Large Data Visualization: Large data visualization of a brain simulation, molecular visualization in the Cave 2, exploration of EM stack reconstructions in a Cave, collaborative data analysis on a tiled display wall.	2
1.2	Sort-last, sort-middle and sort-first parallel rendering	5
1.3	Parallelization and transparent OpenGL interception of the rendering code	7
3.1	Simplified execution flow of a classical visualization application and an Equalizer application.	17
3.2	Synchronous and Asynchronous Execution	19
3.3	Parallel Rendering Entities	20
3.4	Exemplary Dual-Socket NUMA Node	22
3.5	Thread Placement on a Dual-Socket NUMA Node	23
3.6	Wall and Projection Parameters	25
3.7	A Canvas using four Segments	26
3.9	Tiled Display Wall using a six-segment canvas with a two-view layout	27
3.8	Layout with four Views	27
3.10	Compound executing rendering of a part of the data set into a given region of the viewport.	29
3.11	Compound performing image compositing.	29

3.12	Dynamic Focus in a Cave	31
3.13	Tiled Display Wall showing remote rendering of the Equalizer-based RTNeuron Application	33
3.14	Remote Streaming Scenario	33
3.16	Direct Send Compositing	35
3.15	Direct Send Compound	36
3.17	Communication between two Collage objects	39
4.1	Anaglyphic Stereo Compound	42
4.2	Pixel, Subpixel and Tile Compounds.	43
4.3	Time-Multiplex Compound	45
4.4	Stereo-Selective Compound	47
5.1	Depth-Sorted and Back-to-Front Sort-Last Compositing.	50
5.2	Binary swap sort-last compositing	52
5.3	Synchronous readback and upload (a) as well as asynchronous readback and upload (b) for two overlapping frames.	55
5.4	32 bit, 64 bit and per-component RLE compression schemes	57
5.5	Swizzling scheme for reordering bits of 32-bit RGBA values.	57
6.1	Static, Reactive and Predictive Load Balancing	62
6.2	Load Balancing	63
6.3	Load cost area map with (top) and without (bottom) using region of interest information.	63
6.4	Six-to-two Cross-Segment load Balancing	67
6.5	A dual-GPU, dual-display cross-segment load balancing setup	69
6.6	Dynamic Frame Resolution	71
6.7	Monitoring	72
7.1	UML class diagram of the major Collage classes	76
7.2	Communication between two Nodes	78
7.3	RSP data flow	87
8.1	Livre running on a 4x3 tiled display wall	89
8.2	RTT Deltagen rendering mixing OpenGL rendering and raytracing (for the head light)	90
8.3	RTNeuron running in a six-sided CAVE	91
8.4	RASTeR running on a 3x2 tiled display wall	91
8.5	Bino video player on a semi-cylindrical multi-projector wall	92
8.6	An Omegalib application running in the Cave2	92

LIST OF BENCHMARKS

3.1	Driving a Tiled Display Wall	18
3.2	Thread Affinity on NUMA hardware	23
3.3	Remote RTNeuron - Tide Parallel Rendering	34
5.1	Spatial versus Depth-Sorted Sort-Last Rendering	51
5.2	Region of Interest for Sort-First Rendering	53
5.3	Region of Interest for Sort-Last Rendering	54
5.4	Asynchronous Compositing Sort-First Rendering	56
5.5	Image Compression in Sort-First Polygonal Rendering	58
6.1	Sort-First and Sort-Last Scalability	66
6.2	Sort-First and Sort-Last Equalizer Behaviour	66
6.3	Cross-Segment Load Balancing	70
6.4	Cross-Segment Load Balancing for six Displays and 12 GPUs compared to a static two-to-one six Display Sort-First Rendering .	71
7.1	Object Mapping and synchronisation	81
7.2	Compression Performance for Binary Data	83
7.3	Data Compression for the PLY Data and Raw Volumes from Benchmark 7.1	84
7.4	synchronisation Performance over different Network Protocols .	85

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 digitalisation 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 organisations and are getting deployed at an increasing rate. This increased resolution and display size helps with understanding the data through higher fidelity, but with the quadratic increase in pixels to be rendered, it increases the pressure on rendering

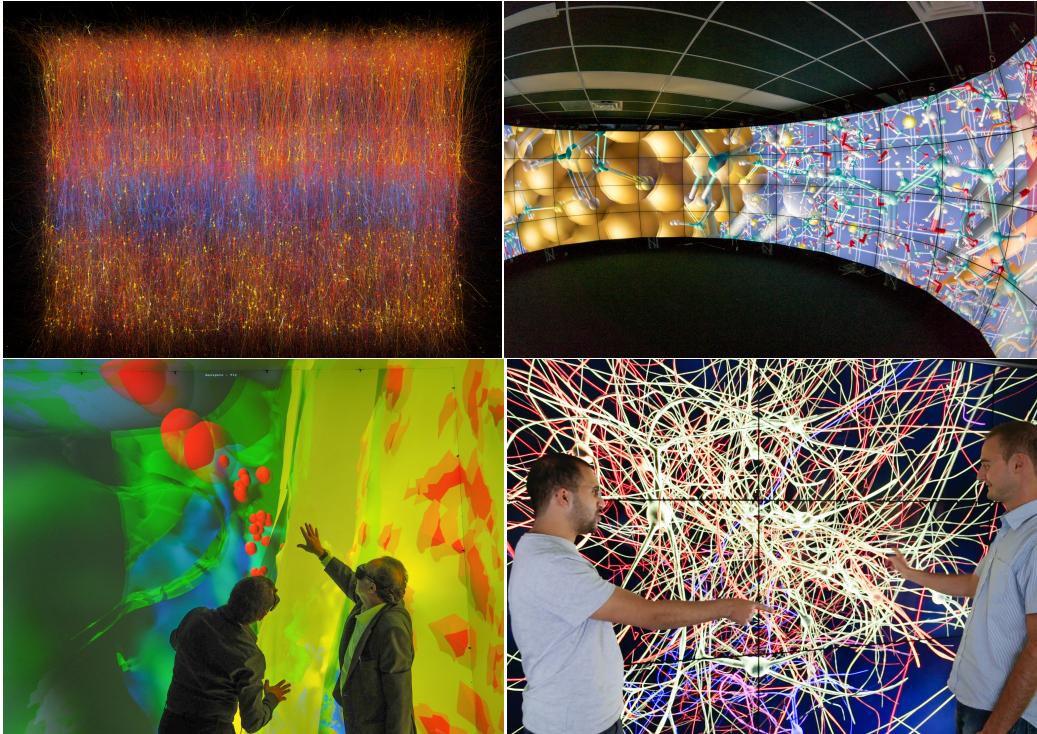


Figure 1.1: *Large Data Visualization*: Large data visualization of a brain simulation, molecular visualization in the Cave 2, exploration of EM stack reconstructions in a Cave, collaborative data analysis on a tiled display wall.

algorithms to deliver an interactive frame rate. Such large-scale visualization systems are often driven by multiple GPUs and workstations, making it natural, and most times necessary, to drive them using 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 has been 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 organisations.

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 development typically only starts once the hardware is available. On the other hand, existing

software is often engineered for different design parameters and 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 recognised among the major current and future challenges.

1.2 Challenges

The motivation to visualise more data more efficiently through increased display fidelity and improved rendering performance creates a new set of research challenges. The key goal is to improve the rendering performance of existing and new visualization applications to enable users to explore more data. This goal can be broken down in more concrete challenges, starting with formalising and implementing the architecture of a parallel rendering framework, which allows to decompose the problem into more manageable tasks.

These sub-challenges to build a better scalable parallel rendering application can be identified as finding better task decompositions, decreasing the cost for the result composition, reducing the latency of the overall system, and minimising synchronisation between the parallel execution threads.

When starting from a given rendering problem, the first task of a parallel rendering system is to decompose (parallelise) this task into independent sub-tasks, each rendered by a separate resource in parallel. While the basics of this decomposition has been researched extensively, there are architectural challenges to make these decompositions easily available in a generic and structured manner. When it comes to load balancing these tasks for an optimal parallelization, many challenges are still unaddressed when it comes to modern visualization cluster sizes using tens to hundreds of GPUs, and increasingly affordable high-fidelity visualization systems with tens of displays and hundreds of millions of pixels.

With the scaling up the amount of resources employed to accelerate the rendering task, the task of combining the partial results from each resource becomes more challenging. In particular for sort-last rendering, where the amount data to composite grows linearly with the amount of parallel resources used, keeping the compositing time within the available budget is a non-trivial problem.

Interactive visualization poses an unique set of challenges. Its goal is to present a believable alternate universe to the visual system of the user. This process turns interactive visualization into a powerful tool, since it utilises the brains' native capabilities to interpret and understand data. Virtual Reality takes this goal to the extreme, and when done right, makes the user forget that he interacts with a virtual world.

To achieve this goal, visualization has the daunting task to transform large amount of data into coloured pixels in a short amount of time. Believable visualization has to minimise the latency between user input and the resulting output, and to maximise the number of frames rendered per second. With increased immersion in the data, these parameters become more important – for Virtual Reality, a 60 Hz refresh rate and a latency below 50 ms is needed, whereas for non-immersive desktop visualization 10 Hz and 200 ms are acceptable.

In the context of parallel rendering, these constraints make building a parallel and distributed application harder compared to other distributed applications for simulations and cloud computing. In particular, one has to be careful with synchronisation and pipelining of operations to minimise latency. In addition, an interactive application has different requirements when it comes to resource allocation compared to other large-scale distributed computing domains.

Last, but not least, a significant challenge is how to make all this research available to the large data scientists with the actual needs and use cases for parallel rendering.

1.3 Parallel Rendering

Parallel rendering utilises multiple rendering units (GPUs), potentially on different computers, to generate images for one or more output displays. The goal is to increase the output resolution, rendering performance or rendering quality. Traditionally the focus has been on the first two goals, often in isolation to each other, e.g., algorithms and implementations for Cave systems tend to be different from scalable rendering for large data visualization.

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 thesis 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] (Figure 1.2). 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.

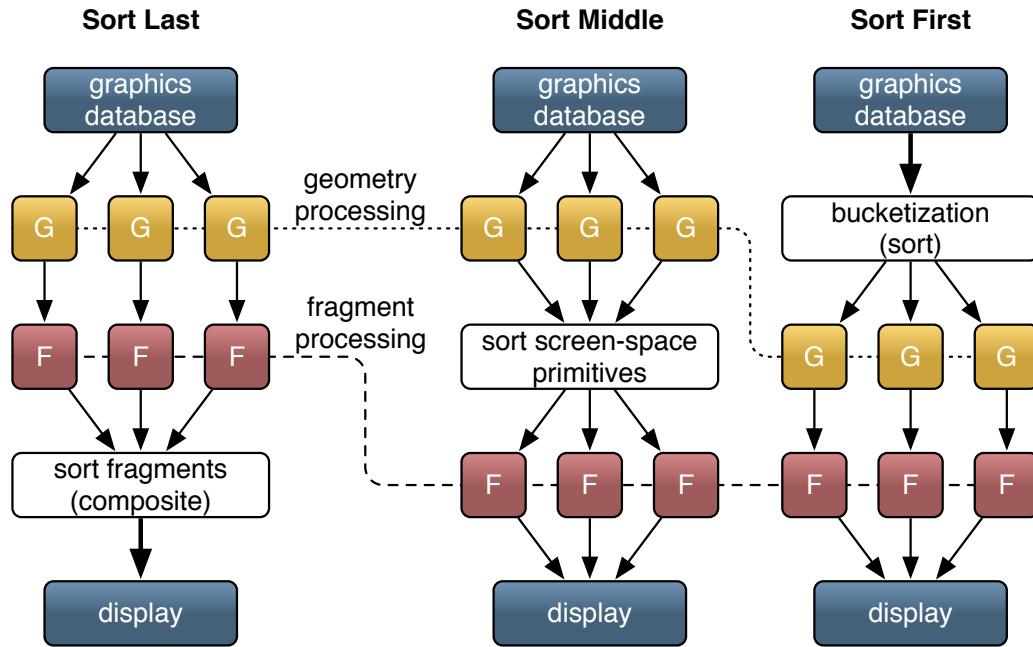


Figure 1.2: Sort-last, sort-middle and sort-first parallel rendering

Sort-last rendering decomposes the rendering task at the data level, that is, each resource renders a part of the data, and in the end partial fragments from each resource are composited to form a final results. Sort-middle rendering also decomposes the rendering at the data level, but collects and sorts the unshaded primitives before or after rasterisation, and then performs the fragment shading on the sorted data. Sort-first rendering decomposes the rendering task in screen space, and the application needs either to be fill-rate bound or have efficient view frustum culling to scale the rendering performance. 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 data processed and transferred in the sorting stage.

1.3.1 Domain Specific solutions

Cluster-based parallel rendering has been commercialised 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 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 supercomputers. 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-first 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; Eyles et al., 1997], 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 and GPU-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 Multipipe SDK [Jones et al., 2004; Bhaniramka et al., 2005; MPK, 2005]. These approaches can be categorised into transparent interception and distribution of the OpenGL command stream and into the parallelisation of the application rendering code (Figure 1.3).

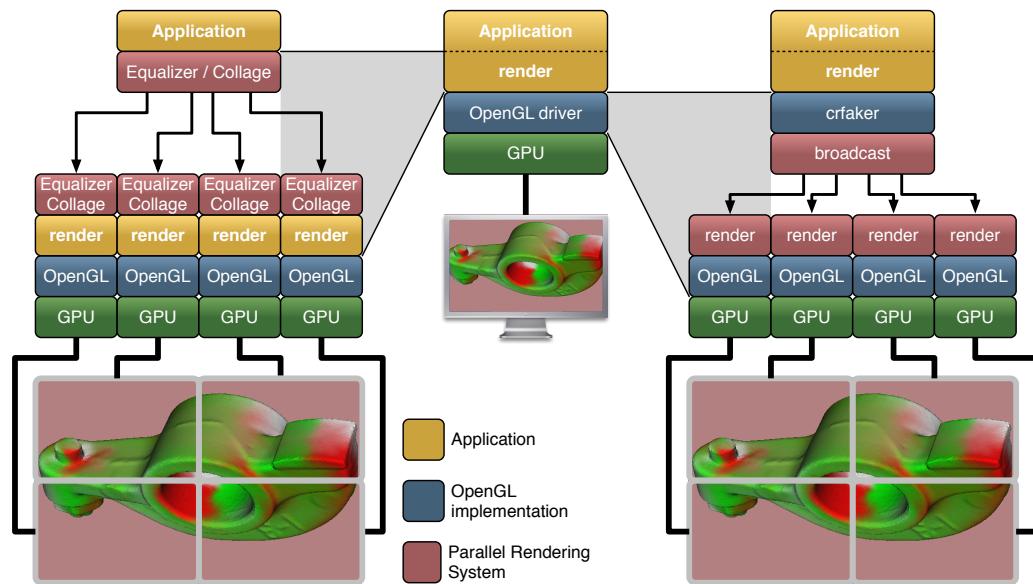


Figure 1.3: Parallelization and transparent OpenGL interception of the rendering code

VRJuggler

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 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 synchronisation 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 (synchronisation), distributed objects, image compression and transmission, or multiple rendering threads per process, important for multi-GPU systems.

Chromium

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 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 multi-resolution 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 synchronisation 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 popularised 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

CGLX [Doerr and Kuester, 2011] aims to bring parallel execution transparently to OpenGL applications, by emulating the GLUT API and intercepting certain OpenGL calls. Its target use case are multi-display installations, i.e., static sort-first rendering with no compositing. 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 synchronised across processes. For realistic applications, writing parallel applications remains the only viable approach for scalable rendering, as shown by the success of Paraview, Visit and Equalizer-based applications.

OpenGL Multipipe SDK

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. The author used to be the technical lead developer of OpenGL Multipipe SDK, therefore Equalizer is in many ways an evolution of MPK for distributed execution, improved performance and better configurability.

Tiled Display Walls

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 Thesis Structure

The remainder of this thesis is structured as follows: In the next chapter, we give a summary of the contributions of this thesis, listing relevant publications and the contribution of the author to these publications. Chapter 3 introduces the architecture of a parallel rendering framework, the foundation for this thesis. Chapter 4 presents new algorithms for the task decomposition in parallel rendering. Chapter 5 focuses on optimisations to reduce the cost of recombining the results of a parallel rendering decomposition. Chapter 6 describes better approaches to balance the task assignment to rendering resources. Chapter 7 describes the design and architecture of a network library tailored for parallel rendering. Before a conclusion in Chapter 9, Chapter 8 provides an overview of major Equalizer applications.

C H A P T E R

2

CONTRIBUTIONS

In this chapter we summarise the main contributions of this thesis. For each section, we list the relevant publications and specify the contributions of the author.

2.1 Parallel Rendering Architecture

A major contribution of this thesis is the formalisation and implementation of an architecture for a parallel rendering framework, which advances the state of the art in many aspects:

Minimally invasive API: The guiding principle for the API design was to enable applications to retain all their rendering code and application logic. The programming interface is based on a set of C++ classes, modelled 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. The contract for the implementation of the task methods does not assume any specific rendering library, algorithm or technology, thus facilitating the adaptation of existing applications for parallel rendering. This parallel rendering interface is significantly different from Chromium [Humphreys et al., 2002] and more similar to VR-Juggler [Bierbaum et al., 2001] and MPK [Bhaniramka et al., 2005].

Runtime configuration: The architecture of our parallel rendering framework makes a clear separation between rendering algorithm and the runtime con-

figuration. It provides a contract between the framework and the application code based on a rendering context, and uses this context to drive the application output depending on the runtime configuration. Application developers are unaware of parallel rendering setups and make no assumptions on how the rendering code will be executed. This clear separation yields parallel rendering applications which can be deployed on a wide set of installations, and are often configured in ways unforeseen during their deployment.

Compound trees: The introduction of compounds, and their underlying formalism, provides a formalisation of a flexible task decomposition and result recomposition for parallel rendering. Compound trees allow for easy specification of complex parallel task decomposition strategies which are automatically implemented and executed by the Equalizer system. They generalise parallel rendering principles without hardcoding a specific parallel rendering algorithm, thus proposing an orthogonal parameter set for decomposing rendering tasks, assembling results, and adapting these parameters at runtime.

Display abstraction: Large scale visualization systems cover a wide set of use cases from classical workstation setup to monoscopic tiled display walls, stereoscopic, edge-blended multi-projector walls to fully immersive installations such as CAVE systems. Consequently, applications running on these systems serve many different usage scenarios. Our novel canvas-layout abstraction provides a simple configuration of all these installations and empowers applications using these installations with 2D and 3D contextual information, runtime stereo configuration, and head tracking.

Modular architecture: Our architecture uses layered abstractions which gradually provide higher level abstractions. On the low level, a network library for distributed abstractions provides the substrate for Equalizer and applications. Within each library, a clear separation of responsibilities allows to combine existing algorithms easily. For example, an advanced feature such as cross-segment load balancing relies on per-segment load balancers, and both load balancers reconfigure the underlying compound tree each frame.

[Eilemann et al., 2009] and [Eilemann et al., 2018] publish the architectural foundations of parallel rendering frameworks. Any algorithmic, implementation and architectural contributions in these publications are contributed by the author, while experimental results have significant contributions from the secondary authors. [Bhaniramka et al., 2005] provides in many ways the foundation for Equalizer, to which the author was a contributor for the implementation of a parallel rendering framework for shared memory systems.

2.2 Scalable Rendering

Based on the flexible system architecture we implemented new scalable rendering algorithms, introduced in [Eilemann et al., 2009] and [Eilemann et al., 2018]. A particular focus was given to reduce the cost of the costly compositing step for sort-last rendering.

In [Eilemann and Pajarola, 2007], we provide an analysis of parallel compositing algorithms in an early version of our parallel rendering framework, and show that direct send compositing has advantages on commodity visualization clusters. The implementation, algorithm and experimental analysis in this paper are contributed by the author.

[Makhinya et al., 2010] introduced more sort-last compositing optimizations, most notably automatic region-of-interest detection and new compression algorithms. The author contributed the foundations for using region of interest, and the fast RLE compression with optimised data preconditioning.

[Eilemann et al., 2012] introduces many algorithmic optimizations for modern visualization clusters, ranging from asynchronous compositing, thread and memory placement on NUMA architectures, region of interest, and an analysis of real-world application performance. We show that careful system design and detailed optimizations are necessary to achieve scalability on larger visualization clusters. For this publication, the author contributed the algorithms, large parts of the implementation in Equalizer, and some experimental analysis.

2.3 Load Balancing

Optimal resource usage in larger visualization clusters relies on an even distribution of work over the available resources. This load balancing problem requires real-time algorithms based on imperfect knowledge of the system and application behaviour. In our architecture, load balancing acts by modifying compound tree parameters at runtime. For example, a sort-first load balancer adapts the sub-viewports assigned to each resource at runtime. These so-called **equalizers** are a component hooked into the compound tree, which makes their use and implementation independent of the rest of the framework.

Sort-first load balancing has been researched previously, while we also introduce sort-last load balancing based on the same principles. In [Eilemann et al., 2009] and [Eilemann et al., 2018] we provide experimental results on the effectiveness of our implementations. In the latter publication, we compare two different reactive load balancing algorithms and show that theoretically superior algorithms do not necessarily provide better performance in realistic scenarios.

[Erol et al., 2011] introduces a novel algorithm for load balancing an arbitrary set of rendering resources for driving visualization installations with many output displays, such as tiled display walls or multi-projector systems. The author contributed the algorithm and implementation for this publication.

[Steiner et al., 2016] provides an implementation and detailed analysis of central task queueing with work packages and different task affinity modes for sort-first and sort-last rendering. The author provided the base queueing infrastructure for this publication.

PARALLEL RENDERING 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 visualise 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.

Parallel rendering has similarities to other distributed computing domains such as cloud computing and high-performance computing (HPC): It aims to accelerate the completion of a task by parallelising a time-consuming algorithm, or to allow to compute a larger problem by employing multiple resources. Certain aspects are shared across these distributed computing domains, such as the need to load

balance the tasks executed in parallel, to minimise synchronisation and communication overheads, as well as to find a task decomposition which allows to produce correct results.

Scalable rendering however has one significant additional constraint: serving an interactive use case. Depending on the application domain and visualization system, typically a framerate between 10 Hz and 120 Hz is required to allow useful user interaction. This, in turn, translates to a budget of 8 ms to 100 ms to decompose the task to render a frame, perform rendering in parallel, and to composite and display the result. In comparison, cloud computing and HPC typically have turnaround times of seconds to hours. Consequently, many algorithms for parallel rendering need to rather compute a suboptimal solution, but do so in at most a few milliseconds.

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 parallelising 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 synchronising execution. For scalable rendering, when multiple GPUs are used to accelerate a single output, partial results need to be collected from all contributing resources, combined, and send to 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 configure the resources for parallel and scalable rendering. The configuration is a dynamic runtime structure, with a serialised configuration file format. In the following we will first describe the execution model and resource configuration, 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. Normally, the configuration of the rendering is largely hard-coded, with a few configurable parameters 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 to be managed.

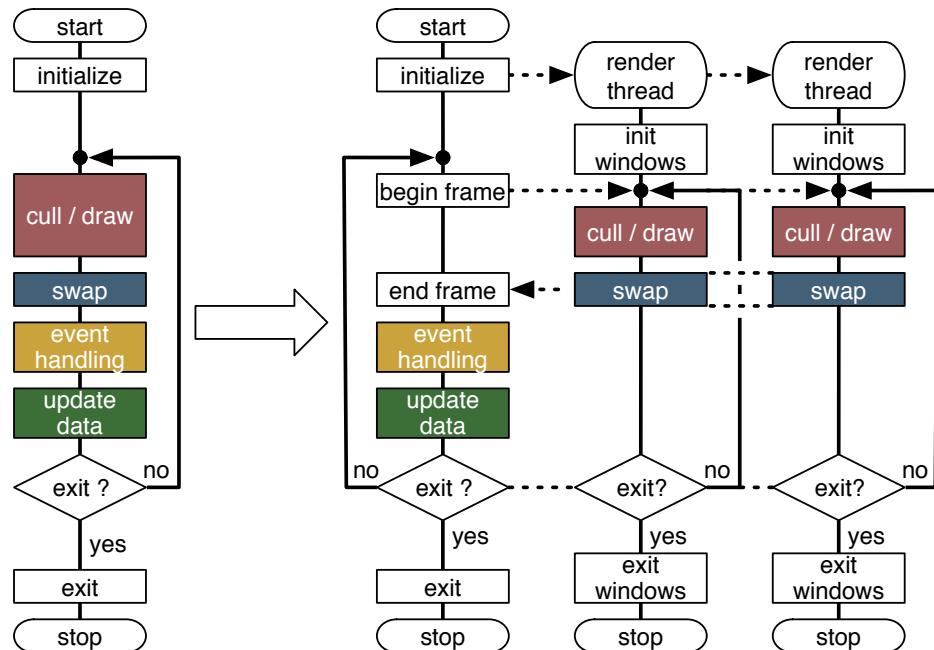
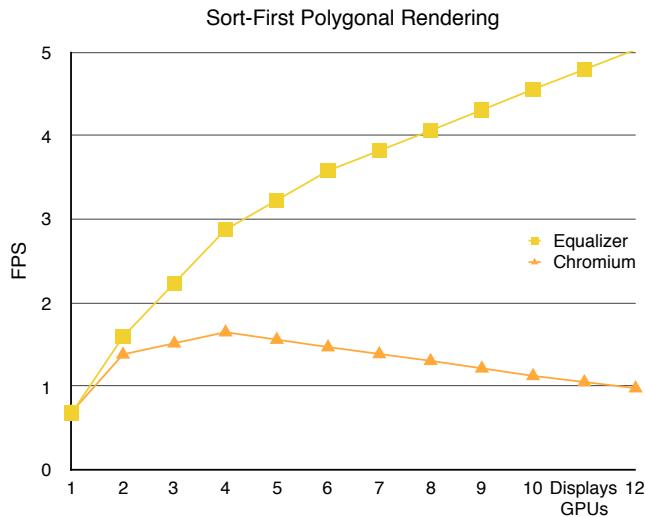


Figure 3.1: Simplified execution flow of a classical visualization application and an Equalizer application.

