



**University of
Zurich**^{UZH}

Department of Informatics

Modern Distributed Rendering Systems

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. ABC DEF

March 15, 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, March 15, 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 simulations. While large scale analysis and simulations have received significant attention for cloud computing and HPC systems, software to efficiently visualize large amounts of data is struggling to keep up.

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

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

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

KURZFASSUNG

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

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

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

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

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, in particular the visualization team, and all the other contributors for their support in the research leading to this proposal. Furthermore, I would like to thank Prof. Renato Pajarola for his long-term commitment to my research work.

CONTENTS

Abstract	i
Kurzfassung	iii
Acknowledgments	v
List of Figures	ix
List of Tables	xi
1 Background	1
1.1 Motivation	1
1.2 Interactive Visualization	3
1.3 Parallel Rendering	3
1.3.1 Domain specific solutions	3
1.3.2 Special-purpose architectures	4
1.3.3 Generic approaches	5
1.4 Dissertation Structure	8
2 Contributions	9
2.1 Generic Parallel Rendering Framework	9
2.2 Parallel Rendering Modes	9
2.3 Load Balancing	9

2.4 Applications	9
3 The Architecture of a Parallel Rendering Framework	11
3.1 Rendering Context	12
3.2 Asynchronous Execution Model	12
3.3 Compounds	12
3.4 Load Balancing	12
3.5 Compositing	12
3.6 Distribution Layer	12
4 New Parallel Rendering Modes	13
5 Compositing Optimisations	15
6 New Load Balancing Algorithms	17
7 Data Distribution and Synchronization	19
8 Conclusion	21
8.1 Future Work	21
Bibliography	23
Curriculum Vitae	29

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	4
1.3	Transparent OpenGL interception and parallelization of the rendering code	5

LIST OF TABLES

C H A P T E R

1

BACKGROUND

1.1 Motivation

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

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

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

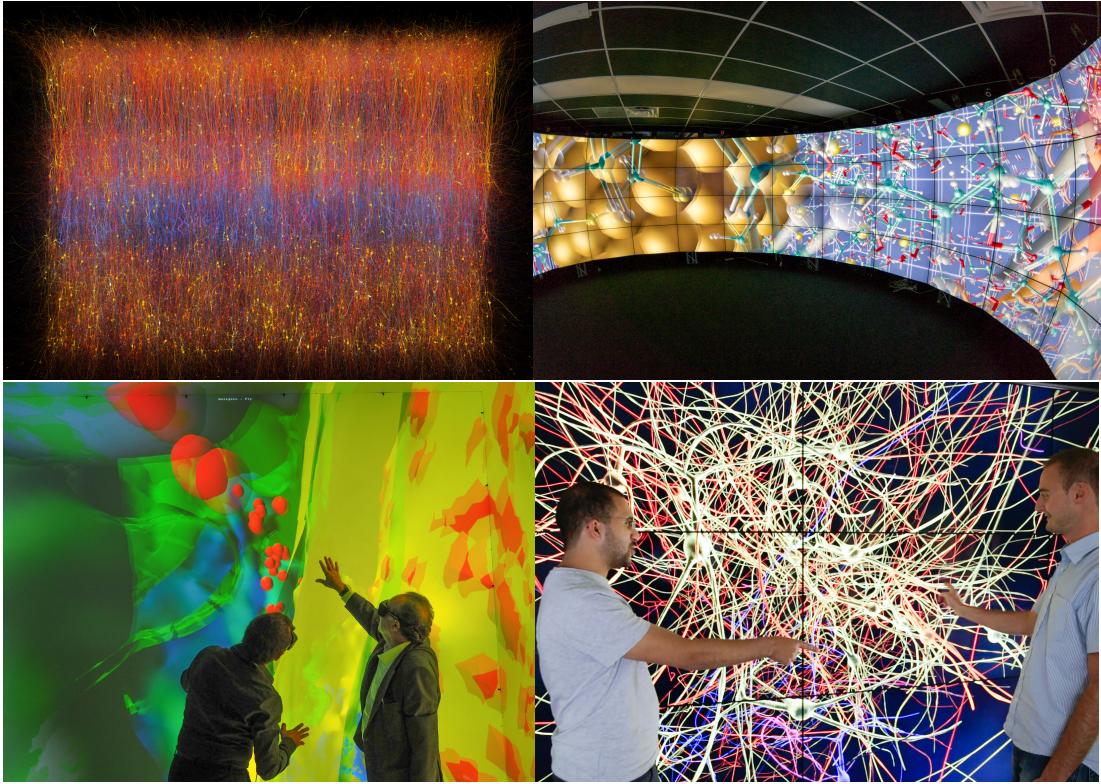


Figure 1.1: *Large Data Visualization: Large data visualization of a brain simulation, molecular visualization in the Cave², exploration of EM stack reconstructions in a Cave, collaborative data analysis on a tiled display wall.*

