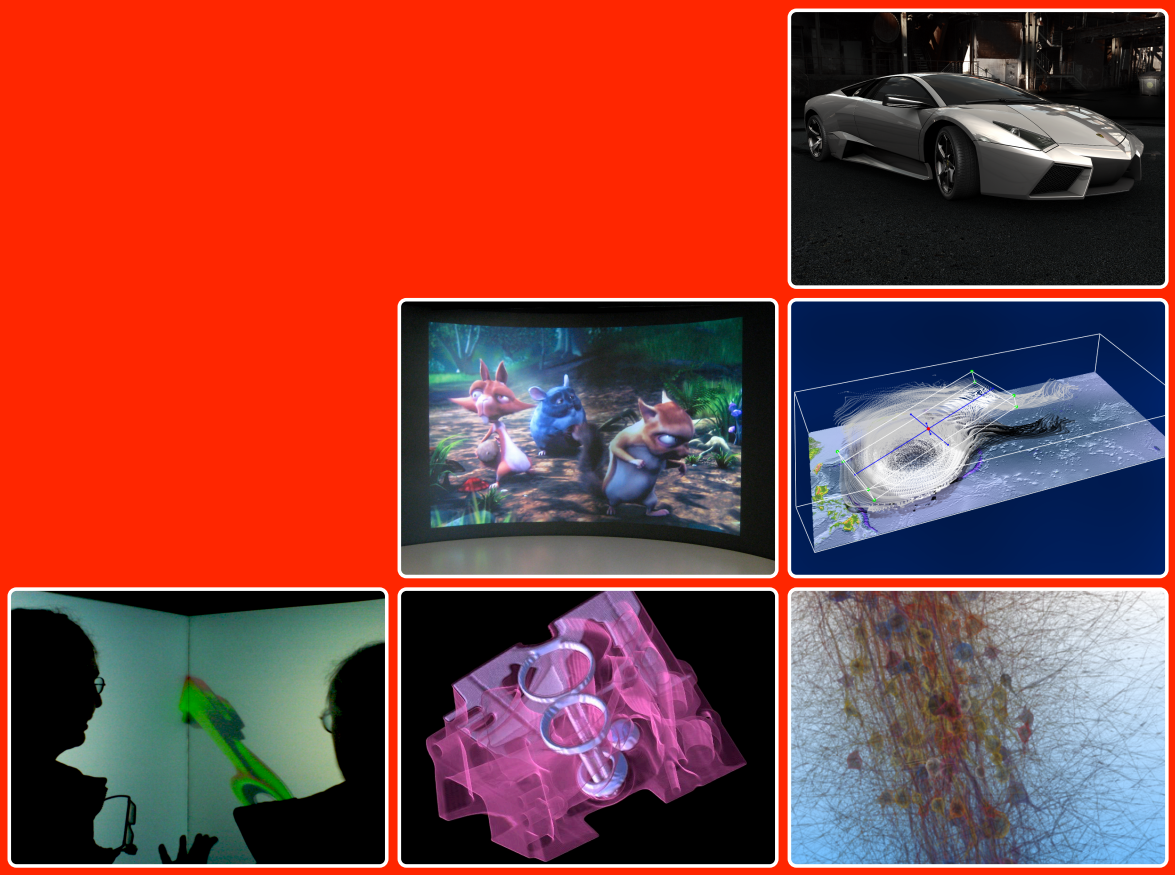
Equalizer
Programming and User Guide

Eyescale Software GmbH



The official reference for developing and deploying parallel, scalable OpenGL™ applications using the Equalizer parallel rendering framework

Version 1.14 for Equalizer 1.6

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Front and Back Page

The images on the front page show the following applications build using Equalizer: RTT DeltaGen[1] [top right], Bino, a stereo-capable, multi-display video player[2] [middle center], a flow visualization application for climate research[3] [middle right], the eqPly polygonal renderer in a three-sided CAVE [bottom left], the eVolve volume renderer[4] [bottom center], and the RTNeuron[5] application to visualize cortical circuit simulations [bottom right].

The images on the back page show the following scalable rendering modes: Subpixel (FSAA) [top left], DPlex [middle left], Pixel [middle center], 2D [bottom left], DB [bottom center] and stereo [bottom right].