Without going into the details at this point, another critical design parameter are synchronisation points. Most implementations use a per-frame barrier or similar synchronisation 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 synchronisation points when strictly needed. The main synchronisation points are: configured swap barriers between a set of output channels which have to display simultaneously, the availability of input frames for scalable rendering, and a task

synchronisation 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. This 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. It also hides small imbalances in the task distribution, as they can average out over multiple frames.

Figure 3.2 shows the execution of the rendering tasks of a two-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. We have observed a speedup of 15% on a five-node rendering cluster when using a latency of one frame instead of no latency in a sort-first configuration.



Benchmark 3.1: Driving a Tiled Display Wall

each case a single GPU and node are responsible for driving the attached display. The polygonal model is rendered using eqPly and uses display lists for the static geometry. Using display lists allows Chromium to send geometry and texture data once to the rendering nodes (retained mode rendering) and display them repeatedly using `glCallLists()`, which is inexpensive in terms of network overhead. This setup is favourable for Chromium because the display lists have to be transmitted only once over the network, and only simple display calls will be processed and distributed by Chromium for each rendered frame.

Compared to interception approaches such as used by Chromium, our asynchronous programming model can inherently provide better performance. Benchmark 3.1 tests the rendering performance for driving a simple tiled display wall configuration with a static model, rotating about its vertical axis, placed such that it nicely covers the different screens.

A standard tile-sort Chromium configuration is compared to a simple Equalizer display wall setup, where in

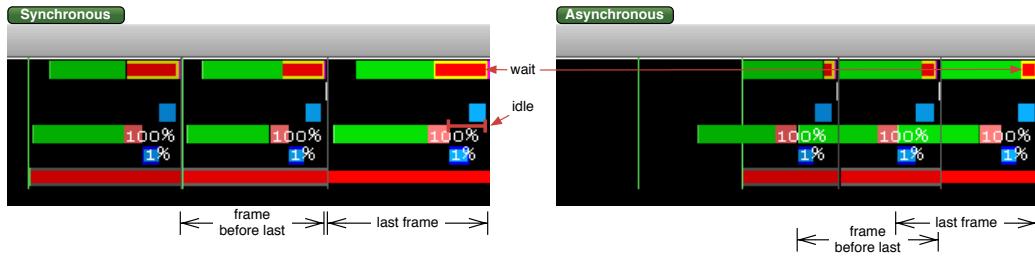


Figure 3.2: Synchronous and Asynchronous Execution

Chromium initially increases performance when adding nodes, but it quickly stagnates and even decreases when more nodes are added. In contrast, Equalizer continually improves performance with more added nodes and exhibits a smooth drop-off in speedup, due to the expected synchronisation and network overhead as the rendered data gets negligible in size per node. This performance difference is also due to the fact that Equalizer can benefit from distributed parallel view frustum culling.

3.2.1 Programming Interface

Equalizer provides a framework to facilitate the development of distributed and multi-threaded parallel rendering applications. The programming interface is based on a set of C++ classes, modelled 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 to control the parallel rendering configuration, render clients to execute the rendering tasks, and an administrative API to reconfigure the rendering session at runtime. All processes are communicate with each other through a common network library (Collage) and a client library implementing the Equalizer API.

The administrative API can connect to a server, and modify some aspects of the resource hierarchy, e.g., to create new output channels. Its description is outside of the scope of this thesis, and is mentioned here for completeness.

3.2.2 Application

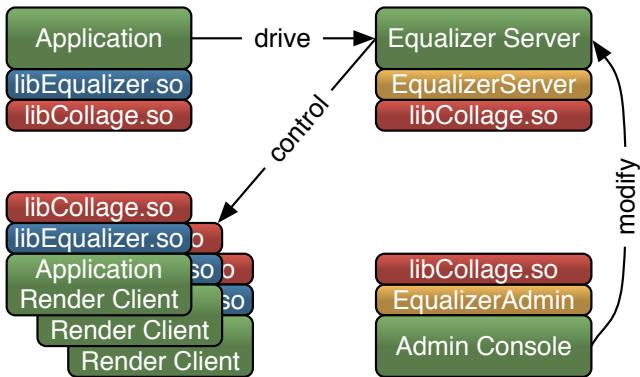


Figure 3.3: Parallel Rendering Entities

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. These render client threads are identical in behaviour and implementation to render threads on render client nodes. 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, synchronises on the completion of a frame and processes events received from the render clients. It may perform idle processing between the start and synchronisation of a frame. 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 synchronising 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 another executable which only contains the application-specific rendering code. The server deploys this rendering client on all nodes specified in the configuration. Render clients may run on a different architecture or operating system from the main application, the underlying network library ensures type safety and endian ordering.

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 commands. A render client consists of the following threads: the node main thread, one network receive thread, one thread for each graphics card (GPU) to execute rendering tasks, and potentially one thread for asynchronous compositing per GPU. 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 unordered *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. 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 is used to set up the OpenGL projection matrix. The frustum is influenced by the destinations 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.

View The view object from the logical rendering rendering configuration, introduced below. Holds view-specific data, such as camera, model or any other application state.

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. This follows the natural data flow for most windowing systems, and has natural semantics for thread safe event handling. For Qt, which centralises the event dispatch, Equalizer will reroute events to the render threads to ensure consistent behaviour.

3.2.5 NUMA Aware Thread Scheduling

Non-Unified Memory Access (NUMA) is a common hardware architecture for high-performance visualization clusters. Modern multi-socket render nodes use a NUMA architecture, where each CPU socket has a number of locally-attached memory buses, GPU and network devices, and CPU sockets are linked with an interconnect to each other. Accessing a memory address located on another processor has a performance penalty for both bandwidth and latency, and accessing a GPU or network interface from a remote processor is slower than a local access.

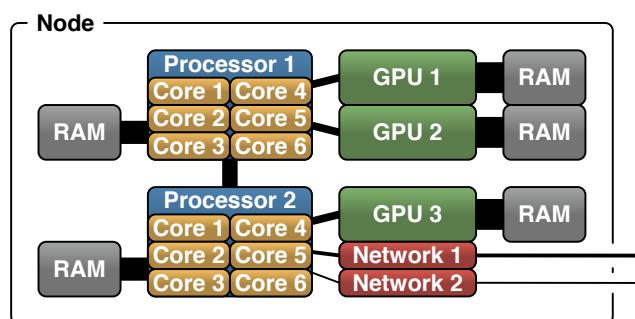


Figure 3.4: Exemplary Dual-Socket NUMA Node

Figure 3.4 shows one such NUMA visualization node, used in the experiments of [Eilemann et al., 2012]. It has two CPU sockets with six cores each, three GPUs connected to the two sockets, and two network cards (10 Gigabit Ethernet and InfiniBand) connected to one socket.

In our parallel rendering system, a number of threads are used to drive a single process in the cluster: the main thread (main), one rendering thread for each GPU (draw) and one thread to finish asynchronous downloads (read), one thread for receiving network data (recv), one command processing thread (cmd), and one thread for image trans-

mission to other nodes (xmit). We have implemented automatic thread placement by extending and using the hwloc library in Equalizer using the following rules:

- Restrict all node threads (main, recv, cmd, xmit) to the cores of the processor local to the network card.
- Restrict all GPU threads (draw, read) to the cores of the processor close to the respective GPU.

Figure 3.5 shows the thread placement for the example node used in Figure 3.4. The threads are placed to all cores of the respective processor, and the ratio of cores to threads varies with the used hardware and software configuration. Furthermore, many of the threads do not occupy a full core at runtime, especially the node threads which are mostly idle on a rendering client.

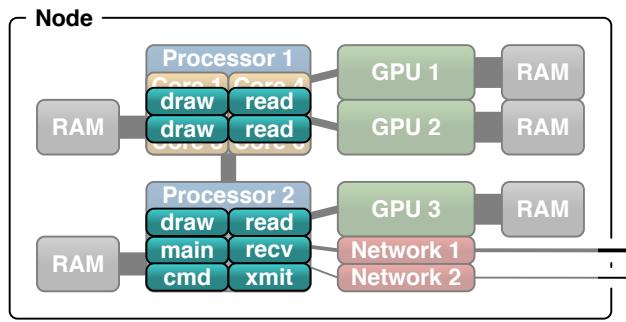
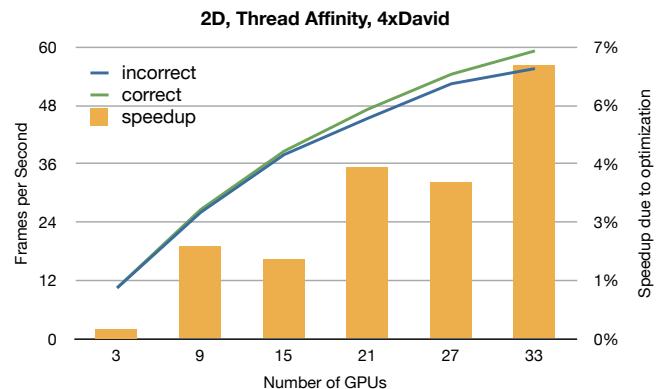


Figure 3.5: Thread Placement on a Dual-Socket NUMA Node

When using the default memory placement strategy, memory is allocated on the processor where it is accessed first (first-touch NUMA allocation). In Equalizer, all GPU-specific memory allocations are done by the render threads executing the rendering code, therefore placing the CPU-side buffers onto the same socket as the corresponding GPU. Similarly, network buffers are allocated and used from the one of the node threads.

We tested the influence of thread placement by explicitly placing the threads either on the correct or incorrect processor. We found that this leads to a performance improvement of more than 6% in real-world rendering loads, as shown in Benchmark 3.2. This benchmark uses the aforementioned cluster nodes, and renders polygonal data using sort-first scalable rendering.



Benchmark 3.2: Thread Affinity on NUMA hardware

The exact experiment setup is described in [Eilemann et al., 2012]. While this

is a relatively small influence, it becomes more important with higher frame rates as the relative draw time decreases, and the memory-intensive compositing step increases.

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 (2D rendering area in a window).

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. Observers observe multiple views and represent a head-tracked user in a visualization application.

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 rendering context 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. They group a set of segments (displays or projectors) into a 2D projection surface. A canvas uses layouts, which describe logical views. Typically, a desktop window uses one canvas, one segment, one layout and one view. One configuration might drive multiple canvases, for example a projection wall with 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 global reference system shared with the head-tracking matrix of 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 3.6 illustrates the wall and projection frustum parameters. All size units are in meters.

A canvas consists of one or more segments. A planar canvas typically has a frustum description, which is inherited by the segments. Non-planar frusta are

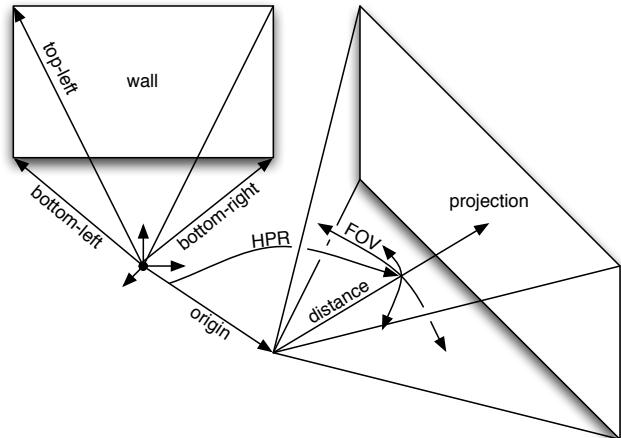


Figure 3.6: Wall and Projection Parameters

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 synchronise the video output, a canvas swap barrier or a swap barrier on each segment synchronise the respective window buffer swaps.

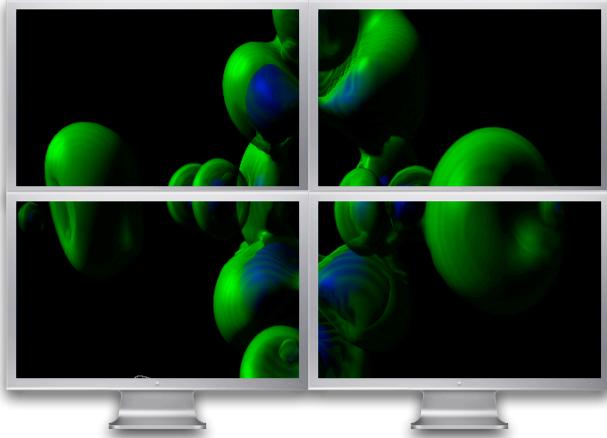


Figure 3.7: A Canvas using four Segments

A segment covers a two-dimensional region of its parent canvas, configured by the segment viewport. The viewport is in normalised coordinates relative to the canvas. Segments might overlap (edge-blended projectors) or have gaps between each other (display walls, Figure 3.7¹). 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. The view object is accessible to the application thread and all render threads contributing to its rendering. This allows the application to manage view-specific data by attaching it as a distributed object to the view.

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



Figure 3.9: Tiled Display Wall using a six-segment canvas with a two-view layout

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 3.8 shows an example layout using four views on a single segment. Figure 3.9 shows a real-world setup of a single canvas with six segments using underlap for the display bezels, with a two-view layout activated. This configuration generates eight destination channels.

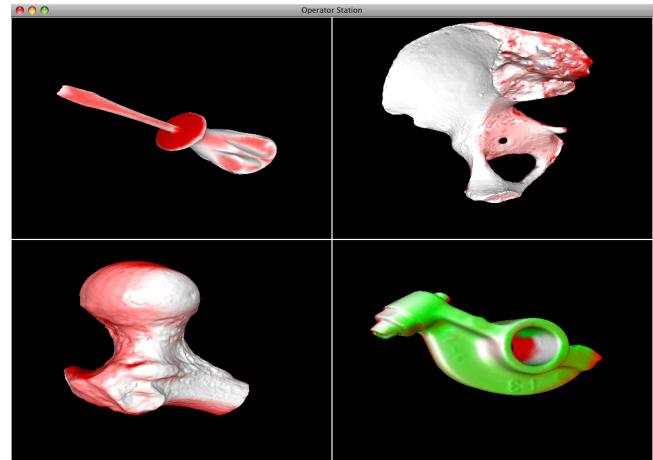


Figure 3.8: Layout with four Views

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

3.3.3 Compounds

Compound trees 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. They are modified at runtime by **equalizers** to implement dynamic behaviour, e.g., for load balancing.

Compounds are a data structure to describe the 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. The allocation of channels on pipes and nodes determines which resources execute the task, and what can be executed in parallel. A compound may provide output frames from the readback task to others, and can request input frames from others for its own assembly task. 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 3.10. 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`.

A non-leaf compound performing some image assembly and compositing task is provided in Figure 3.11. Framebuffer data is read from two other compounds

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

Figure 3.10: Compound executing rendering of a part of the data set into a given region of the viewport.

which supposedly execute rendering for part_a and part_b of the data set in parallel. The compound itself executes by default z -depth visibility compositing of the two input images on its channel and returns the resulting color framebuffer in the output frame named frame.display.

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

Figure 3.11: 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 readback 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, temporal, pixel, subpixel 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 synchronising multiple destination channels.

Destination compound(s) are the top-most compounds 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 and restricting the task to assemble and readback.

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

3.4 Virtual Reality

Virtual Reality is an important field for parallel rendering. It does require special attention to support it as a first-class citizen in a generic parallel rendering framework. Equalizer has been used in many virtual reality installations, such as the Cave2 [Febretti et al., 2013], the high-resolution C6 CAVE at the KAUST visualization laboratory, and head-mounted displays (Figure 1.1). In the following we

lay out the features needed to support these installations, motivated by application use cases.

3.4.1 Head Tracking

Head tracking is the minimal feature needed to support immersive installations. Equalizer does support multiple, independent tracked views through the observer abstraction. Built-in VRPN support enables the direct, application-transparent configuration of a VRPN tracker device. Alternatively, applications can provide a 4×4 tracking matrix. Both CAVE-like tracking with fixed projection surfaces and HMD tracking with moving displays are implemented.

3.4.2 Dynamic Focus Distance

To our knowledge, all parallel rendering systems have the focal plane coincide with the physical display surface. For better viewing comfort, we introduce a new dynamic focus mode, where the application defines the distance of the focal plane from the observer, based on the current *lookat* distance.

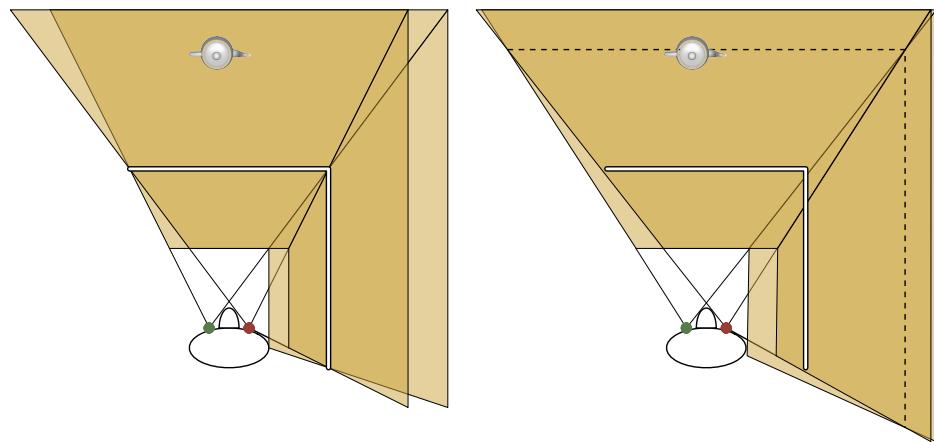


Figure 3.12: Dynamic Focus in a Cave

Figure 3.12 illustrates this feature in a top-down view of a CAVE. The observed teapot is significantly behind the front projection wall in the virtual world. In a standard implementation (left side), the focal plane coincides with the projection surface. In our implementation, the application configures a focus distance to coincide with the observed teapot (right side). The dotted line shows the focal plane for both projection walls. Initial experiments show that this provides better viewing comfort, in particular for objects placed in front of the physical displays.

3.4.3 Asymmetric Eye Position

Traditional head tracking computes the left and right eye positions by using an interocular distance. However, human heads are not symmetric, and by measuring individual users a more precise frustum can be computed. Equalizer supports this through the optional configuration of individual 3D eye translations relative to the tracking matrix.

3.4.4 Model Unit

This feature allows applications to specify a scaling factor between the model and the real world, to allow exploration of macroscopic or microscopic worlds in virtual reality. The unit is per view, allowing different scale factors within the same application. It scales both the specified projection surface as well as the eye position (and therefore eye separation) to achieve the necessary effect.

3.4.5 Runtime Stereo Switch

Applications can switch each view between mono and stereo rendering at runtime, and run both monoscopic and stereoscopic views concurrently. This switch does potentially involve the start and stop of resources and processes for passive stereo or stereo-dependent task decompositions.

3.5 Tiled Display Walls

Simulations performed on today's high performance supercomputers produce massive amounts of data, which are often too expensive to move to another system. Tiled display walls have proven to help understanding complex data due to their size, resolution and collaborative usage. Often the two systems are not located in the same facility due to power constraints or other factors.

Software for driving tiled display walls has converged on the collaborative aspect of these installations. Sage, Sage 2, DisplayCluster and, to a certain extent, Omegalib, implement a multi-window environment around a shared framebuffer concept. DisplayCluster provides a dynamic, desktop-like windowing system with built-in media viewing capability that supports ultra high-resolution imagery and video content, as well as remote streaming allowing arbitrary applications from remote sources to be shown. Figure 3.13 shows our evolution of DisplayCluster called Tide [Blue Brain Project, 2016] running on a 24 megapixel, 4×3 tiled display wall.

Streaming to a Tide wall is implemented using the Deflect [Nachbaur et al., 2014] client library. The application provides an image buffer to Deflect, which is compressed using libjpeg-turbo, and sent asynchronously and in parallel by the stream library. Multiple stream sources from multiple processes can provide content to a single window on the wall, enabling parallel streaming for parallel rendering applications. The stream library also implements an event model, where an application can register itself to receive keyboard, mouse and window management events from the display wall.

We integrated the stream library into Equalizer to send the framebuffer of each destination channel to DisplayCluster, using a direct FBO download (if possible) or a texture download. The compression and sending uses asynchronous transmission, pipelining compression and streaming with rendering. Received events from DisplayCluster are converted and forwarded to Equalizer’s event system. This integration allows all Equalizer applications to benefit from streaming without any code changes, it is configured simply by specifying the DisplayCluster hostname on all views to be streamed.

We evaluated the overall system performance using the Blue Brain Project setup shown in Figure 3.14. The supercomputer and data is located in a remote supercomputing center in Lugano, whereas the tiled display wall is at the project’s main office in Lausanne. Both locations are linked using a high-speed WAN link. The HPC installation has a collocated visualization cluster for remote rendering scenarios.

Benchmark 3.3 shows the performance of streaming RTNeuron rendering from the Lugano cluster to the remote 24 Megapixel wall. We tested three resolutions (1920×1080 , 3840×2160 and 7680×3240), and four different tile sizes (256^2 ,



Figure 3.13: Tiled Display Wall showing remote rendering of the Equalizer-based RTNeuron Application

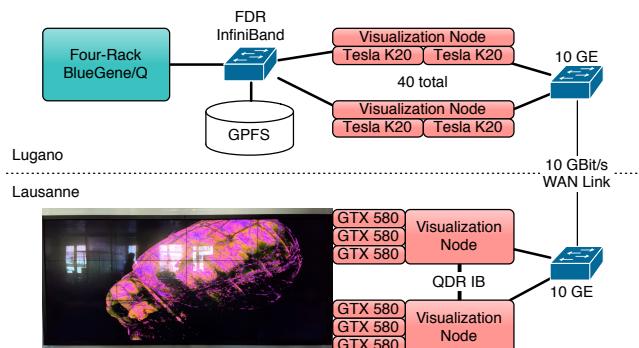
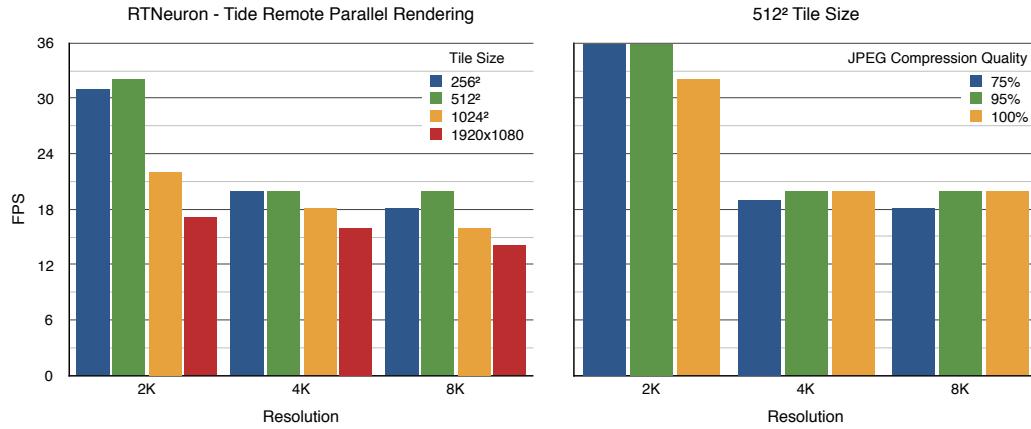


Figure 3.14: Remote Streaming Scenario



Benchmark 3.3: *Remote RTNeuron - Tide Parallel Rendering*

512², 1024² and 1920 × 1080). Due to a configuration issue, the WAN link delivered only 1 GBit/s throughput during the benchmark test. RTNeuron is an Equalizer-based application used in the Blue Brain Project to analyse results from detailed simulations of neuronal simulations.

