Modern Distributed Rendering Systems

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Abstract

We are living in the big data age: An ever increasing amount of data is being produced by users through data acquisition and simulations. While large scale analysis and simulatons 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.

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Zürich, March 15, 2018 Stefan Eilemann

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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.

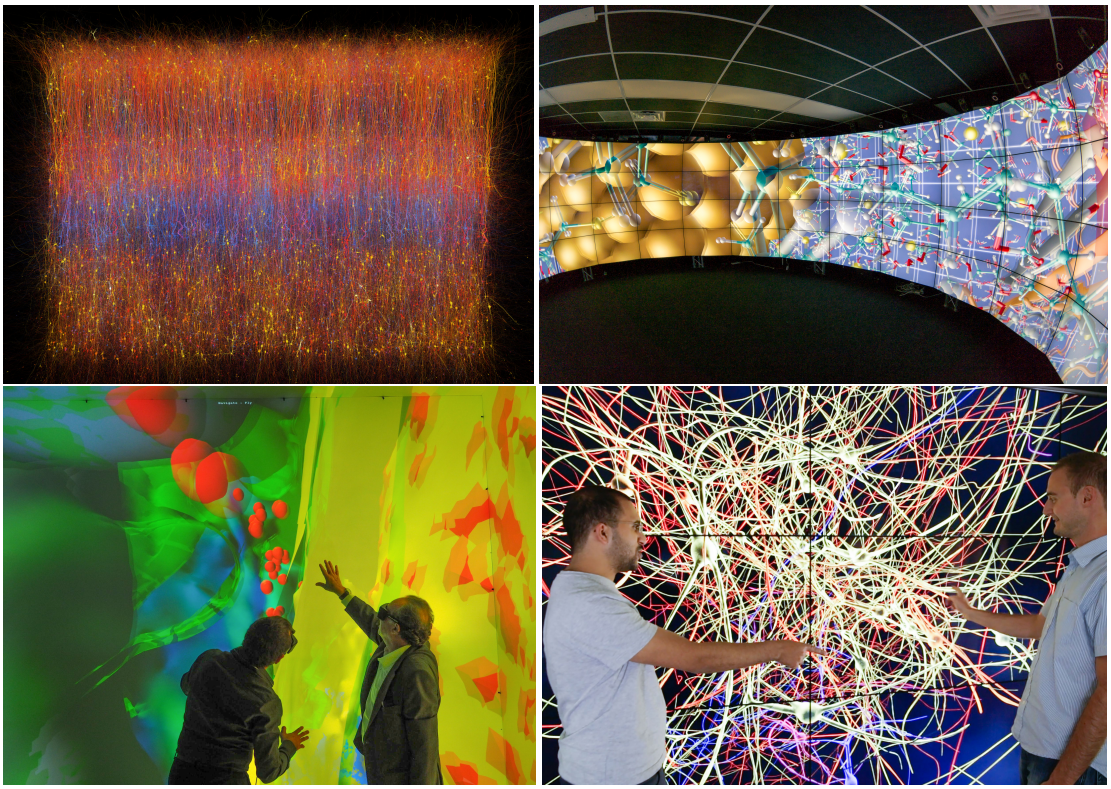

Figure 1 – Large Data Visualization: Large data visualization of a brain simulation, molecular visualization in the Cave[2], exploration of EM stack reconstructions in a Cave, collaborative data analysis on a tiled display wall.

Display technology has made significant progress in the last decade. High-resolution screens and tiled display walls are now affordabe 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 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 development 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 [MCEF94] and [Cro97]. 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 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.