[1] Image copyright Realtime Technology AG, 2008
[2] http://bino.nongnu.org/
[3] Image courtesy of Computer Graphics and Multimedia Systems, University of Siegen
[4] Data set courtesy of General Electric, USA
[5] Image courtesy of Cajal Blue Brain / Blue Brain Project

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Revision History

Rev	Date	Changes
1.0	Oct 28, 2007	Initial Version for Equalizer 0.4
1.2	Apr 15, 2008	Revision for Equalizer 0.5
1.4	Nov 25, 2008	Revision for Equalizer 0.6
1.6	Aug 07, 2009	Revision for Equalizer 0.9
1.8	Mar 21, 2011	Revision for Equalizer 1.0
1.10	Feb 17, 2012	Revision for Equalizer 1.2
1.12	Jul 20, 2012	Revision for Equalizer 1.4
1.14	Jul 25, 2013	Revision for Equalizer 1.6

Part I.
User Guide

1. Introduction

Equalizer is the standard middleware for the development and deployment of parallel OpenGL applications. It enables applications to benefit from multiple graphics cards, processors and computers to improve the rendering performance, visual quality and display size. An Equalizer-based application runs unmodified on any visualization system, from a simple workstation to large scale graphics clusters, multi-GPU workstations and Virtual Reality installations.

This User and Programming Guide introduces parallel rendering concepts, the configuration of Equalizer-based applications and programming using the Equalizer parallel rendering framework.

Equalizer is the most advanced middleware for scalable 3D visualization, providing the broadest set of parallel rendering features available in an open source library to any visualization application. Many commercial and open source applications in a variety of different markets rely on Equalizer for flexibility and scalability.

Equalizer provides the domain-specific parallel rendering expertise and abstracts configuration, threading, synchronization, windowing and event handling. It is a 'GLUT on steroids', providing parallel and distributed execution, scalable rendering features, an advanced network library and fully customizable event handling.

If you have any question regarding Equalizer programming, this guide, or other specific problems you encountered, please direct them to the eq-dev mailing list[6].

1.1. Parallel Rendering

Figure 1 illustrates the basic principle of any parallel rendering application. The typical OpenGL application, for example using GLUT, has an event loop which redraws the scene, updates application data based on received events, and eventually renders a new frame.

A parallel rendering application uses the same basic execution model, extending it by separating the rendering code from the main event loop. The rendering code is then executed in parallel on different resources, depending on the configuration chosen at runtime.

This model is naturally followed by Equalizer, thus making application development as easy as possible.

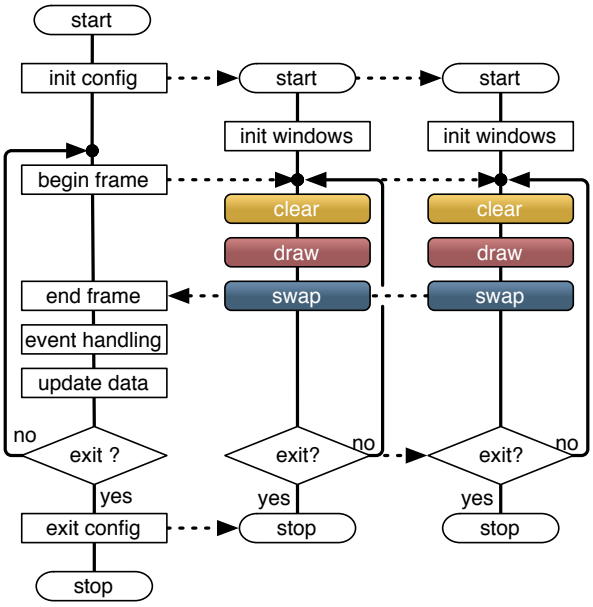


Figure 1: Parallel Rendering

[6] http://www.equalizergraphics.com/lists.html

1.2. Installing Equalizer and Running eqPly

Equalizer can be installed by using a package or building the source code[7]. After installing Equalizer, please take a look at the Quickstart Guide[8] to get familiar with the capabilities of Equalizer and the eqPly example. Currently we provide Ubuntu packages on launchpad[9] and MacPorts portfiles[10].

Equalizer uses Buildyard and cmake to generate platform-specific build files. Compiling Equalizer from source consist of cloning Buildyard, the Eyescale configurations and then building Equalizer:

```
git clone https://github.com/Eyescale/Buildyard.git
cd Buildyard
git clone https://github.com/Eyescale/config.git config.eyescale
make Equalizer
```

The Windows build is similar, except that CMake will generate a Visual Studio solution which is used to build Equalizer.