The results show that interactive frame rates are available even at the full native resolution, that a 512² tile size is the best option found, and that 95% compression delivers the best performance in most cases. Based on the experiments we settled on a 512² tile size and 100% compression quality to avoid artefacts as the default settings in Equalizer.

3.6 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 specialised 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 customisation 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 3.16 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 neighbours, 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, whereas the third tile is already in place.

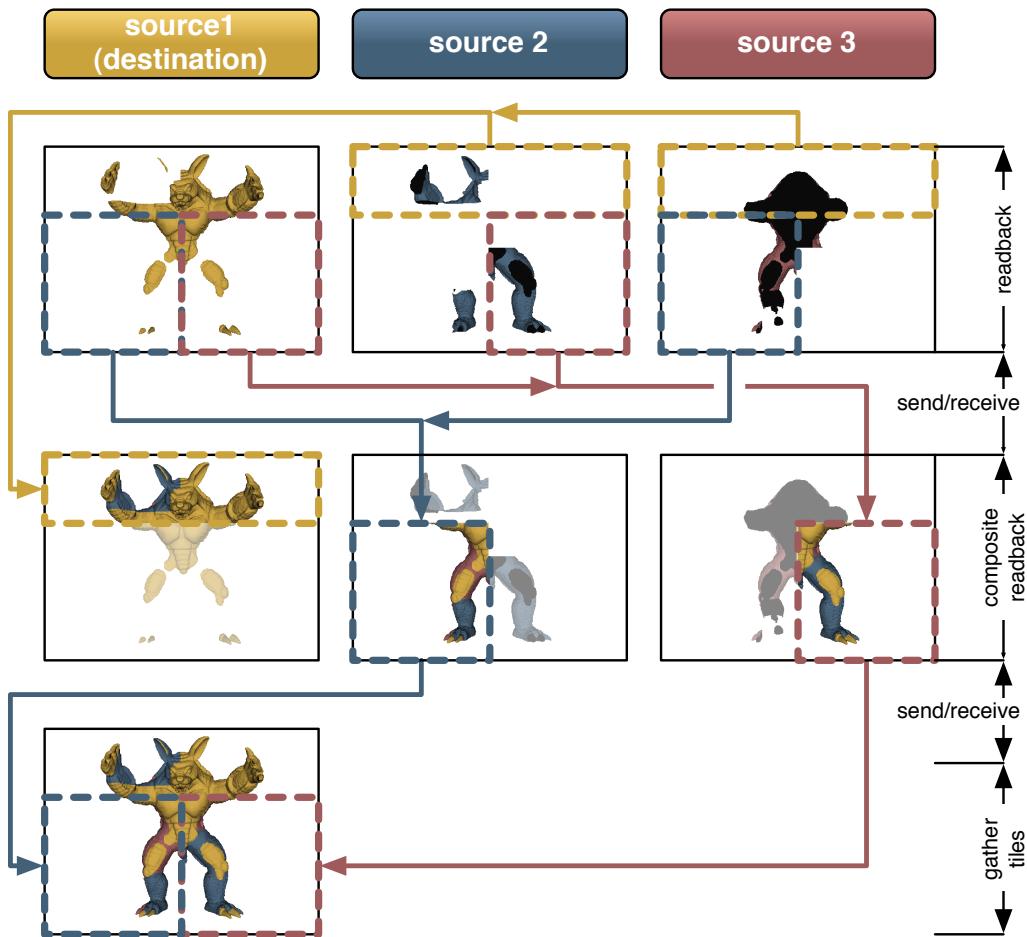


Figure 3.16: Direct Send Compositing

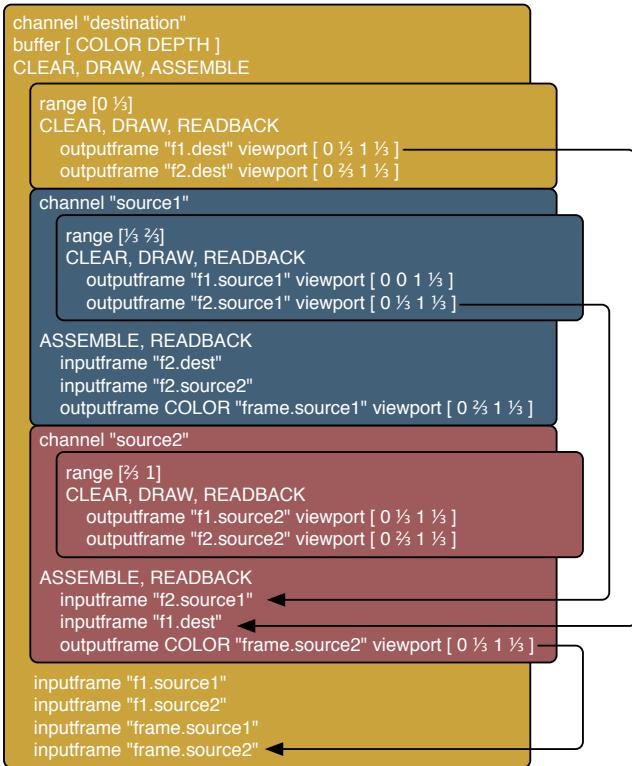


Figure 3.15: Direct Send Compound

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 honours the `range` parameter of the render context to decompose its rendering. All other tasks, in particular the parallel 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, before passing them on to the compositing code.

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 3.16, 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.

The corresponding compound tree is shown schematically in Figure 3.15. Each of the three channels has a child compound to execute the rendering and read back two 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

Parallel Compression, Downloads 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 minimises 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.

In Chapter 5 we provide detailed information on our compositing advances.

3.7 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 optimise the resource usage. Each equalizer focuses on tuning one aspect of the decomposition, allowing them to be composed in a configuration. Due to their nature, they are transparent to application developers, but might have application-accessible parameters to tune their behaviour. Resource equalisation 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 equalise rendering times between all resources.

In Chapter 6 we provide an extensive overview over the available equalizers.

3.8 Runtime Reconfiguration

Supported by the distributed execution layer, introduced in the next section, Equalizer implements dynamic reconfiguration of a running visualization application. This functionality is used by runtime layout switches and runtime reliability.

Runtime reconfiguration is designed to be a side effect of the internal resource management algorithm, that is, the initialization and exit of a configuration uses the same code path as the runtime addition of a single channel. Rendering resources in Equalizer are ref-counted by the compounds using them, and the state change between inactivated and activated triggers a launch or stop of the associ-

ated resource. These resource counters are propagated up the resource hierarchy, that is, a channel will (de)activate its window, pipe and node.

Channel and window (de)activation are relatively lightweight and only incur the creation and initialization of the class instance (and associated OpenGL resources) on the client. A pipe (de)activation incurs additionally a new (or removed) operating system thread, and a node (de)activation is tied to a process. Depending on the application logic, at some level of the resource hierarchy application data has to be distributed to the rendering client. An application may use pre-launched rendering clients which run even when not active, and can use this to cache application state for faster reconfiguration.

Layout switches are caused by the activation of a different layout on a canvas by the application code. A typical layout switch will only (de)active channels, which is a very lightweight operation. Since each combination of a layout and a canvas creates a unique set of destination channels, the destination compounds of these channels may use a different set of source channels for rendering, which may reside on different GPUs or even nodes in the cluster. Some configurations use a different number of rendering GPUs or even nodes, which may cause the startup or exit of new rendering processes in the cluster.

Runtime reliability detects failed nodes in a visualization cluster, independent of the cause (hardware or software failure). The server tracks a ‘last seen’ time stamp for each node. When waiting for a task to finish, the server uses this time stamp to detect potentially failed node. Potentially failed nodes are pinged with a special command, which is processed even if all application threads are busy. Nodes still answering this command are considered alive for a longer period, after which they are considered failed, likely due to an infinite loop in the application code. Failed nodes are removed from the configuration, and their associated compounds are deactivated. In the case of load balanced source channels, the load equalizer will simply reassign the work to other source channels. For static configurations, the source channel contribution will be missing from the final image. For destination channels, the corresponding output display will disappear from the configuration.

3.9 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 3.17 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 7.3.1.

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.

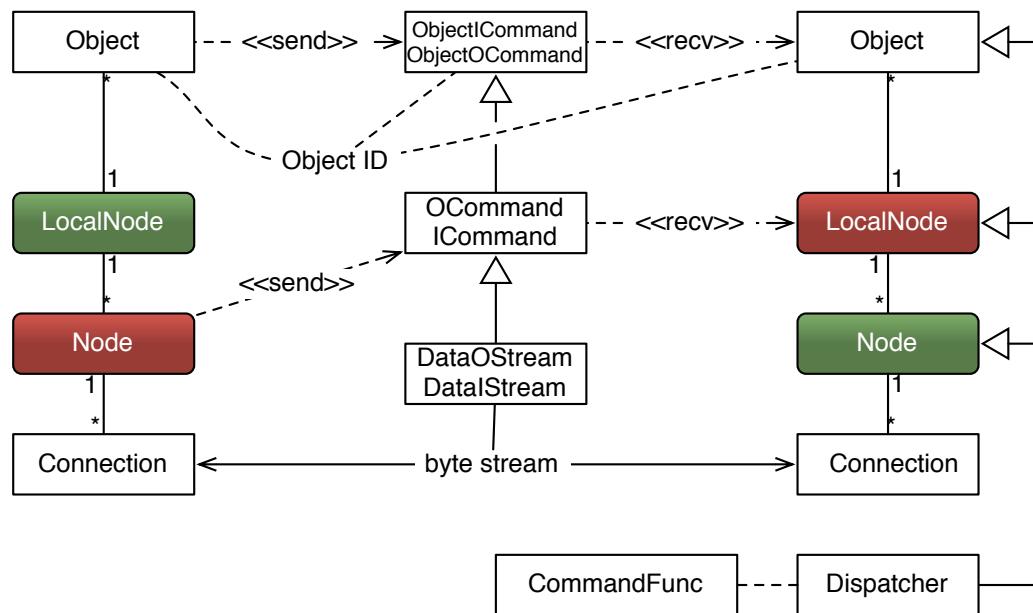


Figure 3.17: Communication between two *Collage* objects

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 synchronisation. 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 latency, the queue is implemented as a ring buffer.

tencies, consumers prefetch items into a local queue. Queues are used for tile and chunk compounds (Section 4.2.4).

An object map facilitates distribution and synchronisation 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 synchronise all mapped instances to the new version recorded in the object map. This effective design allows data distribution with minimal application logic.

Chapter 7 contains more information on our network library.

SCALABLE RENDERING

4.1 Overview

Scalable rendering is a subset of parallel rendering which aims to improve the framerate of a rendering task by decomposing it over multiple rendering resources. Parallel rendering includes other use cases, for example to use multiple GPUs to drive individual displays of a tiled display wall.

Scalable rendering research has put a lot of focus on two of the three architectures classified by [Molnar et al., 1992]: sort-first and sort-last rendering. Sort-middle rendering is still largely confined to hardware implementations due to its high communication cost of sorting and distributing fragments to processing units.

In this chapter, we present a wide set of new parallelization schemes which break out of this standard classification. For each mode, we present its algorithm and implementation, potential impact on the application code, as well as its strengths and weaknesses. Due to the flexible architecture of our parallel rendering system, these modes are largely usable with any Equalizer application and can be combined with all other modes. Equalizer also supports sort-first and sort-last rendering, not further mentioned in this chapter.

Most of these rendering modes are similar to sort-first rendering, in that they decompose the final view spatially or temporally, while computing complete pixels on each source channel. Stereo compounds decompose per eye pass, DPlex compounds temporally, pixel and subpixel compounds use equal spatial decom-

positions. Finally, tile and chunk compounds implement implicit load balancing for sort-first and sort-last rendering using queueing of work items.

This wide set of decomposition modes for scalable rendering, embedded in our generalised compound structure, enables applications and researchers to decompose the rendering task in, as far as we know, any way possible for a rendering pipeline. To our knowledge no other implementation provides this breath and flexibility, and many of these algorithms appear for the first time in Equalizer.

4.2 Sort-First

Sort-first rendering decomposes the rendering task in screen space. It has many variants: tiled display walls and similar installations perform sort-first parallel rendering naturally by using multiple GPUs to drive the output displays, and classic sort-first scalable rendering assigns one screen-space region to each rendering resource, often combined with load balancing. Equalizer supports these classic sort-first modes. In the following subsections we present other variants of sort-first rendering, each tailored to a certain use case.

4.2.1 Stereo

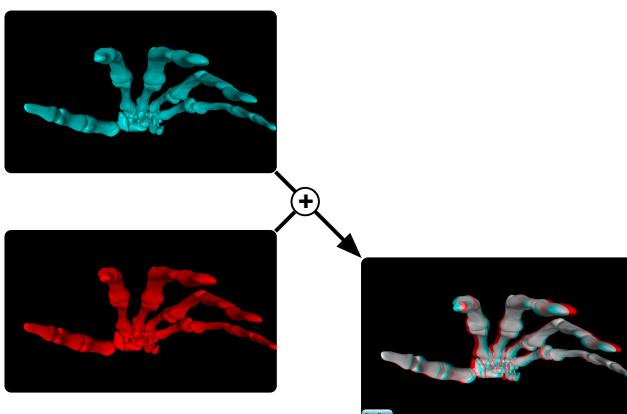


Figure 4.1: Anaglyphic Stereo Compound

balance. Figure 4.1 shows an anaglyphic stereo compound.

While many implementations provide passive or active stereo rendering and sometimes decomposition using two GPUs, our implementation within our flexible compound structure allows to fully exploit stereo decomposition. Stereoscopic and monoscopic rendering is no special case in the architecture, but rather a con-

Stereo, or eye decomposition, is a specialised version of sort-first rendering. Two GPUs get assigned each one of the eye passes during stereo rendering. For passive stereo, there is no compositing step needed, whereas for active and anaglyphic stereo the frame buffer for one eye pass has to be copied to the destination channel. Due to the strong similarity between both eye passes, this mode provides close to perfect load balance.

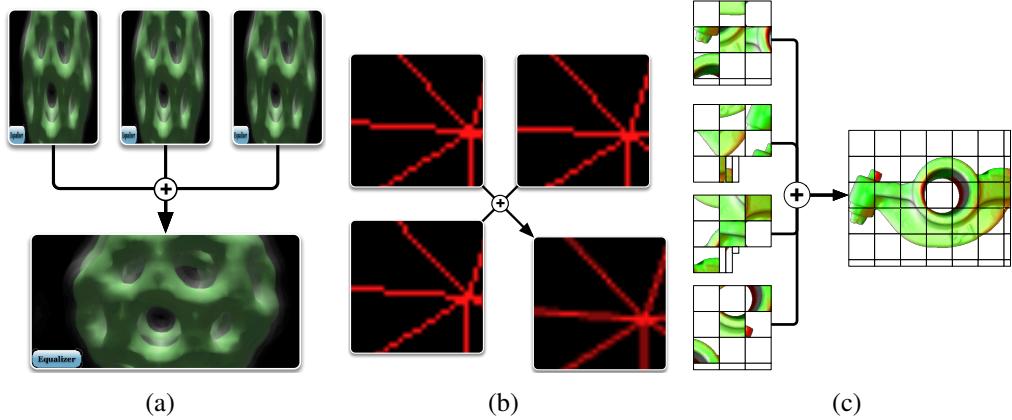


Figure 4.2: Pixel, Subpixel and Tile Compounds.

figuration of the rendering resources. Among other things, this allows extending a two-way stereo decomposition with further resources and any other scalable rendering mode. One can also easily set up an application with mixed rendering, e.g., to render a monoscopic view on a control workstation while rendering stereoscopic on a larger immersive installation.

4.2.2 Pixel

Pixel compounds (Figure 4.2(a)) decompose the destination channel by interleaving pixels in image space. They are a variant of sort-first rendering well suited for fill-limited applications which are not geometry bound, for example direct volume rendering. Source channels cannot reduce geometry load through view frustum culling, since each source channel has almost the same frustum. However, the fragment load on all source channels is reduced linearly and well load balanced due to the interleaved distribution of pixels. This functionality is transparent to Equalizer applications, and the default compositing uses the stencil buffer to blit pixels onto the destination channel.

Pixel compounds are configured by restricting each source compound with a pixel kernel. The kernel describes the size of the decomposition in 2D space, and the 2D pixel offset within this region. This follows our design philosophy of enabling features by generalising the underlying algorithm rather than hardcoding them.

4.2.3 Subpixel

Subpixel compounds (Figure 4.2(b)) are similar to pixel compounds, but they decompose the work for a single pixel, for example with Monte-Carlo ray tracing, FSAA or depth of field rendering. The default compositing algorithm uses accumulation and averaging of all computed fragments for a pixel. Like Pixel compounds, this mode is naturally load balanced on the fragment processing stage but cannot scale geometry processing. This feature is not fully transparent to the application, since it decomposes rendering algorithms which render multiple samples per pixel. Applications needs to adapt their rendering code, for example to jitter or tilt the frustum based on the subpixel executed in the current rendering pass.

Since subpixel compounds increase the amount of pixels to be composited linearly with the number of source channels, they can use the same parallel compositing algorithms as sort-last rendering. Since the compositing logic is decoupled from the task decomposition, it reuses the same code as sort-last parallel compositing except for the combination step on each GPU.

4.2.4 Tiles

Tile (Figure 4.2(c)) decompositions are a variant of sort-first rendering. They decompose the scene into a predefined set of fixed-size image tiles. These tasks, or work packages, are queued and processed by all source channels by polling a server-central queue. Prefetching ensures that the task communication overlaps with rendering. As shown in [Steiner et al., 2016], work packages can provide better performance due to being implicitly load balanced, as long as there is an insignificant overhead for the render task setup. This mode is transparent to Equalizer applications. We have used a tile compound to scale an interactive ray tracing application to hundreds of rendering nodes using RTT Deltagen.

4.3 Sort-Last

Sort-last rendering decomposes the rendering task in object space, that is, each rendering resource produces an incomplete full-resolution image. To our knowledge, sort-last rendering always requires a compositing step, which is the challenging part for this decomposition mode. It is often addressed using parallel compositing, which we discuss in Section 5.2.

Equalizer does support classical sort-last rendering with or without load balancing, where each resource renders one part of the applications database. Furthermore, we also implement chunk compounds, which are similar to tile compounds (Section 4.2.4), with which they share a lot of the infrastructure. Chunk

compounds also produce work packages, although using a fixed-size subrange for each package instead of the tile coordinates used for tile compounds.

4.4 Time-Multiplex

Time-multiplexing distributes full frames over the available resources, such that each resource only renders a subset of the visible frames (Figure 4.3). This mode is also called alternate frame rate or DPlex, was first implemented in [Bhaniramka et al., 2005] for shared memory machines. The algorithm is however much better suited for distributed memory systems, since the separate memory space makes concurrent rendering of different frames much easier to implement. While it increases the framerate almost linearly, it does not decrease the latency between user input and the corresponding output. Consequently, this decomposition mode is mostly useful for non-interactive movie generation.

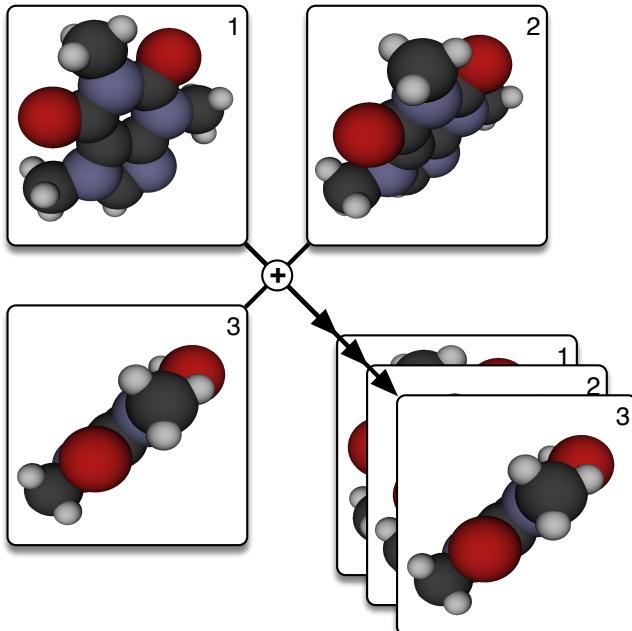


Figure 4.3: Time-Multiplex Compound

DPlex is very well load balanced, since most applications observe a strong frame-to-frame coherence with respect to the rendering load. This decomposition mode has the peculiarity that small imbalances tend to accumulate such that the concurrent frames all finish simultaneously. To provide a smooth framerate, if so desired, a framerate equalizer can be installed on the destination compound. Section 6.5 covers this functionality. It is transparent to Equalizer applications, but does require the configuration latency to be greater or equal than the number of source channels.

DPlex rendering is not hard-coded into our framework, but configured by restricting the rendering task temporally on each source compound. This is achieved by setting a **period** and **phase** parameters, which configure the number of frames skipped and starting offset on the given source compound. A simple DPlex com-

pound would have a destination compound with n source compounds, where each source has a period of n and one phase from $0..n - 1$. While this generalization may seem artificial, it opens up different use cases, for example giving a fast GPU a smaller period, thus giving it more work.

4.5 Mixed Mode Compounds

A major contribution of our parallel rendering system is the flexible system architecture. While many applications and frameworks implement a subset of the features mentioned above, most of them hardcode the algorithms to a certain degree, predetermining the number of possible configurations. In Equalizer, both the decomposition and the recomposition of the rendering task are derived through a number of orthogonal parameters, which are easily combined to configure common scalable rendering modes. For advanced usage, they can also be configured for many other use cases. We have seen many interesting and unforeseen configurations, for example:

- Reusing the `period` parameter used to configure number of frames in a DPlex compound, an underpowered control workstation for a large tiled display wall was configured to render only every other frame using a period of two. Due to the standard latency of one frame, this meant that the display wall rendering became the bottleneck, but could render at a substantially higher framerate than before.
- Rerouting one of the eye passes of a head-mounted display to a large display using an output and input frame, external users could observe the interaction and view of the person using the HMD. The same can be achieved by mirroring the video signal by other means, but this was not available on the given setup.
- Using combined stereo and sort-first decomposition on the central tiles of a tiled display wall. Oftentimes the central tiles of a tiled display wall receive a higher rendering load than the outer tiles. In this particular configuration, each tile was driven by a dual-GPU node using active stereo compounds, and the middle segments were given an additional machine setting up a two-way sort-first decomposition under each node of the two-way stereo compound.
- Combined sort-last and sort-first decomposition: Sort-first rendering is typically limited in the scalability of the decomposition step, where geometry overlap between resources often yields diminishing returns after about ten GPUs. Sort-last rendering on the other hand is often limited by the overhead of the compositing step. Combining both modes enables to balance these constraints for better scalability.

4.6 Stereo-Selective Compounds

Each compound sub-tree can restrict the eye passes it renders from the default left, right, cyclop passes. Depending on the active stereo mode (stereo or mono), restricted compound trees may be skipped or activated. This is used on one hand to configure stereo compounds, but may also be used to configure different decompositions depending on the stereo mode. Figure 4.4 shows a simple example: A dual-GPU setup is used with eye-parallel rendering during stereo rendering, and a standard sort-first parallel rendering during monoscopic rendering. Note that the rendering mode is runtime-configurable, that is, the application can switch the view from monoscopic to stereoscopic rendering at any time, activating and deactivating the configured compounds and attached resources. It is also possible to configure a different set of resources (nodes and GPUs) per stereo mode, triggering the launch and exit of render client processes during the stereo switch.

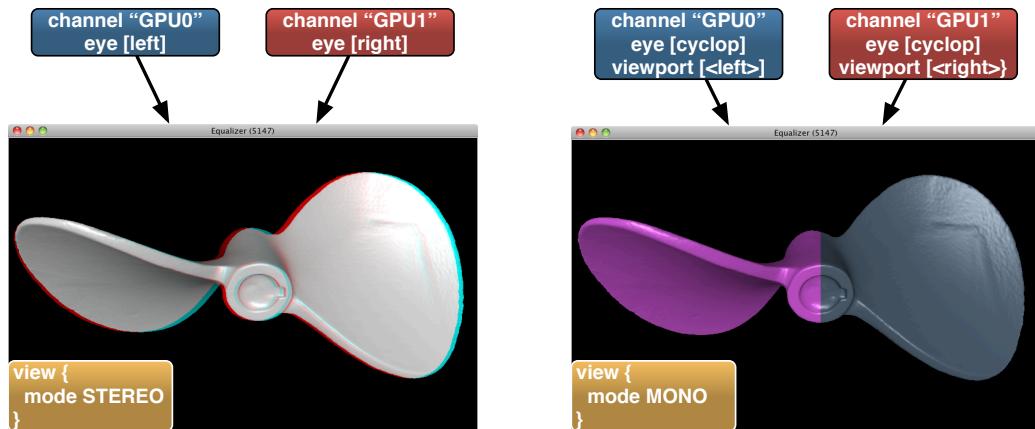


Figure 4.4: Stereo-Selective Compound

C H A P T E R

5

COMPOSITING

5.1 Overview

Compositing collects and combines partial results from multiple resources during scalable rendering onto one or more destination channels. While significant characteristics of the decomposition step, discussed in the previous chapter, are dependent on the application rendering code, compositing is largely a generic problem and can be implemented and optimised in a parallel rendering framework. Consequently, this area of parallel rendering research has received significant attention. By integrating many state-of-the art optimizations into our parallel rendering framework we provide a generic solution which scales well on modern visualization cluster architectures. Furthermore, we present new optimizations for NUMA-aware thread scheduling, insight into spatial sort-last polygonal rendering, and image compression algorithms for high-speed interconnects.