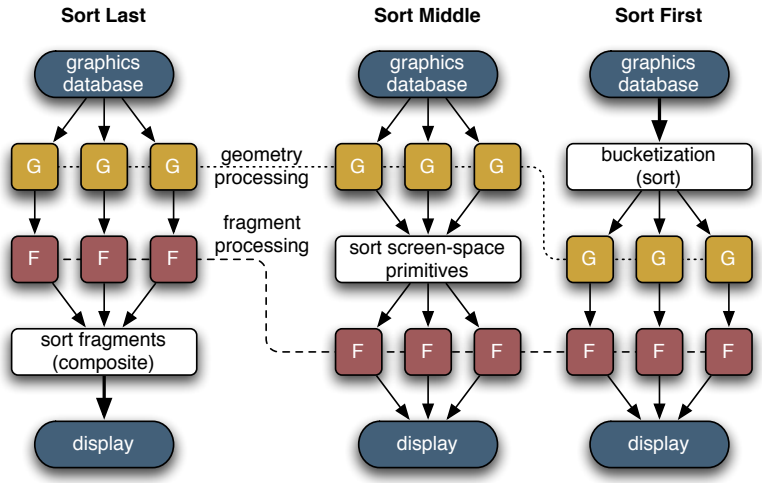

Figure 2 – Sort-last, sort-middle and sort-first parallel rendering

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 [LWMT97, Wit98, HSC+00, SL02, GS02, NSJ+05] or geo-visualization [VR91, AG95, LDC96, JLMVK06]. 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 [NC07], 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 [NC07] 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 [MHS99, Lev04], Sepia 2 [LMS+01a, LMS+01b], Lightning 2 [SEP+01], Metabuffer [BBDZ00, ZBB01], MPC Compositor [MOM+01] and PixelFlow [MEP92, EMP+97], 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 [Mue95, Mue97] (sort-first architecture), [SZF+99, SFLS00] (load balancing), [SFL01] (data replication), or [CMF05, CM06] (scalability). On the other hand, specific algorithms have been developed for cluster based rendering and compositing such as [AP98], [CKS02] and [YYC01, SML+03]. 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 [ISH98].

Only few generic APIs and (cluster-)parallel rendering systems exist which include VR Juggler [BJH+01] (and its derivatives), Chromium [HHN+02] (an evolution of [HH99, HBEH00, HEB+01]), ClusterGL [NHM11] and OpenGL Multipipe SDK [JDB+04, BRE05, MPK]. These approaches can be categorized into transparent interception and distribution of the OpenGL command stream and into the parallization of the application rendering code (Figure 3).

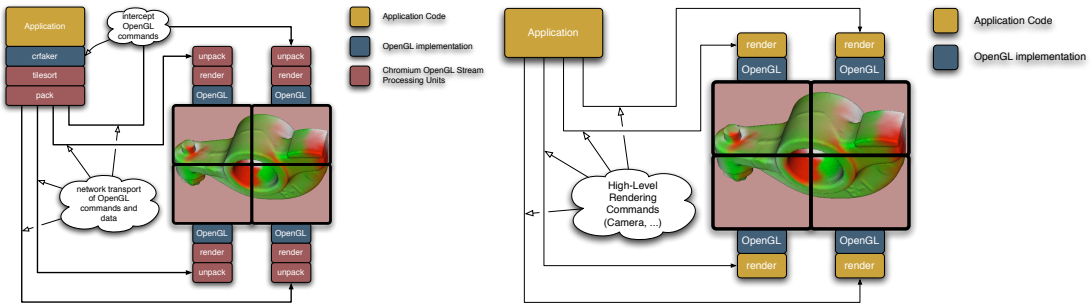

Figure 3 – Transparent OpenGL interception and parallelization of the rendering code

VR Juggler [BJH+01, JBBCN98] 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 [BCN03] and NetJuggler [AGL+02], 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 [SWNH03]. 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 [HHN+02] 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 [SWNH03]. 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 wich 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 [HHN+02] 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 [BHPB03] or the sort-last parallel volume renderer raptor [Hou05]. 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 [NHM11] 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 apporach for some applications since it requires no code changes, but it has inherent limitiations 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 the size of the OpenGL command stream send over the network.

CGLX [DK11] 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) [BRE05] implemented an effective parallel rendering API for a shared memory multi-CPU/GPU system. It is similar to IRIS Performer [RH94] 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 [DLR+09] and Sage 2 [MAN+14] 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 [JAW+12], and its continuation Tide [Blu16], 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

2 Contributions

2.1 Generic Parallel Rendering Framework

2.2 Parallel Rendering Modes

2.3 Load Balancing

2.4 Applications

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.

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