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

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

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

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

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

1.2 Interactive Visualization

1.3 Parallel Rendering

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

1.3.1 Domain specific solutions

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

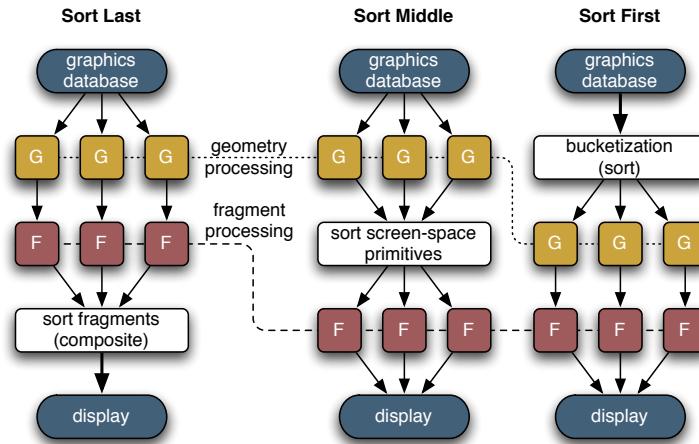


Figure 1.2: Sort-last, sort-middle and sort-first parallel rendering

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

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

1.3.2 Special-purpose architectures

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

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

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

1.3.3 Generic approaches

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

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

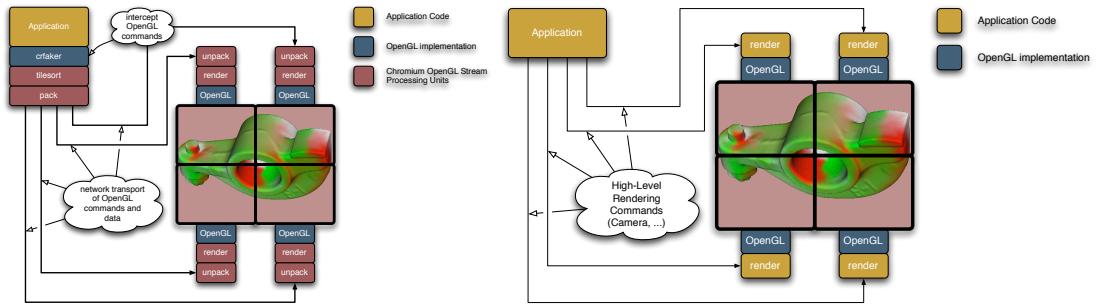


Figure 1.3: Transparent OpenGL interception and parallelization of the rendering code

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

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

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

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

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

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

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

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

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

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

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

1.4 Dissertation Structure

C H A P T E R

2

CONTRIBUTIONS

2.1 Generic Parallel Rendering Framework

2.2 Parallel Rendering Modes

2.3 Load Balancing

2.4 Applications

C H A P T E R

3

THE ARCHITECTURE OF A PARALLEL RENDERING FRAMEWORK

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

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

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

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

The task of parallelizing a visualization application boils down to configuring the application’s rendering code differently for each resource, enabling this rendering code to access the correct data, and synchronizing execution. When multiple GPUs are used to accelerate the rendering of a single output, partial results need to be collected from all contributing resources and combined on the output.

3.1 Rendering Context

3.2 Asynchronous Execution Model

3.3 Compounds

3.4 Load Balancing

3.5 Compositing

3.6 Distribution Layer

C H A P T E R

4

NEW PARALLEL RENDERING MODES

C H A P T E R

5

COMPOSITING OPTIMISATIONS

C H A P T E R

6

NEW LOAD BALANCING ALGORITHMS

C H A P T E R

7

DATA DISTRIBUTION AND SYNCHRONIZATION

C H A P T E R

8

CONCLUSION

8.1 Future Work

BIBLIOGRAPHY

[MPK,] OpenGL Multipipe SDK.

[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 Raf-fin, 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>.
- [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., 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., Glögowski, 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.
- [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.
- [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.
- [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.
- [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.
- [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.
- [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.
- [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.
- [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–.
- [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

Personal Information

Name Fatih Erol
Date of birth XXXXXX XX, 19XX
Place of birth Trabzon, Turkey

Education

Publications

Conference Publications

Journal Articles