5.2 Parallel Compositing

Parallel compositing leverages multiple compute resources, memory bandwidth and network bandwidth within a visualization cluster to accelerate the compositing step in parallel rendering. During sort-last and subpixel decompositions, each rendering resource produces an output which needs to be combined with the result of other resources on a per-pixel level. This compositing step reduces the amount of information, either through depth-sorting or blending multiple input fragments

into a single pixel. This loss of information in the compositing step can be exploited by distributing the work over multiple resources and then collecting the reduced image tiles, commonly called parallel compositing.

For sort-last rendering, there are two approaches to combine the partial results: z -sorting using the depth buffer, and spatial rendering decomposition with ordered compositing.

The first algorithm uses both the color and depth buffer, and assigns the final pixel to the color of the source with the front-most depth buffer values. It requires no spatial ordering of the data during rendering. It does not correctly composite pixels with transparent geometry, since no guarantee of the blending order can be made. Due to the use of the depth buffer, it is also more expensive since more pixel data needs to be processed. Furthermore, depth buffer readback tends to slower, and compression algorithms for depth buffer data tend not to perform as well as color buffer compression. Depth-sorted compositing is often used for polygonal data, as shown in Figure 5.1(a) since these applications often do not sort their geometry onto convex spatial regions.

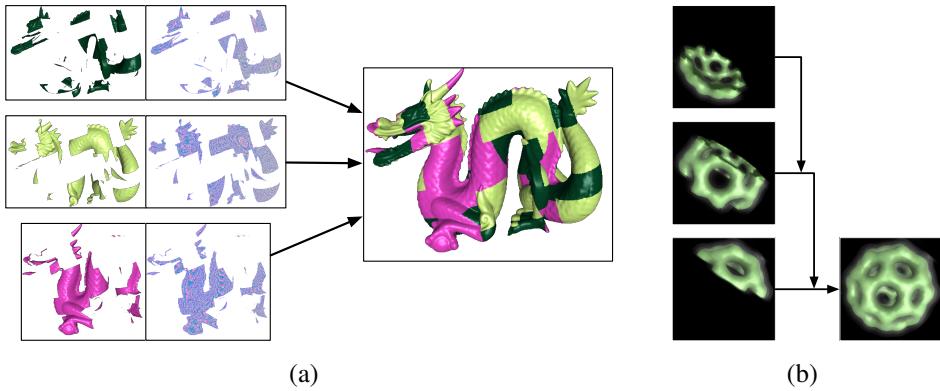


Figure 5.1: Depth-Sorted and Back-to-Front Sort-Last Compositing.

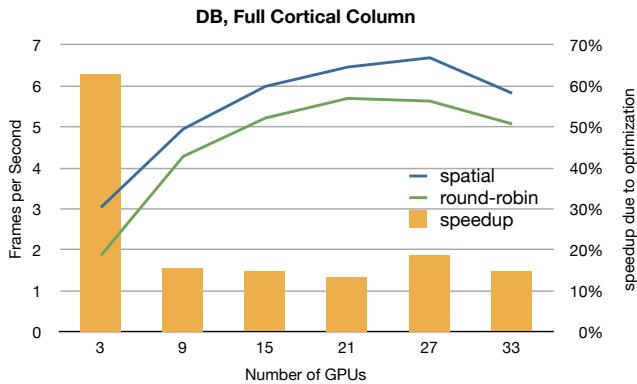
Spatial compositing is often used for direct volume rendering, and requires the application to render convex regions of data on each source, and then depth-sort the partial images produced by each source. The partial images are composited in order, typically with alpha-blending. Since the sorting happens at the image level, rather than the fragment level as in the first algorithm, it can operate using only the color buffer, as shown in Figure 5.1(b).

This algorithm produces correct transparency, unless multi-sampling is used during rendering. Multi-sampling also incurs a loss of information, where multiple samples are collapsed into a single pixel. Pixels where samples are generated from different geometries are problematic, since the averaging operations blends them with incomplete information during sort-last rendering. A fully correct al-

gorithm would need to composite all fragments from all sources before collapsing them, or to operate on the full-size multisample buffer.

Spatial compositing provides better performance, and provides better scalability for other optimisations such as region of interest and load balancing due to compact regions produced by the spatial sorting. Normally used for volume rendering, we have applied spatial sort-last rendering and compositing to polygonal data, by sorting the data spatially and using clipping planes to generate perfectly convex rendering subsets.

Benchmark 5.1 shows the difference between spatial and depth-sorted sort-last rendering in RTNeuron (Section 8.3). Due to complexities in the application data model, and the disadvantageous geometrical structure of neurons, the spatial mode in RTNeuron scales less well than the round-robin allocation used for the depth-sorted mode. Still, due to the significantly reduced compositing load of this mode, both due to a smaller region of interest and no depth buffer transfers, spatial sort-last rendering has a significantly better framerate. The exact experiment setup can be found in [Eilemann et al., 2012].



Benchmark 5.1: *Spatial versus Depth-Sorted Sort-Last Rendering*

Contrary to most other implementations, parallel compositing algorithms in Equalizer are not hardcoded, but rather configured explicitly in the configuration. The transport of pixel data for compositing is expressed through connected output and input frames. Output and input frames are connected by name; they do not need to follow the compound hierarchy, and a single output frame may be consumed by multiple input frames. Output frame parameters configure a subset of the rendering (viewport and framebuffer attachments), and are read back after rendering and assembly. Besides this, every step of the compositing pipeline is implemented in Equalizer and transparent for the application developer. Some steps may be replaced with application code, for example to order frames during compositing.

Two commonly used parallel compositing algorithms are direct send and binary swap. Both distribute the compositing task equally over all available resources, and then collect the composited tiles on the destination channel.

Direct send, shown in Figure 3.16, uses one assemble operation on each resource to fully composite a single tile. Binary swap, shown in Figure 5.2, exchanges pixels between pairs of nodes using a binary compositing tree which gradually assembles a tile on each resource. Both use a sort-first-like assembly operation to collect the fully assembled tiles on the destination channel. 2-3 swap [Yu et al., 2008] is an extension to binary swap, which overcomes the power-of-two source channel requirement by exchanging compositions between groups of two or three nodes in the compositing tree.

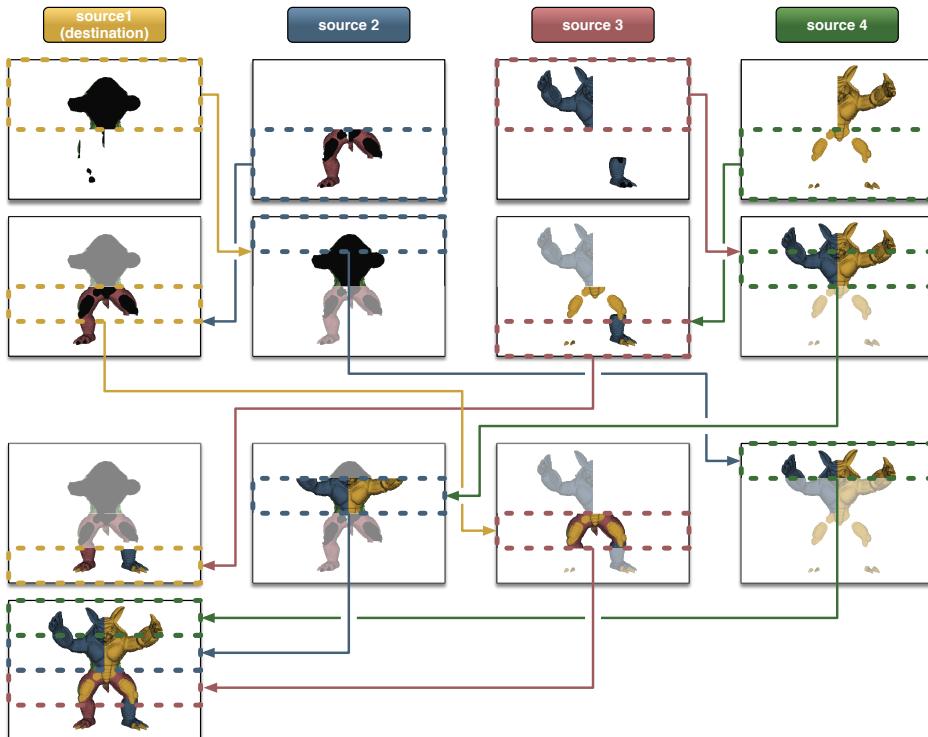


Figure 5.2: Binary swap sort-last compositing

In [Eilemann and Pajarola, 2007] we have shown that on commodity clusters, direct send compositing provides better performance over binary swap commonly used on HPC systems. While it uses more messages in total, direct send has fewer synchronisation points than binary swap. Furthermore, due to the early assembly optimization (Section 5.6), direct send can handle imbalances between nodes better since a late channel has a smaller penalty for the overall execution time.

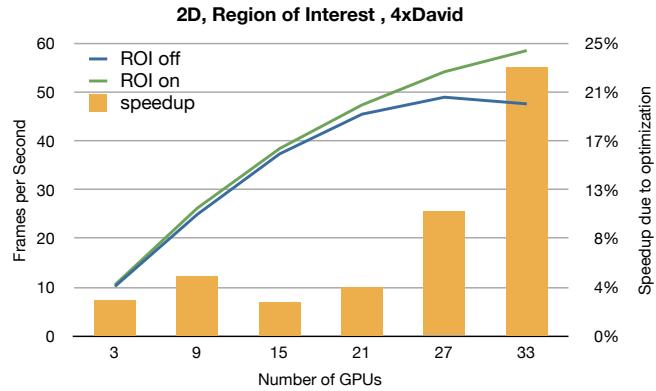
5.3 Region of Interest

During scalable rendering, pixel data has to be copied from the source channel framebuffer to either the destination channel framebuffer, or to an intermediate channel during parallel compositing. The associated distributed image compositing cost is directly dependent on how much data has to be sent over the network, which in turn is related to how much screen space is actively covered. For sort-last rendering every node potentially renders into the entire frame buffer, resulting in a linear increase in the amount of pixels composited for increasing number of nodes. However, depending on the data set and viewpoint, only a subset of the framebuffer shows pixels generated from the data. With an increasing number of nodes, the set of affected pixels typically decreases, leaving blank areas that can be omitted for transmission and compositing.

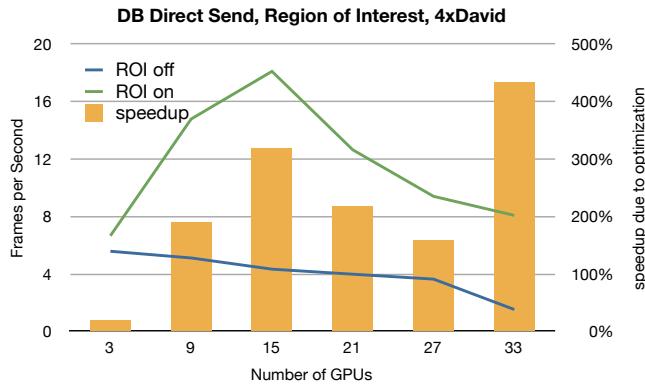
Equalizer provides an API for the programmer to provide the region of interest (ROI). The ROI is the screen-space 2D bounding box fully enclosing the data rendered by a single resource, which can be easily computed by computing the screen-space projection of the model's bounding volume. We have extended the core parallel rendering framework to use this application-provided ROI to optimise the `load_equalizer` as well as the image compositing.

The compositing code uses the ROI to minimise image readback size, and consequently network transmission. The ROI is an output frame parameter, and is transmitted to all input frames together with the pixel data. On the input frame, the compositing code respects this parameter to place the pixel data on the right position. The usage of ROI for load balancing is described in Section 6.2.

Applying ROI for sort-first rendering provides a small improvement for the rendering performance, as shown in Benchmark 5.2 from [Eilemann et al., 2012]. As the number of resources increases, the ROI becomes more important since the relative amount of time spent in compositing increases as the rendering load decreases. With ROI enabled we observed performance improvements between 5-20%, reaching 60 Hz when using 33 GPUs. Without ROI, the framerate peaked at less than 50 Hz when using 27 GPUs.



Benchmark 5.2: *Region of Interest for Sort-First Rendering*



Benchmark 5.3: *Region of Interest for Sort-Last Rendering*

4x), as shown in Benchmark 5.3.

In [Makhinya et al., 2010], this application-provided ROI was extended with an algorithm which automatically computes the ROI by analyzing the framebuffer to maximise the amount of blank framebuffer omitted during compositing.

For sort-last rendering performance, ROI is crucial. In our experiments in [Eilemann et al., 2012], we used a polygonal renderer which uses relatively compact regions during sort-last decomposition, while still using depth-sorted compositing. This is a relatively common use case for sort-last rendering. In this mode, we can observe significant speedups with ROI (up to

5.4 Asynchronous Compositing

Compositing in a distributed parallel rendering system is decomposed into read-back of the produced pixel data (1), optional compression of this pixel data (2), transmission to the destination node consisting of send (3) and receive (4), optional decompression (5) and composition consisting of upload (6) and assembly (7) in the destination framebuffer.

In a naive implementation, operations 1 to 3 are executed serially on one processor, and 4 to 7 on another. In our parallel rendering system, operations 2 to 5 are executed asynchronously to the rendering and operations 1, 6 and 7. Furthermore, we use a latency of one frame which means that two rendering frames are always in execution, allowing the pipelining of these operations, as shown in Figure 5.3(a). We have implemented asynchronous readback using OpenGL pixel buffer objects, further increasing the parallelism by pipelining the rendering and pixel transfers, as shown in Figure 5.3(b).

In the asynchronous case, the rendering thread performs only application-specific rendering operations, since the overhead of starting an asynchronous read-back becomes negligible. Equalizer uses a plugin system to implement GPU-CPU transfer modules which are runtime loadable. We extended this plugin API to allow the creation of asynchronous transfer plugins, and implemented such a plugin using OpenGL pixel buffer objects (PBO). At runtime, one rendering thread and

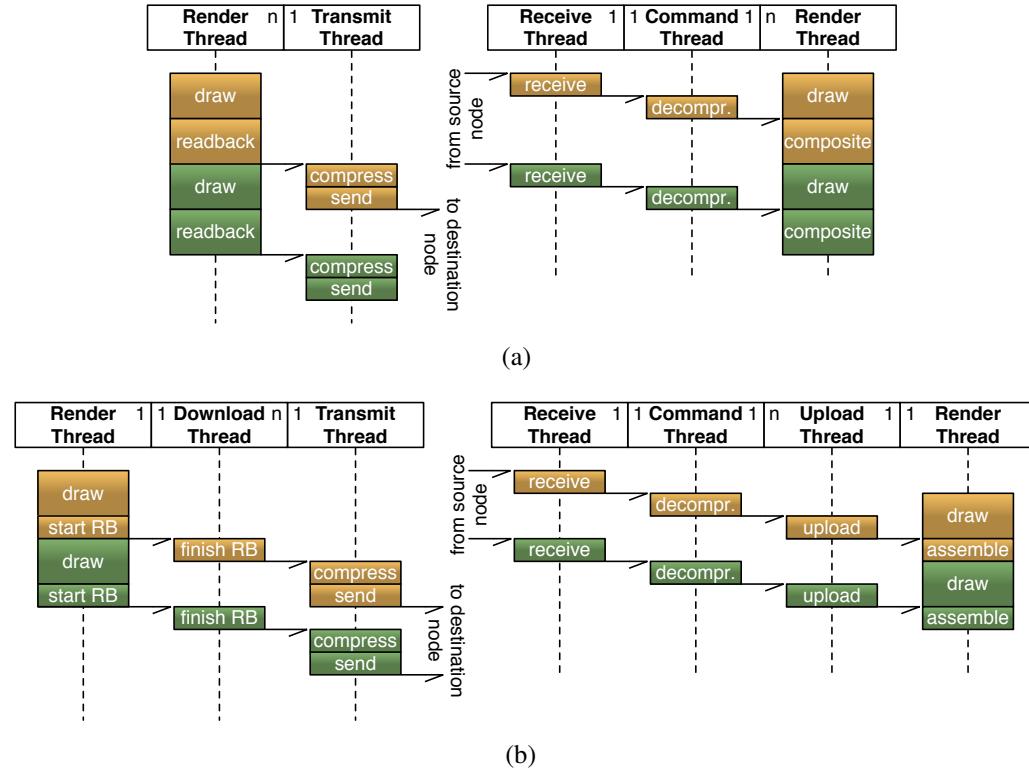


Figure 5.3: Synchronous readback and upload (a) as well as asynchronous readback and upload (b) for two overlapping frames.

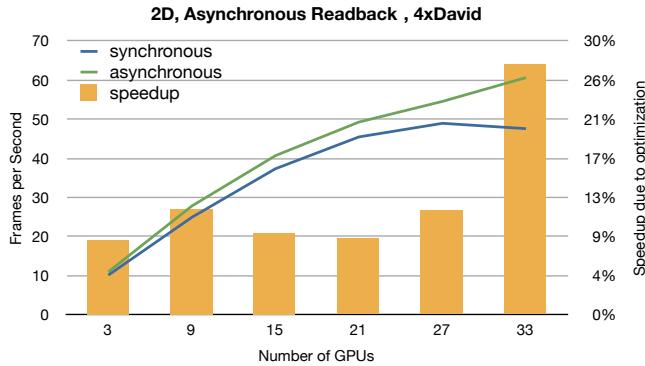
one download thread is used for each GPU, as well as one transmit thread per process. The download threads are created lazy, when needed.

Asynchronous compositing is, together with ROI, one of the most influential optimizations for scalable rendering. For sort-first rendering, shown in Benchmark 5.4 from [Eilemann et al., 2012], pipelining the readback with the rendering yields a performance gain of about 10%. At higher frame rates, when the rendering time of a single resource decreases, asynchronous readback has even a higher impact, of over 25% for large node counts.

5.5 Compression for Image Compositing

The image compositing stages in distributed rendering for gathering and combining partial rendering results into a final display frame are fundamentally limited by the GPU-to-node and node-to-node image throughput. Therefore, efficient im-

age coding, compression and transmission must be considered to minimise that bottleneck.



Benchmark 5.4: *Asynchronous Compositing Sort-First Rendering*

non-trivial full frame color results. We developed two enhancements to improve this, per-component RLE compression and reordering of color bits. These preconditioning steps exploit typical characteristics of image data.

Equalizer also integrates more complex compression algorithms such as `libjpeg-turbo`, which are however of little practical use on modern interconnects. Their compression overhead is often too high to be amortised by the decreased network transmission time on modern 10 GBit/s or faster interconnects.

[Makhinya et al., 2010] implemented GPU-based YUV subsampling before the image download, which has negligible overhead, reasonable compression artefacts, and a good compression ratio.

5.5.1 Enhanced RLE Compression

Run-length encoding (RLE) is a simple compression scheme, which on modern architectures is purely constrained by the available memory bandwidth. For image compression in visualization applications, we can exploit some characteristics of the data to improve the compression ratio over the standard RLE compression.

Our basic RLE implementation is a fast 64-bit version that compares two pixels at the same time (8 bit per channel RGBA format). While this method is very fast it shows poor compression results in most practical settings since it can only compress adjacent pixels of the same color. We have observed a compression rate of up to 10% in practical scenarios.

The first improvement is to treat each color component separately by producing four independent RLE-compressed output streams as illustrated in Figure 5.4. This per-component RLE improves the compression rate from 10% to about 25%

Basic run-length encoding (RLE) has been used as a fast standard to improve network throughput for interactive image transmission. However, it only gives sufficient results in specific rendering contexts and fails to provide a general improvement as shown in [Makhinya et al., 2010]. RLE only works to compact large empty or uniform color areas but is often useless for

since individual color components change less often than full pixels (based on results from [Makhinya et al., 2010]).

The second improvement is *bit-swizzling* of color values before per-component compression. This swizzling step is a data pre-conditioner, which reorders and interleaves the per-component bits as shown in Figure 5.5 by grouping them by significance of the corresponding bits. Now the per-component RLE compression separately compresses

the higher, medium and lower order bits in separate streams, thus achieving stronger compression for smoothly changing color values since high-order bits change less often.

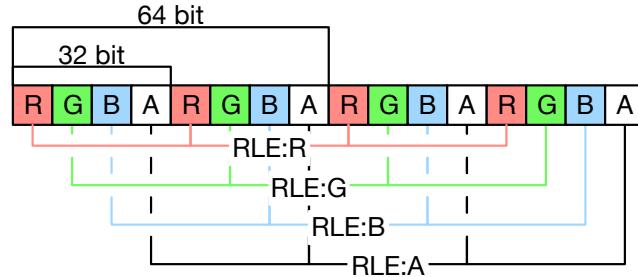


Figure 5.4: 32 bit, 64 bit and per-component RLE compression schemes

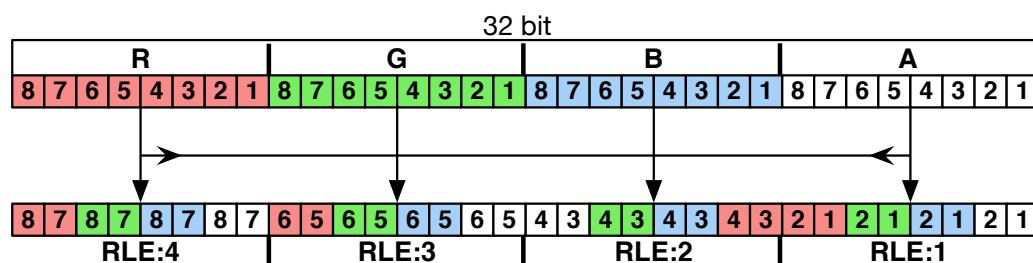


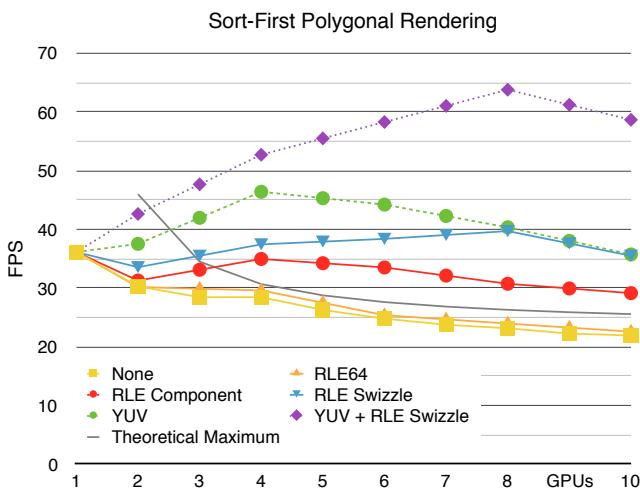
Figure 5.5: Swizzling scheme for reordering bits of 32-bit RGBA values.

Swizzling improves the compression rate to up to 40% for the same scenario as above. Since the preconditioning step only requires bit shift and mask operations, it is entirely executed in registers and has no measurable impact on performance, since the whole algorithm is memory bound on modern CPUs.

All RLE compressors perform a data decomposition on the input image, and parallelise the compression of data chunks across multiple threads. This parallel execution improves the performance by saturating multiple memory channels compared to a single-threaded implementation.

Benchmark 5.5 summarises the compression results from [Makhinya et al., 2010]. We have chosen sort-first rendering, since this highlights the results for the RLE compressor which is optimised for color image data. This benchmark did run a visualization cluster with Gigabit Ethernet at a resolution of 1280×1024

pixels. It rendered the David statuette at 1mm resolution, which resulted in a rendering time of about 28 ms on a single GPU. The theoretical maximum line shows the upper limit for sort-first compositing with uncompressed image data and no rendering time. It decreases since the destination channel contributes to the sort-first rendering, and does not require a pixel transfer. With an increasing number of remote source channels, its size decreases, requiring more pixels to be transferred.



Benchmark 5.5: *Image Compression in Sort-First Polygonal Rendering*

ances and non-zero rendering time. The swizzling pre-conditioner can significantly reduce the compositing time, and even improve the overall framerate.

The YUV compressor is an on-GPU compression plugin which performs a color space conversion and lossy chroma subsampling. It can be combined with the CPU-based RLE compressor, which then interleaves and compresses the Y, U and V channels, resulting in major performance improvements. Both compression steps have virtually no computational overhead, and are memory bandwidth bound. Since the YUV compressor runs on the GPU, it reduces the costly GPU to CPU transfer time over the PCI Express link.

The graph shows how the various incremental improvements add up to significant performance gains. Even in a relatively difficult scenario with a fast rendering time and, by modern standards, slow network interconnect, we were able to more than double the performance to above 60 Hz.

The basic 8-byte RLE Compressor performs just minimally better than no compression. Both stay relatively close the theoretical maximum, but can't quite reach it due to load imbalances and non-zero rendering time. The swizzling pre-conditioner can significantly reduce the compositing time, and even improve the overall framerate.

5.5.2 GPU Transfer and CPU Compression Plugins

Equalizer uses runtime-loadable plugins to transfer pixel data from and to the GPU, as well as plugins to compress and decompress pixel data for network compression. This separation allows different code paths for multi-GPU machines

where no CPU-based compression is used, and for distributed execution where data is compressed before network transfer.

The GPU transfer might also apply compression. This is typically done on the GPU to reduce the amount of memory transferred over the GPU-CPU interconnect. One example is YUV subsampling, where a shader implements the RGB to YUV color space conversion and subsequent chroma subsampling. Furthermore, a GPU transfer plugin may implement asynchronous downloads, where the download is started from the render thread and finished in a separate download thread as shown in Figure 5.3(b). CPU compression plugins are always executed from asynchronous threads concurrently to the rendering threads.

The implementation of these steps in plugins provides a clean separation and interface for users and researchers interested in experimenting with image compression for interactive parallel rendering.

5.6 Out-of-Order Assembly

Early assembly provides better pipelining when the frame assembly order is not important, for example for sort-first rendering and sort-last rendering with z -compositing. Our default compositing code uses a signal on all input frames, which is triggered for each input frame arrival. The compositing code then picks and composites this image, assembling images early, out of order as they become available. This decreases the time to solution, since the assemble operation finishes once the last frame arrives, plus the time to assemble this last frame. In-order assembly would have a statistical probability of $\frac{n}{2}$ frames to assemble after the last frame arrives (unless other constraints make the arrival not fully random or network-constrained).

C H A P T E R

6

LOAD BALANCING

6.1 Overview

Load balancing is the resource assignment per source channel based on resource load, with the goal of optimising resource utilisation. Static load balancing, shown in Figure 6.1 top, performs this assignment during initialization. Dynamic load balancing can either be reactive or predictive (middle and bottom of Figure 6.1). Reactive load balancing utilises statistics from previous frames to predict future load distribution. Predictive load balancing uses an application-provided load estimation (also called cost function) to estimate the load distribution of the current frame. Both approaches reassign resources dynamically, typically for each rendered frame. Implicitly load balanced algorithms achieve a good load balance by other means, for example through work stealing between resources.

Load balancing is implemented by *Equalizers*. Equalizers are an addition to compound trees. They modify parameters of their respective compound subtree at runtime to dynamically optimise the resource usage, by each tuning one aspect of the decomposition or recomposition. Due to their nature, they are transparent to application developers, but might have application-accessible parameters to tune their behaviour. Resource equalisation is the critical component for scalable parallel rendering, and therefore the eponym for the Equalizer project name.

In this section we present various *equalizer* implementations: two variants for reactive load balancing for sort-first and sort-last rendering, implicitly load balanced work packages for sort-last and sort-first rendering, cross-segment load

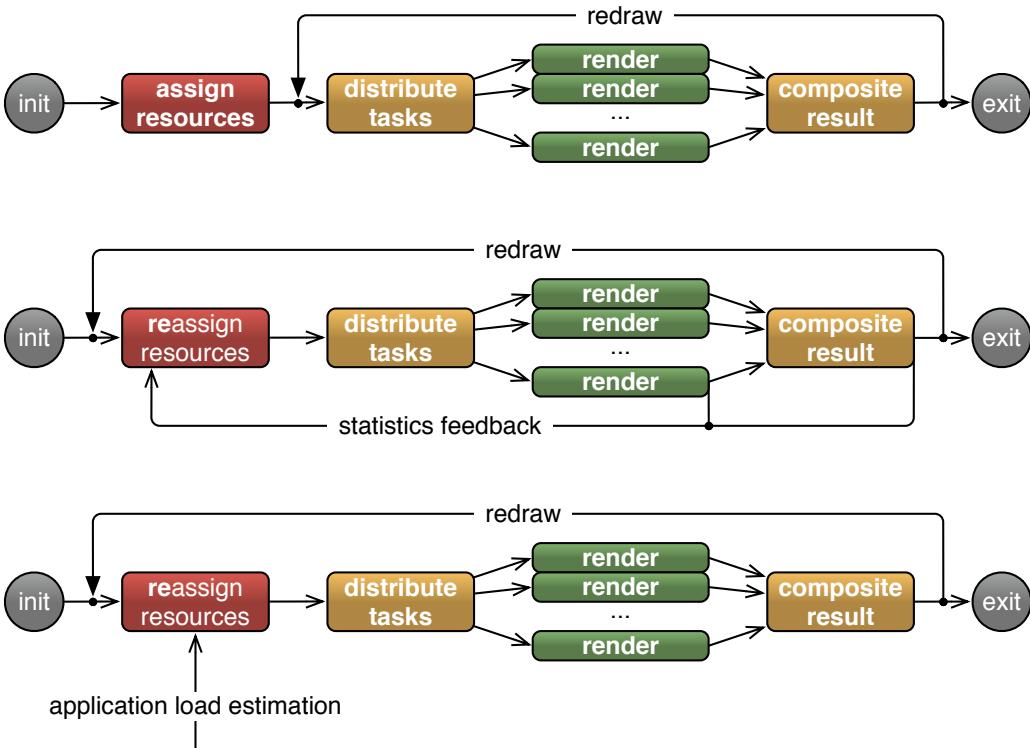


Figure 6.1: Static, Reactive and Predictive Load Balancing

balancing for multi-display installations, constant frame rate rendering using dynamic frame resolution, and monitoring of large-scale visualization systems.

6.2 Sort-First and Sort-Last Load Balancing

Sort-first (Figure 6.2) and sort-last load balancing are the most obvious optimizations for these parallel rendering modes. Our load equalizers are fully transparent for application developers; that is, they use a reactive approach based on past rendering times. This requires a reasonable frame-to-frame coherence for good results, which is the case with most rendering applications. Equalizer implements two different algorithms, a `load_equalizer` and a `tree_equalizer`, which have shown to each have their advantage depending on the type of rendering load.

Both equalizers extract their load metrics from statistics collected by the rendering clients, which are sent asynchronously from the clients to the server, where the equalizers subscribe to them for operation. At the beginning of each frame, the server triggers all equalizers on all compound trees, which enables them to set new decomposition parameters before the rendering tasks are computed.

The `load_equalizer` builds a model of the rendering load in screen space or data space. It stores a 2D (for sort-first) or 1D (for sort-last) grid of the load, mapping the load of each channel. The load is stored in normalised 2D/1D coordinates using $\frac{\text{time}}{\text{area}}$ as the load, the contributing source channels are organised in a binary kD-tree, and then the algorithm balances the two branches of each level by equalising the integral over the cost area map on each side. This algorithm is similar to [Abraham et al., 2004], which uses a dual-level tree, first decomposed into horizontal tiles and then each horizontal tile into vertical sub-tiles. Our binary split tree provides more compact tiles for larger cluster configurations.

The load balancer has to operate on the assumption that the load is uniform within one load grid tile. This leads naturally to estimation errors, since in reality the load is not uniformly distributed, e.g., it tends to increase towards the center of the screen in Figure 6.3. We reuse the region of interest (ROI) from compositing of each source channel to automatically refine the load grid as shown Figure 6.3, top. In cases where the rendered data projects only to a limited screen area, this ROI refinement provides the load balancer with a more accurate load estimation leading to a better load prediction during the balancing step.

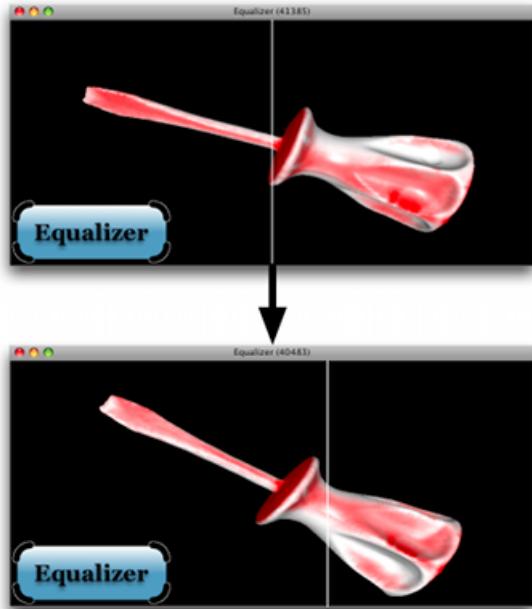


Figure 6.2: Load Balancing

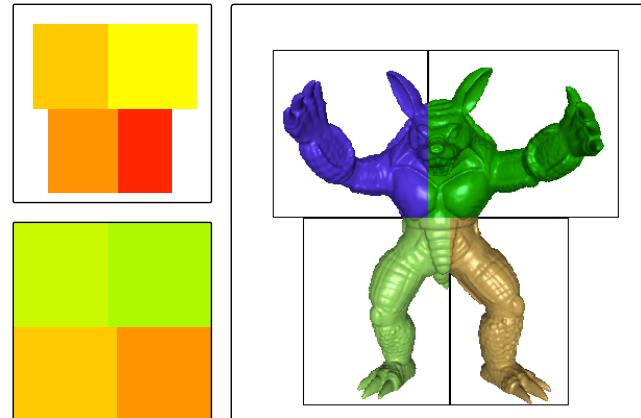


Figure 6.3: Load cost area map with (top) and without (bottom) using region of interest information.

The `tree_equalizer` uses the same binary kD-tree structure as the `load_equalizer` for recursive load balancing. It computes the accumulated render time of all children for each node of the tree, and uses this to allocate an equal render time to each subtree. It makes no assumption of the load distribution in 2D or 1D space, it only tries to correct the imbalance in render time.

Both equalizers implement tuneable parameters allowing application developers to optimise the load balancing based on the characteristics of their rendering algorithm. These parameters are accessible through an API from the application main thread:

Split Mode configures the tile layout: horizontal or vertical stripes, and 2D, a binary tree split alternating the split axis on each level, resulting in compact 2D tiles.

Damping reduces frame-to-frame oscillations. The equal load distribution within the region of interest assumed by the load balancers is in reality not equal, causing the load balancing to overshoot. Damping is a normalised scalar defining how much of the computed delta from the previous position is applied to the new split.

Resistance eliminates small deltas in the load balancing step, i.e., it only changes the viewport or range if the change is over the configured limit. This can help the application to cache visibility computations since the frustum does not change each frame.

Boundaries define the modulo factor in pixels onto which a load split may fall. Some rendering algorithms produce artefacts related to the OpenGL raster position, e.g., screen door transparency, which can be eliminated by aligning the boundary to the pixel repetition. Furthermore, some rendering algorithms are sensitive to cache alignments, which can again be exploited by choosing the corresponding boundary.

Usage is a per-child normalised resource utilisation coefficient. The equalizer will assign proportional work to this resource, and deactivate it if the usage is 0. This parameter is primarily used by the cross-segment load balancer to reassigning resources between destination channels, but can also be used to configure heterogeneous GPU resources more efficiently.

6.2.1 Dynamic Work Packages

load balancing can be classified into explicit and implicit approaches, where explicit methods centrally compute a task decomposition up-front, before a new frame is rendered, while implicit methods decompose the workload into task units that can dynamically be assigned to the resources during rendering, based on the work progress of the individual resources. Explicit load balancing typically as-

signs a single task to each resource to minimise static per-task costs. The aforementioned equalizers implement explicit reactive load balancing.

Implicit load balancing generally uses a finer granularity of many more tasks than resources to minimise the load imbalance due to a fixed coarse task granularity. Implicit load balancing uses central task distribution or distributed task stealing between resources. Implicit algorithms are more commonly used for off-line raytracing compared to real-time rasterisation algorithms due to the practically non-existent per-tile cost in raytracing. Furthermore, since each rendered task directly sends its result for compositing, work packages exhibit a better pipelining of rendering and compositing operations.

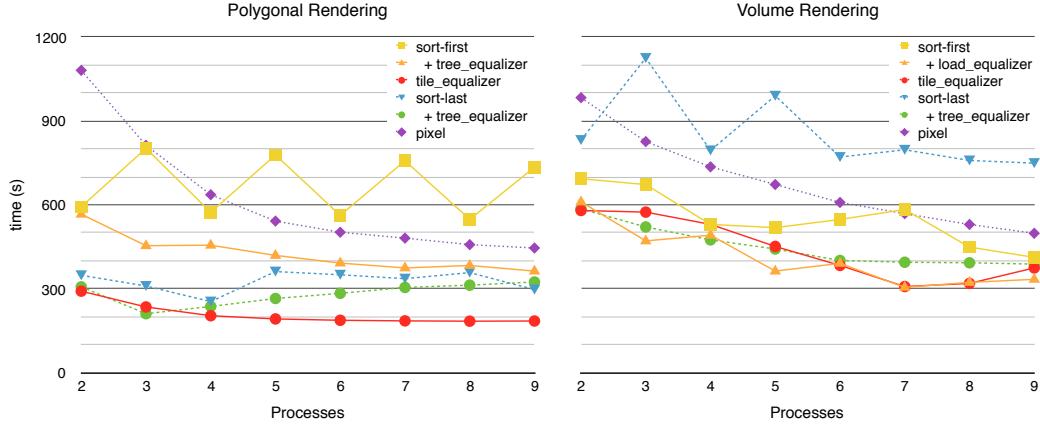
Our work package implementation uses a task pulling mechanism, an approach that has been employed before in distributed computing. Rather than having the server push tasks to the rendering clients, our dynamic work packages approach works by managing fine grained tasks on a server side queue, while the clients request and execute the tasks as they become available. Every rendering client employs a small local, prefetched queue of work packages to hide the round-trip latency to fetch new packages. During rendering, a client first works on packages from its local queue and concurrently requests packages from the server whenever the amount of available packages sinks below some threshold. In [Steiner et al., 2016], this basic, random task assignment was extended with client-affinity models.

Depending on the sort-first or sort-last decomposition mode, a `tile_equalizer` or `chunk_equalizer` generates tiles or database ranges of a configurable size and enqueues them at the beginning of each frame. This active equalizer is the central component of the tile and chunk compounds introduced in Section 4.2.4.

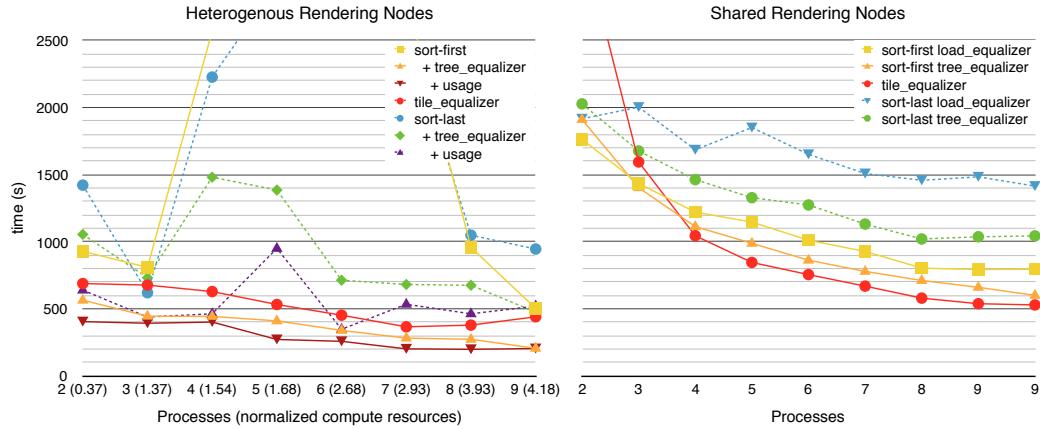
6.2.2 Benchmarks

Benchmark 6.1 shows the performance of static and load balanced sort-first and sort-last rendering. The experiment setup is described in [Eilemann et al., 2018]. The results show that, as expected, load balancing improves the performance over a static task decomposition significantly. The simpler `tree_equalizer` outperforms the load grid-driven `load_equalizer` in most cases, except for sort-first volume rendering where the load in the region of interest is relatively uniform. This result is counterintuitive since the `load_equalizer` operates with more information and should be able to produce better results. It seems to confirm that simple algorithms often outperform theoretically better, but more complex implementations. The decoupling of the load balancing algorithm from the rest of the system enabled by the compound architecture opens the possibility for more research in this area.

Benchmark 6.2 provides a more detailed analysis of the different equalizers. Using volume rendering, we measure the performance of decomposition modes

**Benchmark 6.1:** Sort-First and Sort-Last Scalability

under heterogeneous load, which was easily achievable by varying the number of volume samples used for each fragment (1-7) while rendering. This allowed for a consistent linear scaling of rendering load, which was randomly varied either per frame or per node. Such a linear scaling of load per node corresponds to a scaling of resources, e.g., doubling the rendering load on a specific node corresponds to halving its available rendering resources. To the system this node would then contribute the value 0.5 in terms of normalised compute resources.

**Benchmark 6.2:** Sort-First and Sort-Last Equalizer Behaviour

Benchmark 6.2 (left) gives an impression of how individual modes perform on heterogeneous systems. In this case the tree equalizer performs best, as it allows us to a priori define how much usage it should make of individual nodes, i.e., bias the allocation of rendering time in accordance with the (simulated) compute

resources. Benchmark 6.2 (right), on the other hand, illustrates how the decomposition modes perform on a system where compute resources fluctuate randomly every frame, as can arguably be the case for shared rendering nodes in virtualised environments. For this scenario tile equalizer seems best suited, as it performs load balancing implicitly and does not assume coherence of available resources between frames. The simpler tree equalizer outperforms the load equalizer in this experiment.

The tile_equalizer often outperforms tree_equalizer. This suggests that the underlying implicit load balancing of task queues can be superior to the explicit methods of load_equalizer and tree_equalizer in high load situations, where the additional overhead of tile generation and distribution is more justified. The relatively simple nature of our benchmark application’s rendering algorithms is also favouring work packages, since they have a near-zero static overhead per rendering pass. [Steiner et al., 2016] contains additional experiments.

6.3 Cross-Segment Load Balancing

A serious challenge for all distributed rendering systems driving large multi-display installations is to deal with the varying rendering load per display, and thus the graphics load on its driving GPUs. Cross-segment load balancing (CSLB) is a novel dynamic load balancing approach to dynamically allocate n rendering resources to m output channels (with $n \geq m$), as shown in Figure 6.4.

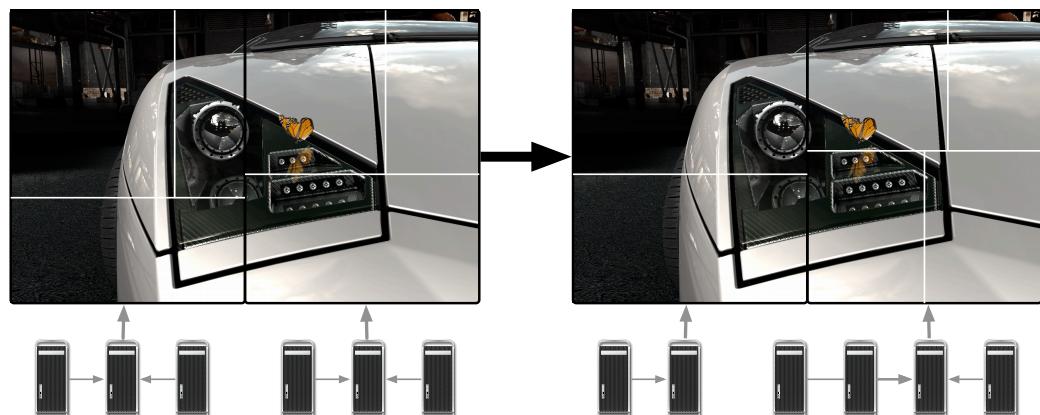


Figure 6.4: Six-to-two Cross-Segment load Balancing

The m output channels typically each drive a display or projector of a multi-display system. Commonly, each destination channel is solely responsible for rendering and/or compositing of its corresponding display segment.

A key element of CSLB is that the m GPUs physically driving the m display segments will not be restricted in a one-to-one mapping to rendering tasks of the corresponding display segment. In fact, CSLB performs dynamic assignment of n graphics resources from a pool to drive m different destination display segments, where the m destination channel GPUs themselves may also be part of the pool of graphics resources.

CSLB also does not require a planar display surface, that is, the algorithm works equally for tiled display walls and immersive installations.

Dynamic resource assignment is performed through load balancing components that exploit statistical data from previous frames for the decision of optimal GPU usage for each segment as well as optimal distribution of workload among them. The algorithm can easily be extended to use predictive load balancing based on a load estimation given the application.

CSLB is implemented in Equalizer as two layers of hierarchically organised components, specified in the configuration. The first level globally assigns fractions of resources to each destination channel, and the second level consist of `load_equalizers` or `tree_equalizers` balancing the assigned resources for each destination channel.

Figure 6.5 depicts a snapshot of a simple CSLB setup along with its configuration file. Two destination channels, *Channel1* and *Channel2*, each connected to a projector, create the final output for a multi-projector view. Each projector is driven by a distinct GPU, constituting the source channels *Source1* and *Source2*. Each source channel GPU can contribute to the rendering of the other destination channel segment. For each destination channel, a set of potential resources are allocated. A top-level *view_equalizer* assigns the usage of each resource, based on which a per-segment *load_equalizer* computes the 2D split to balance the assigned resources within the display. The left segment of the display has a higher workload, so, both *Source1* and *Source2* are used to render for *Channel1*, whereas *Channel2* makes use of only *Source2* to assemble the image for the right segment.

CSLB uses a two-stage approach: a `view_equalizer` is attached to the top level of the parallel rendering task decomposition compound hierarchy, and handles the resource assignment. Each child of this root compound has one destination channel, constituting one of the m display segments, with a `load_equalizer` or `tree_equalizer` each. Hence the `view_equalizer` supervises the different destination channels of a multi-display setup. The `load_equalizer` on the other hand is responsible for the partitioning of the rendering task among its child compounds using the precomputed usage for each child. Therefore, each destination channel of a display segment has its source channel leaf nodes sharing the actual rendering load. One physical graphics resource (GPU), being assigned to a source channel, can be referenced in multiple leaf nodes and thus contribute to different displays.

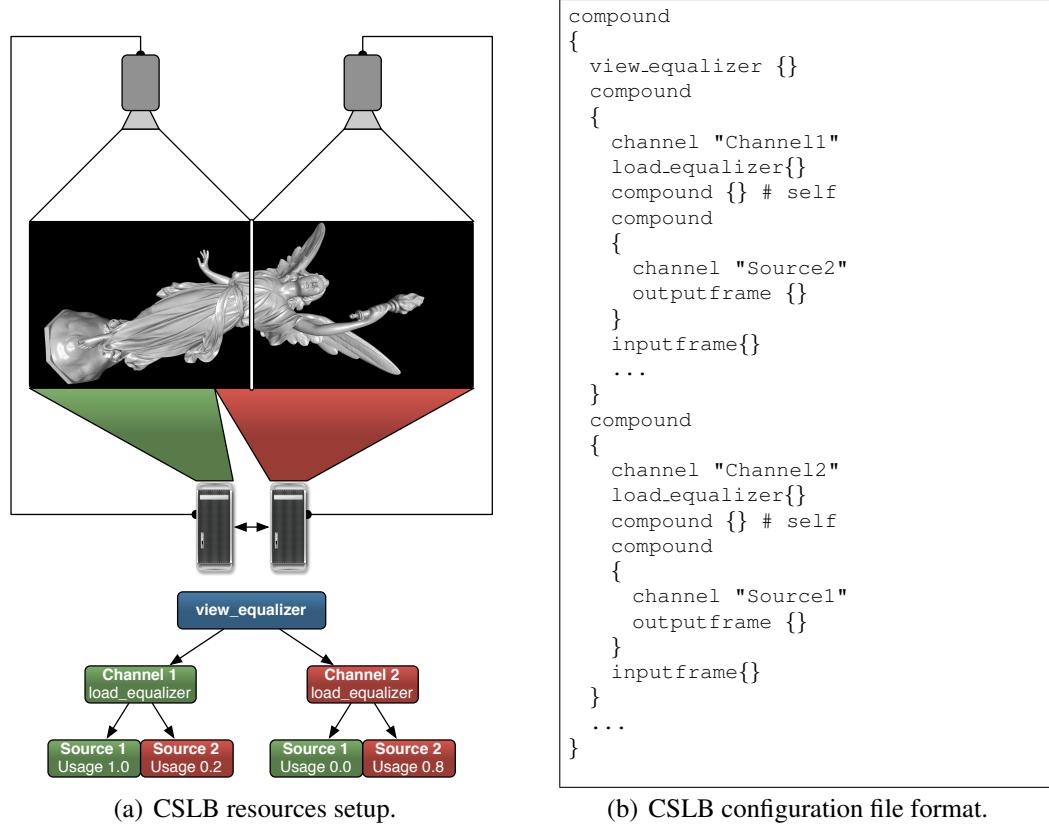
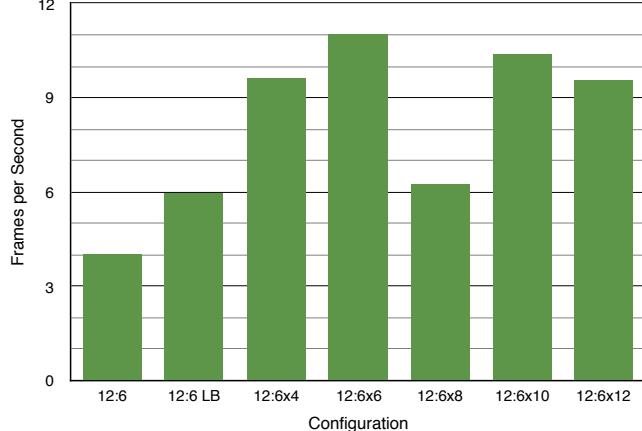


Figure 6.5: A dual-GPU, dual-display cross-segment load balancing setup

For performance reason, the view equalizer assigns each resource to at most two rendering tasks, e.g., to update itself and to contribute to another display. Furthermore, it gives priority to the source compound using the same channel as the output channel of each segment, thus minimising pixel transfers.

The rendered data, algorithm and camera will produce different rendering load over time for each segment of a multi-display system. Since the slowest segment determines the overall performance of the system, it is important to dynamically adjust load among segments. The **view_equalizer** analyses the load of all segments based on past frame rendering statistics and adapts resource usage for each segment. For each rendered frame, the **view_equalizer** sets the usage of each leaf source channel compound, to activate or deactivate it for rendering on the given destination channel. This usage is picked up by the per-segment load balancers, which will assign work proportionally to the usage, with no rendering task for 0 usage. [Erol et al., 2011] provides a detailed description of the algorithm.

Cross-segment load balancing thus allows for optimal resource usage of multiple GPUs used for driving the display segments themselves, as well as any additional source GPUs for rendering. It combines multi-display parallel rendering with scalable rendering for optimal performance.



Benchmark 6.3: Cross-Segment Load Balancing

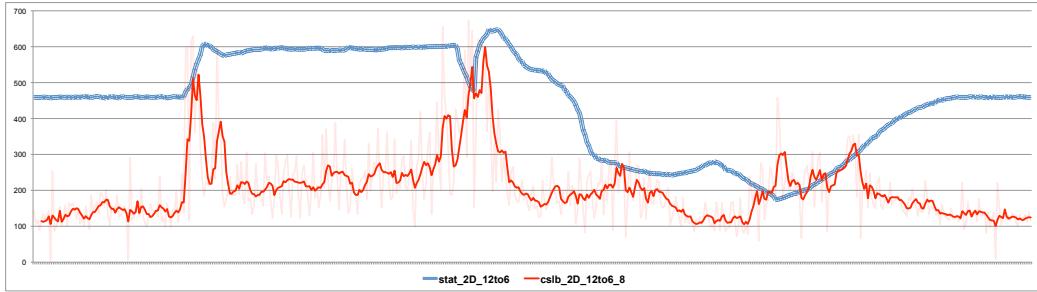
GPUs. Already this 2D load balancing improves the framerate by almost 50%.

The remaining configurations add a view equalizer on top of the per-segment 2D load equalizer. The configuration assigns up to 4, 6, 8, 10 or all GPUs to each segment, that is, any segment may use up to n GPUs, and the GPUs are shared evenly across multiple segments. While theoretically the all-to-all ($12 : 6 \times 12$) configuration should provide the best performance, mispredictions of the equalizers lead to a sweet spot of GPU sharing between segments. In our $12 : 6$ setup, assigning up to six GPUs per segment almost doubles the performance over the state-of-the-art sort-first load balanced setup.

Benchmark 6.4 shows the rendering time over a fixed camera path of 540 frames. In the static case, two GPUs are responsible for each of the six outputs of the tiled display wall used. For the CSLB graph, up to eight GPUs were dynamically reassigned each frame to each of the six output channels, depending on the current load distribution. Except for a few camera positions where the model is positioned evenly over all outputs, CSLB outperforms the fixed assignment.

A strength of this algorithm lies in its flexibility. On one hand, it can perform dynamic resource assignment not only for a planar display system as some approaches which built a single virtual framebuffer for all output displays, but also for curved displays and CAVE installations. On the other hand, it allows a flexible assignment of potential contributing GPUs to each output channel individually, that is, each output may have a different, potentially overlapping, set of GPUs

[Erol et al., 2011] provide experimental results for a six-monitor tiled display wall driven by 12 source GPUs. Benchmark 6.3 shows an overview for the achievable performance improvements. The first two configurations use a static assignment of two GPUs to one output channel, where the first one statically assigns one half to each GPU, and the second uses a load balancer to dynamically split the segment between the two



Benchmark 6.4: Cross-Segment Load Balancing for six Displays and 12 GPUs compared to a static two-to-one six Display Sort-First Rendering

which may contribute to its rendering. [Erol et al., 2011] shows in its experiments that there is a sweet spot of the number of resources per channel.

6.4 Dynamic Frame Resolution

The DFR equalizer (Figure 6.6) provides a functionality similar to dynamic video resizing [Montrym et al., 1997], that is, it maintains a constant framerate by adapting the rendering resolution of a fill-limited application. While the aforementioned uses a now-obsolete hardware implementation, our implementation is purely in software.

Dynamic frame resolution (DFR) works by rendering into a source channel (typically on a FBO) separate to the destination channel, and then scaling the rendering during the transfer (typically through an on-GPU texture) to the destination channel. The DFR equalizer monitors the rendering performance and accordingly adapts the resolution of the source channel

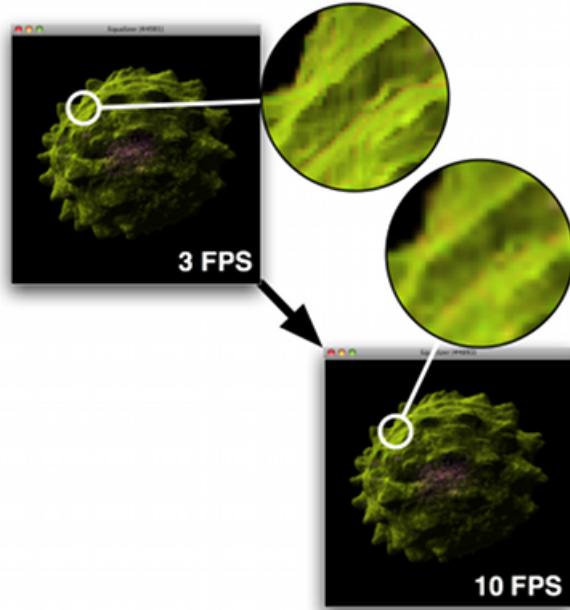


Figure 6.6: Dynamic Frame Resolution

and the zoom factor for the source to destination transfer. If the performance and source channel resolutions allow, this will not only subsample, but also supersample the destination channel to reduce aliasing artefacts.

DFR can be combined with other scalability features, e.g., sort-first rendering. It is also notable that it does not need any additional code in the core compound logic, it simply exploits existing functionality such as texture-based compositing frames and frame zoom with dynamic per-frame adjustments.

6.5 Frame Rate Equalizer

The framerate equalizer smoothens the output frame rate of a destination channel by instructing the corresponding window to delay its buffer swap to a minimum time between swaps. This is regularly used for time-multiplexed decompositions, where source channels tend to drift and finish their rendering unevenly distributed over time. This equalizer is however fully independent of DPlex compounds, and may be used to smoothen irregular application rendering algorithms. Due to the artificial sleep time before swap, it may incur a small performance penalty, but it greatly improves the perceived rendering quality for users in DPlex compounds.

6.6 Monitoring

The monitor equalizer (Figure 6.7) allows to reuse the rendering from one or more channels on another channel, typically for monitoring a larger display setup on a control workstation. Output frames on the display channels are connected to input frames on the monitoring channel. The monitor equalizer changes the scaling factor and offset between the output and input, so that the monitor channel has the same, but typically downscaled view, as the originating segments. While this is not strictly a scalable rendering feature, it optimises resource usage by not needlessly rendering the same view multiple times. It reuses the zoom parameter of compositing frames, and adapts this every time one of the channels is resized.

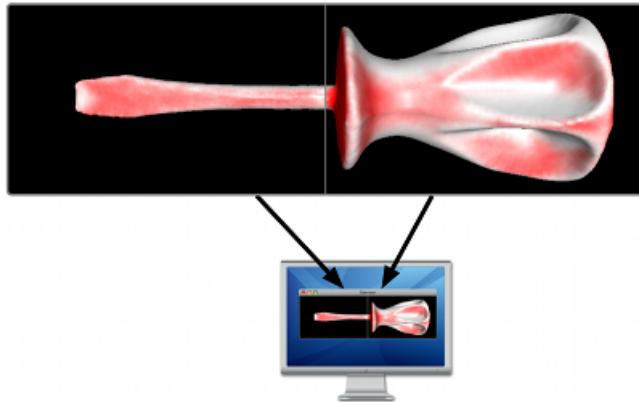


Figure 6.7: Monitoring

C H A P T E R

7

DATA DISTRIBUTION AND SYNCHRONISATION

7.1 Overview

Most research in parallel rendering ignores the problem of managing application state in a distributed rendering session. For basic parallel rendering research this problem is trivially to solve, whereas in real-world applications it often is one of the major challenges for using a distributed rendering cluster. Researching and improving the system behaviour of non-trivial applications is however critical for meaningful parallel rendering research, and therefore providing a distributed network library is a key component of a parallel rendering system.

For this reason, we have spent a significant effort in researching, designing and implementing a distributed execution layer which is used by Equalizer and applications built on Equalizer. This *Collage* network library is an independent open source project. In the following sections we highlight core features and show how they are different from other distribution mechanisms, e.g., the MPI library.

The Collage network library was conceived with the requirements of a dynamic parallel rendering system in mind. Some of the features implemented by Collage came about later, and are often layered on top of the basic primitives. The core requirements were:

Peer-to-peer network: While the execution model of an Equalizer application follows a master-slave approach, and Equalizer internally uses a client-server model, the core transport layer should be agnostic to these higher-level abstractions. In Collage, each communicating process is equal to all others, and no traffic prioritisation or communication pattern is enforced by a node type. This has proven particularly useful during the implementation of parallel compositing algorithms, where the compositing nodes form an ad-hoc peer-to-peer sub-network.

Dynamic connection management: As a consequence of the peer-to-peer network, all nodes in a cluster are equivalent. Due to the heterogenous nature of a parallel rendering application we furthermore imposed no constraints on the management of connections between nodes. Nodes are identified and addressed by an universally unique identifier. The network layer lazily establishes a connection to any given node, by querying its known neighbours or a zeroconf network for connection parameters. Connections may be established concurrently by both sides of a node pair (e.g. during parallel compositing), which requires a robust handshake protocol during connection establishment. For larger cluster installations, a fully connected peer-to-peer network would be suboptimal, for example on Windows operating systems there is a latency penalty once more than 64 connections are needed due to low-level implementation details.

Transport layer abstraction: The actual network protocol is abstracted by an API defining byte-oriented stream semantics. While this choice of abstraction makes it harder for RDMA-based protocols to deliver full performance, it has proven useful in supporting a large set of transports, from standard Ethernet sockets, SDP for InfiniBand, native Verbs for Infiniband, UDT to even a fully-featured multicast-over-UDP implementation. In particular the ease of integration of multicast transport is strong evidence for the usefulness of this abstraction.

Convenient to use for existing applications: The history and code structure of visualization applications is often very different from other distributed applications such as simulation codes. They have been developed for years for desktop systems, often are single-threaded and have data models and object hierarchies built for their domain-specific problems and algorithms. The network library needs to provide primitives which match this reality as closely as possible by providing a modern, object-oriented C++ API for data distribution.

7.2 Architecture

Our Collage network library provides a peer-to-peer communication infrastructure, offering different abstraction layers which gradually provide higher level functionality to the programmer. Collage is used by Equalizer to communicate between the application node, the server and the render clients. Figure 7.1 provides an overview of the major Collage classes and their relationship. The main classes, in ascending abstraction level, are:

Connection: A stream-oriented point-to-point communication line. Different implementations of a connection exists. The connections transmit a raw byte stream reliably between two endpoints for unicast connections, and between a set of endpoints for multicast connections.

DataOStream: Abstracts the output of C++ data types onto a set of connections by implementing output stream operators. Uses buffering to aggregate data for network transmission.

OCommand: Extends DataOStream to implement the protocol between Collage nodes by adding node and command type routing information to the stream.

DataIStream: Decodes a buffer of received data into C++ objects and PODs by implementing input stream operators. Performs endian swapping if the endianness differs between the originating and local node.

ICommand: The other side of OCommand, extending DataIStream.

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 communicating with a remote LocalNode.

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

7.2.1 Connection

A Connection is the basic primitive used for communication between processes in Collage. It provides a stream-oriented communication between two endpoints. A connection is either closed, connected or listening. A closed connection cannot be used for communications. A connected connection can be used to read or write data to the communication peer. A listening connection can accept connection requests leading to new, connected connections.

A ConnectionSet is used to manage multiple connections. The typical use case is to have one or more listening connections for the local process, and a number of connected connections for communicating with other processes. The

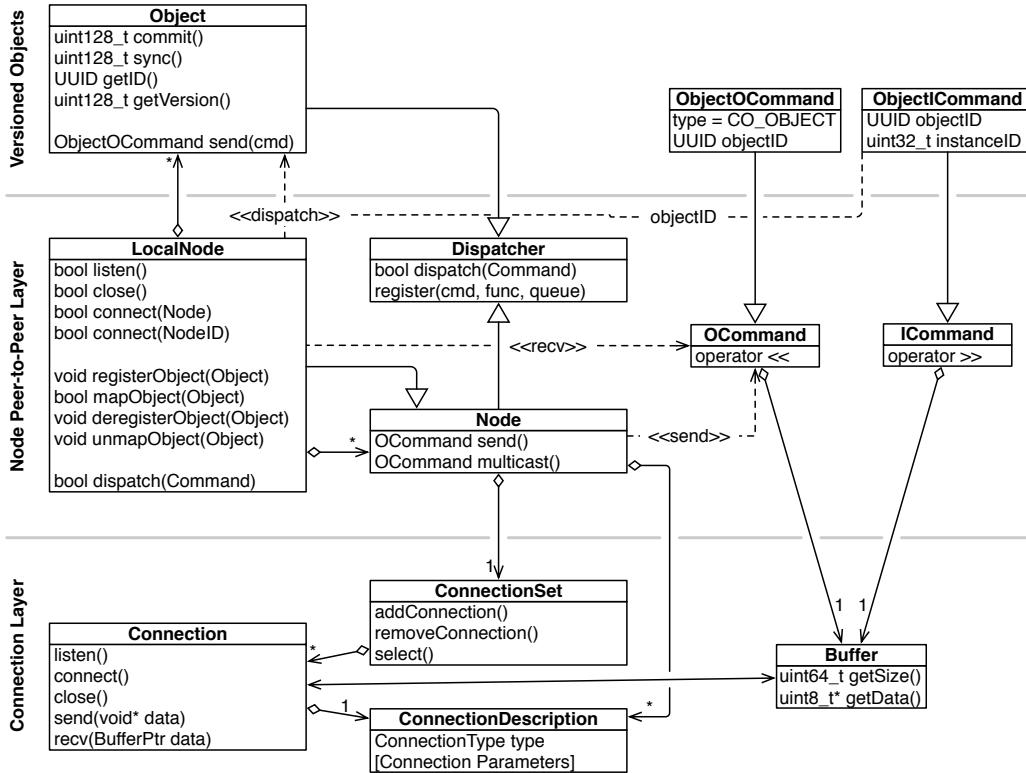


Figure 7.1: UML class diagram of the major Collage classes

connection set is used to select one connection which requires some action. This can be a connection request on a listening connection, pending data on a connected connection or the notification of a disconnect.

The connection and connection set can be used by applications to implement other network-related functionality, e.g., to communicate with a sound server on a different machine. A **LocalNode** has a connection set and uses this to manage connections with other nodes.

7.2.2 Data Streams

Data streams implement serialization and buffering on top of connections. They use output and input stream operators (`<<and >>`) with function overloads to provide serialization for all common data types. The input stream will perform byte swapping if the endianness differs between the sending and receiving node. Applications can easily provide overloads for their own classes for serialization. All serialised data is assembled in a memory buffer and send over the connection

once the data is complete. An output data stream might send its data to many connections, e.g., when an object update is sent to all subscribed slave nodes.

7.2.3 Thread-aware Command Dispatch

Collage sends commands over connections. A command is identified by its type (typically the C++ class handling it) and a command identifier. These fields are used to implement thread-aware dispatching of received commands to handler functions.

Nodes and objects communicate using commands derived from data streams. The basic command dispatch is implemented in the `Dispatcher` class, from which `Node` and `Object` are sub-classed.

The dispatcher allows the registration of commands with a dispatch queue and an invocation method. Each command has a type and command identifier, which is used to identify the receiver, registered queue and method. The dispatch pushes the packet to the registered queue. When the commands are dequeued by the processing thread, the registered command method is invoked.

This dispatch and invocation functionality is used within Equalizer to dispatch commands from the receiver thread to the appropriate node or pipe thread, and then to call a specific method when it is processed by these threads. This dispatching provides object-oriented semantics, since C++ instances can register themselves on the dispatcher, and get automatically invoked in the correct thread when an appropriate command arrives.

7.2.4 Nodes

The `Node` is the abstraction of one process in the peer-to-peer network. Each node has a universally unique identifier. This identifier is used to address nodes, e.g., to query connection information to connect to the node. Nodes use connections to communicate with each other by sending `OCommands`.

The `LocalNode` is the specialisation of the node for the given process. It encapsulates the communication logic for connecting remote nodes, as well as object registration and mapping. Local nodes are set up in the listening state during initialization.

A remote `Node` can either be connected explicitly by the application, or implicitly due to a connection from a remote node. The explicit connection can be done by programmatically creating a node, adding the necessary `ConnectionDescriptions` and connecting it to the local node. It may also be done by connecting the remote node to the local node by using its `NodeId`. This will cause Collage to query connection information for this node from the already connected nodes and zeroconf, instantiating the node and connecting it. Both operations may fail.

Zeroconf Discovery

Each `LocalNode` provides a Zeroconf communicator, which allows node and resource discovery. The zeroconf service "`_collage._tcp`" is used to announce the presence of a listening `LocalNode` using the ZeroConf protocol to the network. The node identifier and all listening connection descriptions are announced, which is used to connect unknown nodes by using the node identifier alone.

Communication between Nodes

Figure 7.2 shows the communication between two nodes. Each `LocalNode` has a receiver thread, which uses a connection set to read and dispatch incoming data from the network, and a command thread used for higher-level functions such as object mapping. When the remote node sends a command, the listening node receives the command and dispatches it from the receiver thread. The dispatch will either invoke the bound function immediately, or enqueue the command into the given queue. The queue consumer, for example the main or command thread, will read the command of this queue and then invoke the bound function.

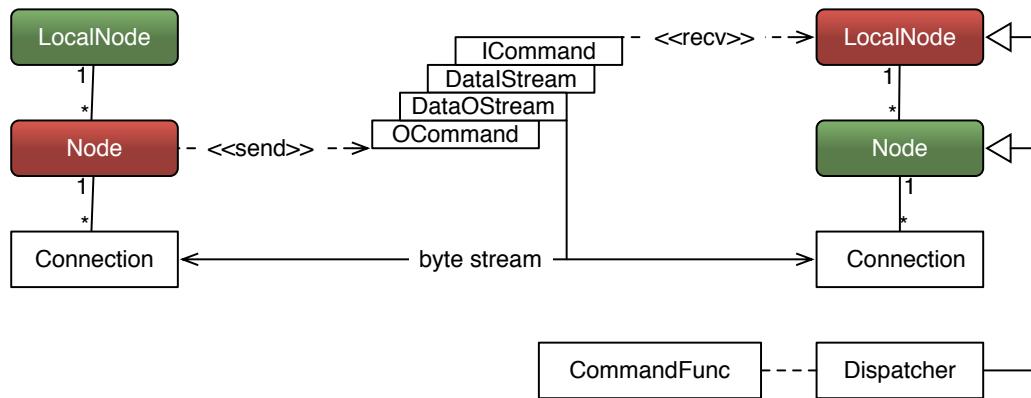


Figure 7.2: Communication between two Nodes

7.3 Distributed, Versioned Objects

Adapting an existing application for parallel rendering requires the synchronisation 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 centralised 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 deserialisation. 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 synchronisation 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 serialised whenever a new slave instance is mapped. No additional data is stored.

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

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

Instance and delta objects have a memory overhead on the master instance to store past data. The number of old versions retained is configurable per object. For Equalizer applications, this overhead typically occurs on the application node holding the master instances, and is configured based on the configuration's latency. When using unbuffered objects, applications only observe inconsistent state during the initial mapping, when a too recent version is used by a render client. The push-based commit-sync logic eventually brings the object into a consistent state with respect to the rendered frame.

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 serialisers 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 synchronise 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:

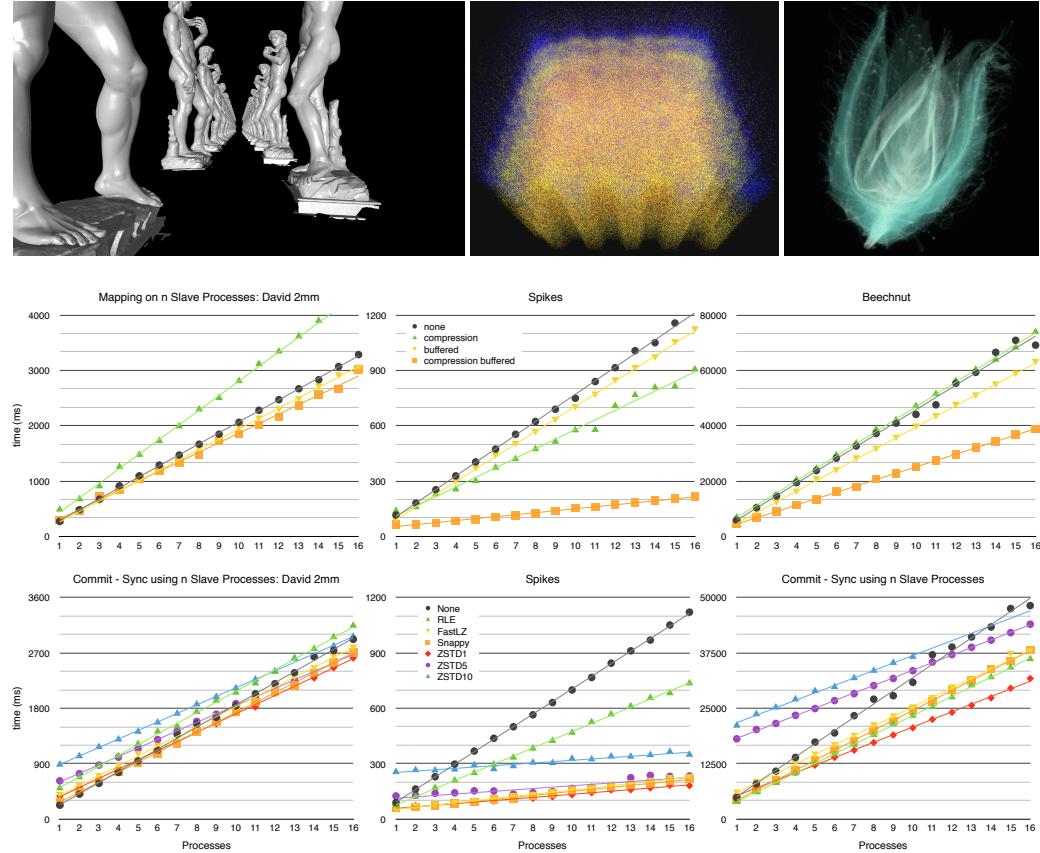
- The master instance of the object generates new versions for all slaves. These versions are continuous. It is possible to commit on slave instances, but special care has to be taken to handle possible conflicts during concurrent commits from multiple slave instances.
- Slave instance versions can only be advanced; that is, `sync(version)` with a version older 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`.

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 unsynchronised versions exist. This is useful to limit the amount of memory consumed by slave instance, and to prohibit run-away conditions of the master instance.

Benchmark 7.1 analyses the performance how data distribution and synchronisation performs in real-world applications. We extracted the existing data distribution code from a mesh renderer (`eqPly`) and a volume renderer (`Livre`) into a benchmark application to measure the time to initially map all the objects on the render client nodes, and to perform a commit-sync of the full data set after mapping has been established. All figures observe a noticeable measurement jitter due to other services running on the shared cluster during benchmarking. The details of the benchmark algorithm can be found in [Eilemann et al., 2018].

We used three different data sets, and ran the benchmark on up to eight physical nodes, that is, after eight processes nodes start to run two processes per node, which share CPU, memory and network interface bandwidth but do run on separate GPUs. Object mapping is measured using the following settings: `none` distributes the raw, uncompressed, and unbuffered data, `compression` uses the Snappy compressor to compress and distribute unbuffered data, `buffered` reuses uncompressed, serialised data for mappings from multiple nodes, and `compression buffered` reuses the compressed buffer for multiple nodes.

Unbuffered operations need to reserialise, and potentially recompress, the master object data for each slave node. Each slave instance needs to deserialise and decompress the data. During data synchronisation, the master commits the object data to all mapped slave instances simultaneously. This is a “push” opera-



Benchmark 7.1: Object Mapping and synchronisation

tion, whereas the mapping is a slave-triggered “pull” operation. During commit, the buffers only have to be serialised and compressed once, and can then be sent directly to all mapped slave nodes. Slave nodes queue this data and consume it during synchronisation. In contrast, object mapping needs to wait for each slave node to request the mapping, and then may need to reserialise and compress the object data. We test the time to commit and sync the data using different compression engines discussed under optimisations below.

The David statue at 2 mm resolution is organised in a k-d tree for rendering. Each node is a separate distributed object, which has two child node objects. A total of 1023 objects are distributed and synchronised. Due to limited compressibility of the data, the results are relatively similar. Compressing the data repeatedly for each client leads to decreased performance, since the compression overhead cannot be amortised by the decreased transmission time. Buffering data slightly improves performance by reducing the CPU and copy overhead. Com-

bining compression and buffering leads to the best performance, although only by about 10%. During synchronisation, data is pushed from the master process to all mapped slaves using a unicast connection to each slave. While the results are relatively close to each other, we can still observe how the tradeoff between compression ratio and speed influences overall performance. Better, slower compression algorithms lead to improved overall performance when amortised over many send operations.

The volume data sets are distributed in a single object, serialising the raw volume buffer. The Spike volume data set has a significant compression ratio, which is reflected by the results. Compression for this data is beneficial for transmitting data over a 10 Gb/s link, even for a single slave process. Buffering has little benefit since the serialization of volume data is trivial. Buffered compression makes a significant difference, since the compression cost can be amortised over many nodes, reaching raw data transmission rates of 3.7 GB/s with the default Snappy compressor and at best 4.4 GB/s with ZStandard at level 1. The distribution of the beechnut data set also behaves as expected. Due to the larger object size, uncompressed transmission is slightly faster compared to the Spike data set at 700MB/s, and compressed transmission does not improve the mapping performance, likely due to increased memory pressure caused by the data size. The comparison of the various compression engines is consistent with the benchmarks in Benchmark 7.3; RLE, Snappy and the LZ variants are very close to each other, and ZSTD1 can provide better performance after four nodes due to the better compression ratio.

Serializable

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. Setters of the class mark the appropriate dirty bit.

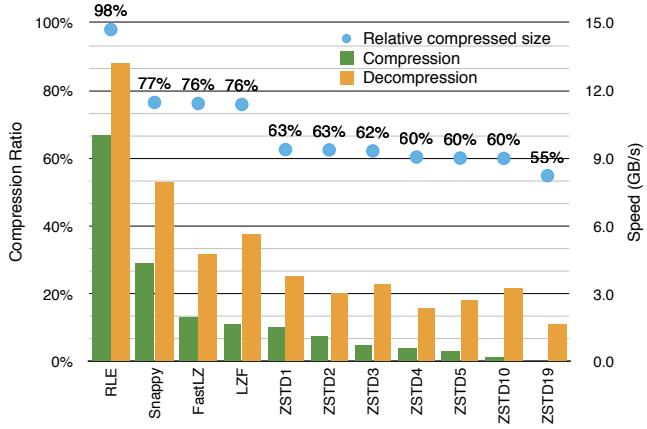
For serialization, the application developer implements `serialize` or `deserialize`, which are called with the bit mask specifying which data has to be transmitted or received. During a commit or sync, the current dirty bits are given, whereas during object mapping all dirty bits are passed to the serialization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

Optimizations

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

Compression 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 [Eyescale Software GmbH and Blue Brain Project, 2016], which provides a unified interface for a number of compression libraries, such as FastLZ [Jesper et al.,], Snappy [opensource@google.com, 2016] and ZStandard [Facebook, 2016]. It also contains a custom, virtually zero-cost RLE compressor. Pression parallelises the compression and decompression using data decomposition. This compression is generic and lossless, implemented transparently for the application. Applications can also use data-specific compression.

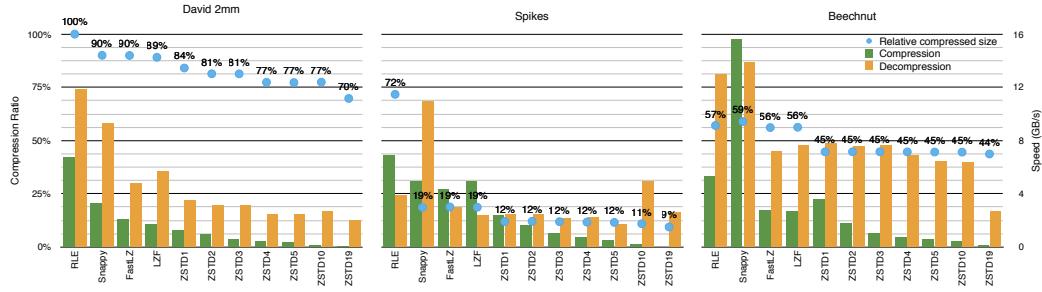
Benchmark 7.2 shows the compression ratio and speed for generic binary data from [Eilemann et al., 2018]. While the structure of the transmitted data varies with each application, this micro-benchmark gives a reasonable estimation of the expected performance. In our context of interactive distributed rendering applications, it is important to use the right tradeoff between spending time and resources for data compression, and the gained network transmission time due data reduction.



Benchmark 7.2: Compression Performance for Binary Data

On modern CPUs (the benchmark was executed on a 12-core node), modern compression libraries provide performance benefits even on fast interconnects such as 10 Gb/s Ethernet. In particular, the modern Snappy and ZStandard libraries deliver impressive performance.

In [Eilemann et al., 2018], we also evaluated the compression performance for more concrete application data. The results are shown in Benchmark 7.3. Polygonal data is difficult to compress with a generic lossless compressor, due to the floating point format used for the vertices. A data-specific compressor aware of the data semantics can provide much better results. Volume data on the other hand has shown to be well compressible, with typical 2 : 1 compression ratios at interactive speeds.



Benchmark 7.3: Data Compression for the PLY Data and Raw Volumes from Benchmark 7.1

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

Caching and Preloading 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 during idle time of the corresponding node. These nodes simply enter the received data to their cache. Preloading uses multicast when available.

Multicast Due to the master-slave nature of data distribution, multicast is used to optimise 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.

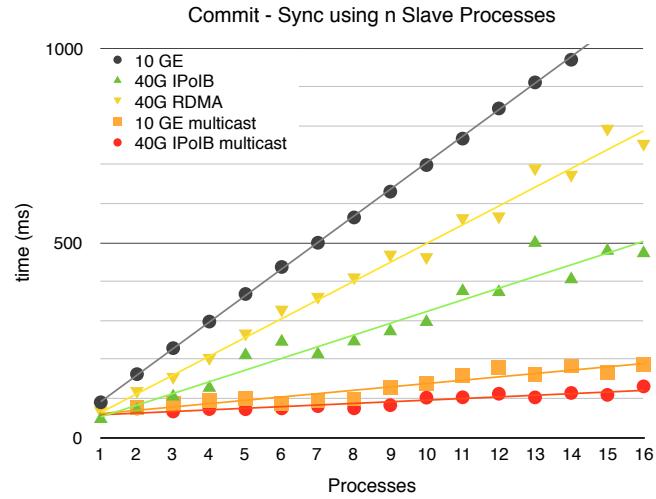
Benchmark 7.4 compares data distribution speed using different network protocols. In this benchmark, data synchronisation time of the Spike volume data set is measured. Buffering is enabled, and compression is disabled to focus on the raw network performance. For the benchmark, eight physical nodes are used, that is, after eight processes two client processes will run on some nodes, sharing CPU and network resources.

TCP over the faster InfiniBand link outperforms the cheaper ten gigabit ethernet link by more than a factor of two. Unexpectedly, the native RDMA connection performs worse, even though it outperforms IPoIB in a simple peer-to-peer connection benchmark. This needs further investigation, but we suspect the abstraction of a byte stream connection chosen by Collage is not well suited for remote

DMA semantics; that is, one needs to design the network API around zero-copy semantics with managed memory for modern high-speed transports. Both Infiniband connections show significant measurement jitter.

RSP multicast performs as expected. Collage starts using multicast to commit new object versions when two or more clients are mapped, since the transmission to a single client is faster using unicast. RSP consistently outperforms unicast on the same physical interface and shows good scaling behaviour (2.5 times slower on 16 vs 2 clients on ethernet, 1.8 times slower on InfiniBand). The scaling is significantly better when only one process per node is used. The increased transmission time

with multiple clients is caused by a higher probability of packet loss, which increases significantly when using more than one process per node. Infiniband outperforms ethernet slightly, but is largely limited by the RSP implementation throughput of preparing and queueing the datagrams to and from the protocol thread, which we observed in profiling.



Benchmark 7.4: synchronisation Performance over different Network Protocols

7.3.1 Reliable Stream Protocol

RSP is an implementation of a reliable multicast protocol over unreliable UDP multicast transport. RSP behaves similarly to TCP; in contrast to the underlying UDP transport, it is not message-oriented but implements byte stream semantics. RSP provides full reliability and ordering of the data, and slow receivers will eventually throttle the sender through a sliding window algorithm. This behaviour 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. Since we use multicast for distributing application data to all rendering clients we want semantics similar to TCP, that is, waiting for a client to read data is preferable over loosing this client.

RSP combines various established multicast algorithms [Adamson et al., 2004; Gau et al., 2002] 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 UDP socket. It implements the protocol handling and communicates with the application threads through thread-safe queues. The queues contain datagrams filled with 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. The header contains two bytes for the datagram type (connection handshake, data, acknowledgment, negative acknowledgment, acknowledgment request), and up to two six bytes of datagram-specific information (e.g. for acknowledgment: two bytes read node identifier, two bytes write node identifier, two bytes sequence number).

Figure 7.3 shows the data flow through the RSP implementation. Each member of the multicast group opens a listening connection, which will send query datagrams to the multicast socket. For each found member, a receiving connection instance is created and, similar to a TCP socket, passed to the application upon `accept`. Each connection instance has a fixed number (1024 by default) of fixed-size (1470 by default) buffers, each used directly as an UDP datagram. The listening connection uses these buffers for writing data, and each receiving connection uses its buffers for received data. These buffers are continuously cycled through two sets of queues: a blocking, thread-safe queue used on the application side for reading and writing data, and a non-blocking, lock-free and thread-safe queue on the protocol thread for data management.

When writing data, the application thread pops empty buffers from its queue (blocking when the data cannot be written fast enough), fills in the `data` datagram header and copies the application data piece-wise into the datagram. The datagrams are then pushed onto the protocol thread buffer queue. The protocol thread writes the datagrams onto the UDP multicast socket, and reads and handles any incoming datagrams. On the receiver side, the protocol receives the data, and pushes them in order to the corresponding application thread queue. Out-of-order datagrams are stored aside and queued in order later, and a negative acknowledgments (`nack`) are immediately sent for missing datagrams. The writer will repeat `nack'd` datagrams, recycle fully acknowledged datagrams to the application queue, and ask for missing acknowledgments if needed. When reading data, the application pops full buffers from the corresponding connection's queue (blocking when no

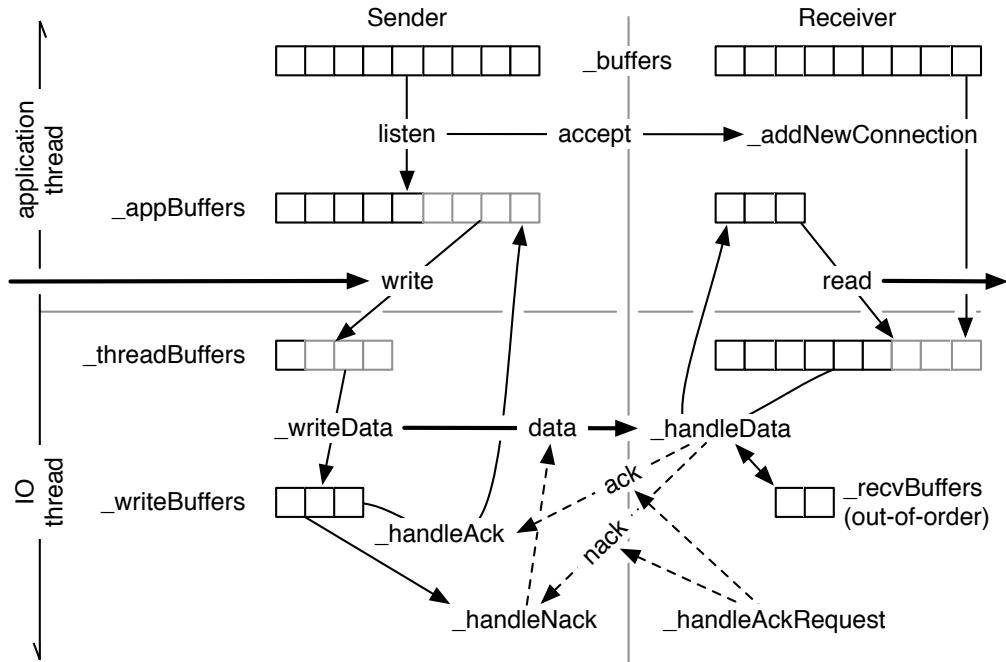


Figure 7.3: RSP data flow

data is available), copies the data piece-wise out of datagram into the application buffer, and recycles the cleared buffers onto the protocol thread queue.

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'd 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 optimise 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.

In [Eilemann et al., 2018] we provide experimental results, showing that our implementation can achieve above 90% wire speed on 10 GBit/s Ethernet, shows good scalability with respect to the multicast group size, and is very effective for distributing structured and unstructured application data to a large number of rendering clients concurrently.

C H A P T E R

8

APPLICATIONS

A key performance measure for a good design of any framework is the acceptance by developers, for which a good indicator is the usage by third-party applications. While the evaluation and architecture of applications build on Equalizer is outside of the scope of this thesis, we name a few examples here to illustrate the variety of use cases supported by our framework.

8.1 Livre

Livre (Large-scale Interactive Volume Rendering Engine) is a GPU ray-casting parallel 4D volume renderer, implementing state-of-the-art view-dependent level-of-detail rendering (LOD) and out-of-core data management [Engel et al., 2006].

Hierarchical and out-of-core LOD data management is supported by an implicit volume octree, accessed asynchronously by the renderer from a data source on a shared file system. Different data sources provide an octree-conform access to

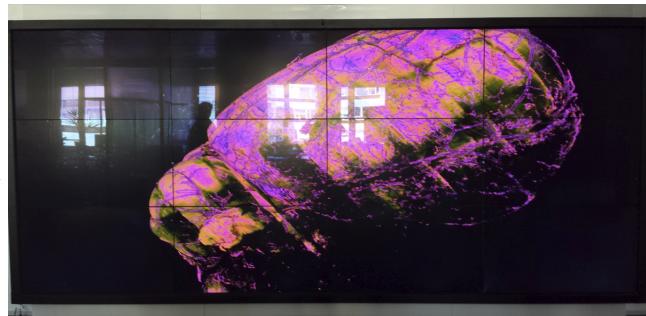


Figure 8.1: *Livre running on a 4x3 tiled display wall*

RAW or compressed files, as well as to on-the-fly generated volume data (e.g. such as from event simulations or surface meshes).

High-level state information, e.g., camera position and rendering settings, is shared in Livre through **Collage** objects between the application and rendering threads. Sort-first decomposition is efficiently supported through octree traversal and culling, both for scalability as well as for driving large-scale tiled display walls.

8.2 RTT Deltagen

RTT Deltagen (now Dassault 3D Excite) is a commercial application for interactive, high quality rendering of CAD data. The RTT Scale module, delivering multi-GPU and distributed execution, is based on **Equalizer** and **Collage**, and has driven many of the features implemented in **Equalizer**.



Figure 8.2: RTT Deltagen rendering mixing OpenGL rendering and raytracing (for the head light)

main application is committed as a delta at the beginning of the next frame. Multicast is used to keep data distribution times during session launch reasonable for larger cluster sizes (tens to hundreds of nodes).

RTT Scale is used for a wide variety of use cases. In virtual reality, the application is used for virtual prototyping and design reviews in front of high-resolution display walls and CAVEs, as well as for virtual prototyping of human-machine interactions using CAVEs and HMDs. For scalability, sort-first and tile compounds are used to achieve fast, high-quality rendering, primarily for interactive raytracing, both based on CPUs and GPUs. For CPU-based raytracing, often Linux-based rendering clients are used with a Windows-based application node.

RTT Scale uses a master-slave execution mode, where a single Deltagen instance can go into “Scale mode” at any time by launching an **Equalizer** configuration. Consequently, the internal representation needed for rendering is based on a **Collage**-based data distribution. The rendering clients are separate, smaller applications which will map their scenes during startup. At runtime, any change performed in the

8.3 RTNeuron

RTNeuron [Hernando et al., 2013] is a scalable real-time rendering tool for the visualization of neuronal simulations based on cable models. It is based on OpenSceneGraph for data management and Equalizer for parallel rendering, and focuses not only on fast rendering times, but also on fast loading times with no offline preprocessing. It provides level of detail (LOD) rendering, high quality anti-aliasing based on jittered frusta and accumulation during still views, interactive modification of the visual representation of neurons on a per-neuron basis (full neuron vs. soma only, branch pruning depending on the branch level, ...). RTNeuron implements both sort-first and sort-last rendering with order independent transparency.



Figure 8.3: RTNeuron running in a six-sided CAVE

8.4 RASTeR

RASTeR [Bösch et al., 2009] is an out-of-core and view-dependent real-time multi-resolution terrain rendering approach using a patch-based restricted quadtree triangulation. For load balanced parallel rendering [Goswami et al., 2010] it exploits fast hierarchical view-frustum culling of the level-of-detail (LOD) quadtree for sort-first decomposition, and uniform distribution of the visible LOD triangle patches for sort-last decomposition. The latter is enabled by a fast traversal of the patch-based restricted quadtree triangulation hierarchy which results in a list of selected LOD nodes, constituting a view-dependent cut or *front*



Figure 8.4: RASTeR running on a 3x2 tiled display wall

of activated nodes through the LOD hierarchy. Assigning and distributing equally sized segments of this active LOD front to the concurrent rendering threads results in a near-optimal sort-last decomposition for each frame.

8.5 Bino



Figure 8.5: *Bino video player on a semi-cylindrical multi-projector wall*

to video playback.

Bino is a stereoscopic 3D video player capable of running on very large display systems. Originally written for the immersive semi-cylindrical projection system at the University of Siegen, it has been used in many installations thanks to its flexibility of configuration. Bino decodes the video on each Equalizer rendering process, and only synchronises the time step globally, therefore providing a scalable solution

8.6 Omegalib



Figure 8.6: *An Omegalib application running in the Cave2*

tiled display wall) as well as virtual reality simulation exploration (traditionally done in VR systems) at a resolution matching human visual acuity. Omegalib supports dynamic reconfigurability of the display environment, so that areas of

Omegplib [Febretti et al., 2014] is a software framework built on top of Equalizer that facilitates application development for hybrid reality environments such as the Cave2. Hybrid reality environments aim to create a seamless 2D/3D environment that supports both information-rich analysis (traditionally done on

the display can be interactively allocated to 2D or 3D workspaces as needed. It makes it possible to have multiple immersive applications running on a cluster-controlled display system, have different input sources dynamically routed to applications, and have rendering results optionally redirected to a distributed compositing manager. Omegalib supports pluggable front-ends, to simplify the integration of third-party libraries like OpenGL, OpenSceneGraph, and the Visualization Toolkit (VTK).

CONCLUSION

9.1 Summary

Formalising, designing and implementing a generic parallel rendering framework which can serve both complex applications and research has been no easy task. Based on the analysis of Cavelib, practical experience in implementing and deploying OpenGL Multipipe SDK, we have been in the unique position to make significant contributions in this area. The base framework allowed us to take parallel rendering research to a new level, by enabling the easy implementation of new decomposition algorithms, many improvements for result composition, novel load balancing schemes, and numerous whole system optimizations, all of which are much harder without such a framework and associated applications. This is not only supported by the contributions of this thesis, but by other publications and doctoral theses completed using Equalizer. This research has not only been performed in the original research group; Equalizer has also been picked up by other laboratories, e.g., the Electronic Visualization Laboratory at the University of Illinois at Chicago for Cave2 research.

Beyond the core system design, we have incorporated many new parallel rendering algorithms in our framework. Most notably, cross-segment load balancing provides a novel approach to better assign multiple rendering resources to multi-display systems. It maximises rendering locality for the display GPUs and is not limited to planar displays as most other approaches.

Having a fully-featured rendering framework and real-world applications enabled us to implement many algorithmic improvements and optimizations, and evaluate them in a holistic and realistic setup. This work advances parallel rendering with new decomposition modes, compositing algorithms, better load balancing and an asynchronous rendering pipeline. Last, but not least, a network library for distributed, interactive visualization applications greatly facilitates the task to distribute and synchronise application state in a parallel rendering system.

Beyond the scope of this thesis, Equalizer has influenced the field and has been used in various commercial and research applications. These applications span a wide field of domains, from virtual prototyping with interactive raytracing, large-scale volume rendering, terrain rendering, neuroscience applications, to next-generation visualization systems such as the Cave2.

9.2 Future Work

We consider the core parallel rendering framework largely feature complete, with the exception of keeping up with new technologies, e.g., providing glue code for the Vulkan API. There remains a large amount of work to make parallel rendering more accessible. This may be addressed by simplified APIs on top of Equalizer, and through integrations with popular rendering toolkits. On the other hand, it should address operators and users of visualization systems through simplified configuration, monitoring and administration tools. In the same spirit, there is still a significant amount of research in automatically selecting the decomposition and recomposition algorithm as well as the resources to be used for a given application. This task becomes even more challenging when considering changes of the rendering load and algorithm during the runtime of an application.

We foresee an increasing importance of interactive raytracing, which has its own set of challenges for parallel rendering. In particular for large data rendering, there are a number of open questions, such as out-of-core parallel raytracing and data-parallel decomposition with global illumination.

Load balancing to better utilize the available resource, and to increase scalability to higher node counts, remains an open area of research. While this thesis provides many new results in this area, a comprehensive benchmark and study of different algorithms and applications would be very valuable, based on which new load-balancing algorithms may be discovered.

One of the remaining challenges is to make interactive supercomputing accessible. Significant research has been performed on how to link simulations with visualization, and how to use this monitoring to interactively steer the simulation. These advances now need to be translated into easily usable software components, integrated well with existing resource management systems.

BIBLIOGRAPHY

- [MPK, 2005] (2005). OpenGL Multipipe SDK.
- [Abraham et al., 2004] Abraham, F., Celes, W., Cerqueira, R., and Campos, J. L. (2004). A load-balancing strategy for sort-first distributed rendering. In *Proceedings SIBGRAPI*, pages 292–299.
- [Adamson et al., 2004] Adamson, B., Bormann, C., Handley, M., and Macker, J. (2004). Negative-acknowledgment (nack)-oriented reliable multicast (norm) protocol. Technical report.
- [Agranov and Gotsman, 1995] Agranov, G. and Gotsman, C. (1995). Algorithms for rendering realistic terrain image sequences and their parallel implementation. *The Visual Computer*, 11(9):455–464.
- [Ahrens and Painter, 1998] Ahrens, J. and Painter, J. (1998). Efficient sort-last rendering using compression-based image compositing. In *Proceedings Eurographics Workshop on Parallel Graphics and Visualization*.
- [Allard et al., 2002] Allard, J., Gouranton, V., Lecointre, L., Melin, E., and Rafin, B. (2002). NetJuggler: Running VR Juggler with multiple displays on a commodity component cluster. In *Proceeding IEEE Virtual Reality*, pages 275–276.
- [Bethel et al., 2003] Bethel, W. E., Humphreys, G., Paul, B., and Brederson, J. D. (2003). Sort-first, distributed memory parallel visualization and rendering. In

- Proceedings IEEE Symposium on Parallel and Large-Data Visualization and Graphics*, pages 41–50.
- [Bhaniramka et al., 2005] Bhaniramka, P., Robert, P. C. D., and Eilemann, S. (2005). OpenGL Multipipe SDK: A toolkit for scalable parallel rendering. In *Proceedings IEEE Visualization*, pages 119–126.
- [Bierbaum and Cruz-Neira, 2003] Bierbaum, A. and Cruz-Neira, C. (2003). ClusterJuggler: A modular architecture for immersive clustering. In *Proceedings Workshop on Commodity Clusters for Virtual Reality, IEEE Virtual Reality Conference*.
- [Bierbaum et al., 2001] Bierbaum, A., Just, C., Hartling, P., Meinert, K., Baker, A., and Cruz-Neira, C. (2001). VR Juggler: A virtual platform for virtual reality application development. In *Proceedings of IEEE Virtual Reality*, pages 89–96.
- [Blanke et al., 2000] Blanke, W., Bajaj, C., D.Fussel, and Zhang, X. (2000). The metabuffer: A scalable multi-resolution 3-d graphics system using commodity rendering engines. Technical Report TR2000-16, University of Texas at Austin.
- [Blue Brain Project, 2016] Blue Brain Project (2016). Tide: Tiled Interactive Display Environment. <https://github.com/BlueBrain/Tide>.
- [Bösch et al., 2009] Bösch, J., Goswami, P., and Pajarola, R. (2009). RASTeR: Simple and efficient terrain rendering on the GPU. In *Proceedings EUROGRAPHICS Areas Papers, Scientific Visulization*, pages 35–42.
- [Cavin and Mion, 2006] Cavin, X. and Mion, C. (2006). Pipelined sort-last rendering: Scalability, performance and beyond. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*.
- [Cavin et al., 2005] Cavin, X., Mion, C., and Filbois, A. (2005). COTS cluster-based sort-last rendering: Performance evaluation and pipelined implementation. In *Proceedings IEEE Visualization*, pages 111–118. Computer Society Press.
- [Correa et al., 2002] Correa, W. T., Klosowski, J. T., and Silva, C. T. (2002). Out-of-core sort-first parallel rendering for cluster-based tiled displays. In *Proceedings Eurographics Workshop on Parallel Graphics and Visualization*, pages 89–96.
- [Crockett, 1997] Crockett, T. W. (1997). An introduction to parallel rendering. *Parallel Computing*, 23:819–843.

- [DeFanti et al., 1998] DeFanti, T. A., Adamczyk, D., Cruz-Neira, C., Czernuszenko, M., Ghazisaedy, M., Hayakawa, H., Pape, D., Sandin, D. J., Nickless, B., and Sherman, B. (1998). CAVELib. <http://www.evl.uic.edu/pape/CAVE/prog/>.
- [DeFanti et al., 2009] DeFanti, T. A., Leigh, J., Renambot, L., Jeong, B., Verlo, A., Long, L., Brown, M., Sandin, D. J., Vishwanath, V., Liu, Q., Katz, M. J., Papadopoulos, P., Keefe, J. P., Hidley, G. R., Dawe, G. L., Kaufman, I., Glogowski, B., Doerr, K.-U., Singh, R., Girado, J., Schulze, J. P., Kuester, F., and Smarr, L. (2009). The optiportal, a scalable visualization, storage, and computing interface device for the optiputer. *Future Gener. Comput. Syst.*, 25(2):114–123.
- [Doerr and Kuester, 2011] Doerr, K.-U. and Kuester, F. (2011). CGLX: A scalable, high-performance visualization framework for networked display environments. *IEEE Transactions on Visualization and Computer Graphics*, 17(2):320–332.
- [Eilemann et al., 2012] Eilemann, S., Bilgili, A., Abdellah, M., Hernando, J., Makhinya, M., Pajarola, R., and Schürmann, F. (2012). Parallel Rendering on Hybrid Multi-GPU Clusters. In *EGPGV*, pages 109–117.
- [Eilemann et al., 2009] Eilemann, S., Makhinya, M., and Pajarola, R. (2009). Equalizer: A scalable parallel rendering framework. *IEEE Transactions on Visualization and Computer Graphics*, 15(3):436–452.
- [Eilemann and Pajarola, 2007] Eilemann, S. and Pajarola, R. (2007). Direct send compositing for parallel sort-last rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*.
- [Eilemann et al., 2018] Eilemann, S., Steiner, D., and Pajarola, R. (2018). Equalizer 2.0 - Convergence of a Parallel Rendering Framework.
- [Engel et al., 2006] Engel, K., Hadwiger, M., Kniss, J. M., Rezk-Salama, C., and Weiskopf, D. (2006). *Real-Time Volume Graphics*. AK Peters.
- [Erol et al., 2011] Erol, F., Eilemann, S., and Pajarola, R. (2011). Cross-segment load balancing in parallel rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*, pages 41–50.
- [Eyescale Software GmbH and Blue Brain Project, 2016] Eyescale Software GmbH and Blue Brain Project (2016). Compression and data transfer plugins. <https://github.com/Eyescale/Pression>.

- [Eyles et al., 1997] Eyles, J., Molnar, S., Poulton, J., Greer, T., Lastra, A., England, N., and Westover, L. (1997). PixelFlow: The realization. In *Proceedings of the ACM SIGGRAPH/EUROGRAPHICS workshop on Graphics Hardware*, pages 57–68.
- [Facebook, 2016] Facebook, I. (2016). Fast real-time compression algorithm. <https://github.com/facebook/zstd>.
- [Febretti et al., 2014] Febretti, A., Nishimoto, A., Mateevitsi, V., Renambot, L., Johnson, A., and Leigh, J. (2014). Omegalib: A multi-view application framework for hybrid reality display environments. In *2014 IEEE Virtual Reality (VR)*, pages 9–14.
- [Febretti et al., 2013] Febretti, A., Nishimoto, A., Thigpen, T., Talandis, J., Long, L., Pirtle, J., Peterka, T., Verlo, A., Brown, M., Plepys, D., et al. (2013). Cave2: a hybrid reality environment for immersive simulation and information analysis. In *IS&T/SPIE Electronic Imaging*, pages 864903–864903. International Society for ‘Optic’s and Photonics.
- [Garcia and Shen, 2002] Garcia, A. and Shen, H.-W. (2002). An interleaved parallel volume renderer with PC-clusters. In *Proceedings Eurographics Workshop on Parallel Graphics and Visualization*, pages 51–60.
- [Gau et al., 2002] Gau, R.-H., Haas, Z. J., and Krishnamachari, B. (2002). On multicast flow control for heterogeneous receivers. *IEEE/ACM Trans. Netw.*, 10(1):86–101.
- [Gemmell et al., 2003] Gemmell, J., Montgomery, T., Speakman, T., and Crowcroft, J. (2003). The PGM reliable multicast protocol. *IEEE Network*, 17(1):16–22.
- [Goswami et al., 2010] Goswami, P., Makhinya, M., Bösch, J., and Pajarola, R. (2010). Scalable parallel out-of-core terrain rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*, pages 63–71.
- [Hernando et al., 2013] Hernando, J. B., Biddiscombe, J., Bohara, B., Eilemann, S., and Schürmann, F. (2013). Practical Parallel Rendering of Detailed Neuron Simulations. In *Proceedings of the 13th Eurographics Symposium on Parallel Graphics and Visualization*, EGPGV, pages 49–56, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- [Houston, 2005] Houston, M. (2005). Raptor. <http://graphics.stanford.edu/projects/raptor/>.

- [Huang et al., 2000] Huang, J., Shareef, N., Crawfis, R., Sadayappan, P., and Mueller, K. (2000). A parallel splatting algorithm with occlusion culling. In *Proceedings Eurographics Workshop on Parallel Graphics and Visualization*.
- [Humphreys et al., 2000] Humphreys, G., Buck, I., Eldridge, M., and Hanrahan, P. (2000). Distributed rendering for scalable displays. *IEEE Supercomputing*.
- [Humphreys et al., 2001] Humphreys, G., Eldridge, M., Buck, I., Stoll, G., Everett, M., and Hanrahan, P. (2001). WireGL: A scalable graphics system for clusters. In *Proceedings Annual Conference on Computer Graphics and Interactive Techniques*, pages 129–140.
- [Humphreys and Hanrahan, 1999] Humphreys, G. and Hanrahan, P. (1999). A distributed graphics system for large tiled displays. *IEEE Visualization 1999*, pages 215–224.
- [Humphreys et al., 2002] Humphreys, G., Houston, M., Ng, R., Frank, R., Ahern, S., Kirchner, P. D., and Klosowski, J. T. (2002). Chromium: A stream-processing framework for interactive rendering on clusters. *ACM Transactions on Graphics*, 21(3):693–702.
- [Igehy et al., 1998] Igehy, H., Stoll, G., and Hanrahan, P. (1998). The design of a parallel graphics interface. *Proceedings of SIGGRAPH 98*, pages 141–150.
- [Jesper et al.,] Jesper, J., Sadakane, K., and Sung, W.-K. Fast lz-compression algorithm.
- [Johnson et al., 2006] Johnson, A., Leigh, J., Morin, P., and Van Keken, P. (2006). GeoWall: Stereoscopic visualization for geoscience research and education. *IEEE Computer Graphics and Applications*, 26(6):10–14.
- [Johnson et al., 2012] Johnson, G. P., Abram, G. D., Westing, B., Navr’til, P., and Gaither, K. (2012). DisplayCluster: An Interactive Visualization Environment for Tiled Displays. In *2012 IEEE International Conference on Cluster Computing*, pages 239–247.
- [Jones et al., 2004] Jones, K., Danzer, C., Byrnes, J., Jacobson, K., Bouchaud, P., Courvoisier, D., Eilemann, S., and Robert, P. (2004). SGI®OpenGL Multipipe™SDK User’s Guide. Technical Report 007-4239-004, Silicon Graphics.
- [Just et al., 1998] Just, C., Bierbaum, A., Baker, A., and Cruz-Neira, C. (1998). VR Juggler: A framework for virtual reality development. In *Proceedings Immersive Projection Technology Workshop*.

- [Lever, 2004] Lever, P. G. (2004). SEPIA – applicability to MVC. White paper Manchester Visualization Centre (MVC), University of Manchester.
- [Li et al., 1996] Li, P. P., Duquette, W. H., and Cerkendall, D. W. (1996). RIVA: A versatile parallel rendering system for interactive scientific visualization. *IEEE Transactions on Visualization and Computer Graphics*, 2(3):186–201.
- [Li et al., 1997] Li, P. P., Whitman, S., Mendoza, R., and Tsiao, J. (1997). Par-Vox: A parallel splatting volume rendering system for distributed visualization. In *Proceedings IEEE Parallel Rendering Symposium*, pages 7–14.
- [Lombeyda et al., 2001a] Lombeyda, S., Moll, L., Shand, M., Breen, D., and Heirich, A. (2001a). Scalable interactive volume rendering using off-the-shelf components. Technical Report CACR-2001-189, California Institute of Technology.
- [Lombeyda et al., 2001b] Lombeyda, S., Moll, L., Shand, M., Breen, D., and Heirich, A. (2001b). Scalable interactive volume rendering using off-the-shelf components. In *Proceedings IEEE Symposium on Parallel and Large Data Visualization and Graphics*, pages 115–121.
- [Makhinya et al., 2010] Makhinya, M., Eilemann, S., and Pajarola, R. (2010). Fast Compositing for Cluster-Parallel Rendering. In *Proceedings of the 10th Eurographics Conference on Parallel Graphics and Visualization*, EGPGV, pages 111–120, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- [Marrinan et al., 2014] Marrinan, T., Aurisano, J., Nishimoto, A., Bharadwaj, K., Mateevitsi, V., Renambot, L., Long, L., Johnson, A., and Leigh, J. (2014). SAGE2: A new approach for data intensive collaboration using Scalable Resolution Shared Displays. In *Collaborative Computing: Networking, Applications and Worksharing*, pages 177–186.
- [Moll et al., 1999] Moll, L., Heirich, A., and Shand, M. (1999). Sepia: scalable 3D compositing using PCI pamette. In *Proceedings IEEE Symposium on Field-Programmable Custom Computing Machines*, pages 146–155.
- [Molnar et al., 1994] Molnar, S., Cox, M., Ellsworth, D., and Fuchs, H. (1994). A sorting classification of parallel rendering. *IEEE Computer Graphics and Applications*, 14(4):23–32.
- [Molnar et al., 1992] Molnar, S., Eyles, J., and Poulton, J. (1992). PixelFlow: High-speed rendering using image composition. In *Proceedings ACM SIGGRAPH*, pages 231–240.

- [Montrym et al., 1997] Montrym, J. S., Baum, D. R., Dignam, D. L., and Migdal, C. J. (1997). InfiniteReality: A real-time graphics system. In *Proceedings ACM SIGGRAPH*, pages 293–302.
- [Mueller, 1995] Mueller, C. (1995). The sort-first rendering architecture for high-performance graphics. In *Proceedings Symposium on Interactive 3D Graphics*, pages 75–84. ACM SIGGRAPH.
- [Mueller, 1997] Mueller, C. (1997). Hierarchical graphics databases in sort-first. In *Proceedings IEEE Symposium on Parallel Rendering*, pages 49–. Computer Society Press.
- [Muraki et al., 2001] Muraki, S., Ogata, M., Ma, K.-L., Koshizuka, K., Kajihara, K., Liu, X., Nagano, Y., and Shimokawa, K. (2001). Next-generation visual supercomputing using PC clusters with volume graphics hardware devices. In *Proceedings ACM/IEEE Conference on Supercomputing*, pages 51–51.
- [Nachbaur et al., 2014] Nachbaur, D., Dumusc, R., Bilgili, A., Hernando, J., and Eilemann, S. (2014). Remote parallel rendering for high-resolution tiled display walls. In *Large Data Analysis and Visualization (LDAV), 2014 IEEE 4th Symposium on*, pages 117–118.
- [Neal et al., 2011] Neal, B., Hunkin, P., and McGregor, A. (2011). Distributed OpenGL rendering in network bandwidth constrained environments. In Kuhlen, T., Pajarola, R., and Zhou, K., editors, *Proceedings Eurographics Conference on Parallel Graphics and Visualization*, pages 21–29. Eurographics Association.
- [Nie et al., 2005] Nie, W., Sun, J., Jin, J., Li, X., Yang, J., and Zhang, J. (2005). A dynamic parallel volume rendering computation mode based on cluster. In *Proceedings Computational Science and its Applications*, volume 3482 of *Lecture Notes in Computer Science*, pages 416–425.
- [Niski and Cohen, 2007] Niski, K. and Cohen, J. D. (2007). Tile-based level of detail for the parallel age. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1352–1359.
- [opensource@google.com, 2016] opensource@google.com (2016). A fast compressor/decompressor. <https://github.com/google/snappy>.
- [Rohlf and Helman, 1994] Rohlf, J. and Helman, J. (1994). IRIS Performer: A high performance multiprocessing toolkit for real-time 3D graphics. In *Proceedings ACM SIGGRAPH*, pages 381–394. ACM Press.

- [Samanta et al., 2001] Samanta, R., Funkhouser, T., and Li, K. (2001). Parallel rendering with K-way replication. In *Proceedings IEEE Symposium on Parallel and Large-Data Visualization and Graphics*. Computer Society Press.
- [Samanta et al., 2000] Samanta, R., Funkhouser, T., Li, K., and Singh, J. P. (2000). Hybrid sort-first and sort-last parallel rendering with a cluster of PCs. In *Proceedings Eurographics Workshop on Graphics Hardware*, pages 97–108.
- [Samanta et al., 1999] Samanta, R., Zheng, J., Funkhouser, T., Li, K., and Singh, J. P. (1999). Load balancing for multi-projector rendering systems. In *Proceedings Eurographics Workshop on Graphics Hardware*, pages 107–116.
- [Schulze and Lang, 2002] Schulze, J. P. and Lang, U. (2002). The parallelization of the perspective shear-warp volume rendering algorithm. In *Proceedings Eurographics Workshop on Parallel Graphics and Visualization*, pages 61–70.
- [Staadt et al., 2003] Staadt, O. G., Walker, J., Nuber, C., and Hamann, B. (2003). A survey and performance analysis of software platforms for interactive cluster-based multi-screen rendering. In *Proceedings Eurographics Workshop on Virtual Environments*, pages 261–270.
- [Steiner et al., 2016] Steiner, D., Paredes, E. G., Eilemann, S., and Pajarola, R. (2016). Dynamic work packages in parallel rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*, pages 89–98.
- [Stoll et al., 2001] Stoll, G., Eldridge, M., Patterson, D., Webb, A., Berman, S., Levy, R., Caywood, C., Taveira, M., Hunt, S., and Hanrahan, P. (2001). Lightning-2: A high-performance display subsystem for PC clusters. In *Proceedings ACM SIGGRAPH*, pages 141–148.
- [Stompel et al., 2003] Stompel, A., Ma, K.-L., Lum, E. B., Ahrens, J., and Patchett, J. (2003). SLIC: Scheduled linear image compositing for parallel volume rendering. In *Proceedings IEEE Symposium on Parallel and Large-Data Visualization and Graphics*, pages 33–40.
- [Vezina and Robertson, 1991] Vezina, G. and Robertson, P. K. (1991). Terrain perspectives on a massively parallel SIMD computer. In *Proceedings Computer Graphics International (CGI)*, pages 163–188.
- [Wittenbrink, 1998] Wittenbrink, C. M. (1998). Survey of parallel volume rendering algorithms. In *Proceedings Parallel and Distributed Processing Techniques and Applications*, pages 1329–1336.

- [Yang et al., 2001] Yang, D.-L., Yu, J.-C., and Chung, Y.-C. (2001). Efficient compositing methods for the sort-last-sparse parallel volume rendering system on distributed memory multicomputers. *Journal of Supercomputing*, 18(2):201–22–.
- [Yu et al., 2008] Yu, H., Wang, C., and Ma, K.-L. (2008). Massively parallel volume rendering using 2-3 swap image compositing. In *Proceedings of the 2008 ACM/IEEE Conference on Supercomputing*, SC ’08, pages 48:1–48:11, Piscataway, NJ, USA. IEEE Press.
- [Zhang et al., 2001] Zhang, X., Bajaj, C., and Blanke, W. (2001). Scalable isosurface visualization of massive datasets on COTS clusters. In *Proceedings IEEE Symposium on Parallel and Large Data Visualization and Graphics*, pages 51–58.

CURRICULUM VITAE

PARTICULARS	<p>Date of Birth Nationality Languages Open Source Profile</p>	
PROFILE	<p>Senior software engineer and technical team lead, with a specialization in interactive large data visualization, C++, parallel and distributed programming. Successful track record of building and leading engineering teams to success.</p>	
EXPERTISE	<p>Technical leadership for high performance C++ applications, parallel programming, distributed systems, Virtual Reality and collaborative visualization Software and library design, test driven development and maintenance using C++, Typescript, Python, CMake and git Software development methodology during the whole lifecycle, ranging from requirements analysis, specification, design, implementation to documentation, education, debugging, optimization and support Broad knowledge of operating systems: Mac OS X, Linux, Windows, Irix</p>	

EXPERIENCE

<i>Frontend Software Engineer</i> <u>Zürich, Switzerland</u> <hr/> Development of frontend APIs and rendering algorithms for 3D mapping.	ESRI R&D Center Nov 2017 – current
--	---

<i>Researcher, Parallel Rendering</i> <u>Zürich, Switzerland</u> <hr/> Research new algorithms for large data visualization, in particular the parallelization, load-balancing and data distribution of parallel OpenGL applications on graphics clusters. Invented and developed Equalizer, a framework for scalable, distributed OpenGL applications.	University of Zürich 2005 – 2007, October 2015 – current
---	---

<i>Visualization Team Manager</i> <u>Lausanne, Switzerland</u> <hr/> Built a team of seven software engineers, one post-doc, one PhD student and one media designer to deliver innovative visualization software as well as media for communication and scientific publications. Developed the long-term interactive supercomputing vision and the corresponding medium-term roadmap with the team, motivated and lead the implementation based on modular software components. Drove the implementation of software engineering best practices for the whole project.	Blue Brain Project, EPFL May 2011 – Sep 2017
--	---

<i>CEO and Founder</i> <u>Neuchâtel, Switzerland</u> <hr/> Co-founder of Eyescale and lead developer of the Equalizer parallel rendering framework and related libraries. Deploying Equalizer in existing ISV applications to scale display size, performance and visual quality. Software architecture, design and development, hardware and software consulting for multi-GPU workstations, visualization clusters and Virtual Reality.	Eyescale Software GmbH January 2007 – current
---	--

<i>Senior Software Engineer, 3D Graphics</i> <u>Neuchâtel, Switzerland</u> <hr/> <i>Senior Software Engineer</i> <u>Neuchâtel, Switzerland</u> <hr/> Job position details available on demand.	Tungsten Graphics January 2007 – June 2007
--	---

Senior Software Engineer
Neuchâtel, Switzerland

Silicon Graphics, Inc.
August 2000 – December 2003

Worked in SGI's advanced graphics division as technical lead for OpenGL Multipipe SDK (MPK), a framework to develop high performance, scalable visualization software. Worked on DataSync, a distributed shared memory API for clusters.

Software Engineer
Munich, Germany

Freelancer
April 2000 – July 2000

Software Engineer
Wessling, Germany

Intec GmbH
October 1998 – March 2000

Job position details available on demand.

EDUCATION

University of Zurich

PhD in Computer Science, in progress

École Polytechnique Fédérale de Lausanne

Master in Computer Science, October 2015, Grade 5.6/6.0

Berufsakademie Heidenheim

Dipl.-Ing. (eq BS) in Computer Science, September 1998

CONFERENCE PUBLICATIONS

- [Bhaniramka et al., 2005] Bhaniramka, P., Robert, P. C. D., and Eilemann, S. (2005). OpenGL Multipipe SDK: A toolkit for scalable parallel rendering. In *Proceedings IEEE Visualization*, pages 119–126.
- [Eilemann et al., 2017] Eilemann, S., Abdellah, M., Antille, N., Bilgili, A., Chevtchenko, G., Dumusc, R., Favreau, C., Hernando, J., Nachbaur, D., Podhajski, P., Villafranca, J., and Schürmann, F. (2017). From Big Data to Big Displays: High-Performance Visualization at Blue Brain. In Kunkel, J. M., Yokota, R., Taufer, M., and Shalf, J., editors, *High Performance Computing*, pages 662–675, Cham. Springer International Publishing.
- [Eilemann et al., 2012] Eilemann, S., Bilgili, A., Abdellah, M., Hernando, J., Makhinya, M., Pajarola, R., and Schürmann, F. (2012). Parallel Rendering on Hybrid Multi-GPU Clusters. In *EGPGV*, pages 109–117.
- [Eilemann et al., 2016] Eilemann, S., Delalondre, F., Bernard, J., Planas, J., Schuermann, F., Biddiscombe, J., Bekas, C., Curioni, A., Metzler, B., Kaltstein, P., et al. (2016). Key/value-enabled flash memory for complex scientific workflows with on-line analysis and visualization. In *Parallel and Distributed Processing Symposium, 2016 IEEE International*, pages 608–617. IEEE.

- [Eilemann and Pajarola, 2007] Eilemann, S. and Pajarola, R. (2007). Direct send compositing for parallel sort-last rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*.
- [Erol et al., 2011] Erol, F., Eilemann, S., and Pajarola, R. (2011). Cross-segment load balancing in parallel rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*, pages 41–50.
- [Hernando et al., 2013a] Hernando, J. B., Biddiscombe, J., Bohara, B., Eilemann, S., and Schürmann, F. (2013a). Practical parallel rendering of detailed neuron simulations. In *Proceedings of the 13th Eurographics Symposium on Parallel Graphics and Visualization*, EGPGV ’13, pages 49–56, Aire-la-Ville, Switzerland. Eurographics Association.
- [Hernando et al., 2013b] Hernando, J. B., Biddiscombe, J., Bohara, B., Eilemann, S., and Schürmann, F. (2013b). Practical Parallel Rendering of Detailed Neuron Simulations. In *Proceedings of the 13th Eurographics Symposium on Parallel Graphics and Visualization*, EGPGV, pages 49–56, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- [Makhinya et al., 2010] Makhinya, M., Eilemann, S., and Pajarola, R. (2010). Fast Compositing for Cluster-Parallel Rendering. In *Proceedings of the 10th Eurographics Conference on Parallel Graphics and Visualization*, EGPGV, pages 111–120, Aire-la-Ville, Switzerland, Switzerland. Eurographics Association.
- [Steiner et al., 2016] Steiner, D., Paredes, E. G., Eilemann, S., and Pajarola, R. (2016). Dynamic work packages in parallel rendering. In *Proceedings Eurographics Symposium on Parallel Graphics and Visualization*, pages 89–98.

JOURNAL ARTICLES

- [Eilemann et al., 2009] Eilemann, S., Makhinya, M., and Pajarola, R. (2009). Equalizer: A scalable parallel rendering framework. *IEEE Transactions on Visualization and Computer Graphics*, 15(3):436–452.
- [Eilemann et al., 2018] Eilemann, S., Steiner, D., and Pajarola, R. (2018). Equalizer 2.0 - Convergence of a Parallel Rendering Framework.