1.3. Equalizer Processes

The Equalizer architecture is based on a client-server model. The client library exposes all functionality discussed in this document to the programmer, and provides communication between the different Equalizer processes.

Collage is a cross-platform C++ library for building heterogeneous, distributed applications. Collage provides an abstraction of different network connections, peer-to-peer messaging, discovery and synchronization as well as high-performance, object-oriented, versioned data distribution. Collage is designed for low-overhead multi-threaded execution which allows applications to easily exploit multi-core architectures. Equalizer uses Collage as the cluster backend, e.g., by setting up direct communication between two nodes when needed for image compositing or software swap barriers.

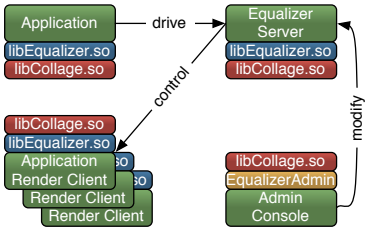


Figure 2: Equalizer Processes

Figure 2 depicts the relationship between the server, application, render client and administrative processes, which are explained below.

1.3.1. Server

The Equalizer server is responsible for managing one visualization session on a shared memory system or graphics cluster. Based on its configuration and controlling input from the application, it computes the active resources, updates the configuration and generates tasks for all processes. Furthermore it controls and launches the application's rendering client processes. The Equalizer server is the entity in charge of the configuration, and all other processes receive their configuration from the server. It typically runs as a separate entity within separate threads in the application process.

[7] http://www.equalizergraphics.com/downloads.html
[8] http://www.equalizergraphics.com/documents/EqualizerGuide.html
[9] https://launchpad.net/ eilemann/+archive/equalizer
[10] https://github.com/Eyescale/portfiles

1.3.2. Application

The application connects to an Equalizer server and receives a configuration. Furthermore, the application also provides its render client, which will be controlled by the server. The application and render client may use the same executable. The application has a main loop, which reacts on events, updates its data and controls the rendering.

1.3.3. Render Clients

The render client implements the rendering part of an application. Its execution is passive, it has no main loop and is completely driven by Equalizer server. It executes the rendering tasks received from the server by the calling the appropriate task methods (see Section 5.3) in the correct thread and context. The application either implements the task methods with application-specific code or uses the default methods provided by Equalizer.

The application can also be a rendering client, in which case it can also contribute to the rendering. If it does not implement any render client code, it is reduced to be the application's 'master' process without any OpenGL windows and 3D rendering.

The rendering client can be the same executable as the application, as it is the case with all provided examples. When it is started as a render client, the Equalizer initialization routine does not return and takes over the control by calling the render client task methods. Complex applications usually implement a separate, lightweight rendering client.

1.3.4. Administration Programs

Equalizer 1.0 introduced the admin library, which can be used to modify a running Equalizer server. The admin library is still in development, but already allows limited modifications such as adding new windows and changing layouts. The admin library may be used to create standalone administration tools or from within the application code. In any case, it has an independent view of the server's configuration. Documentation for admin library is not yet part of this Programming and User Guide.

2. Scalable Rendering

Scalable rendering is a subset of parallel rendering, where more multiple resources are used to update a view.

Real-time visualization is an inherently parallel problem. Different applications have different rendering algorithms, which require different scalable rendering modes to address the bottlenecks correctly. Equalizer supports all important algorithms as listed below, and will continue to add new ones over time to meet application requirements.

This section gives an introduction to scalable rendering, providing some background for end users and application developers. The scalability modes offered by Equalizer are discussed, along with their advantages and disadvantages.

Choosing the right mode for the application profile is critical for performance. Equalizer uses the concept of compounds to describe the task decomposition and result recomposition. It allows the combination of the different compound modes in any possible way, which allows to address different bottlenecks in a flexible way.

2.1. 2D or Sort-First Compounds

2D decomposes the rendering in screen-space, that is, each contributing rendering unit processes a tile of the final view. The recomposition simply assembles the tiles side-by-side on the destination view. This mode is also known as sort-first or SFR.

The advantage of this mode is a low, constant IO overhead for the pixel transfers, since only color information has to be transmitted. The upper limit is the amount of pixel data for the destination view.

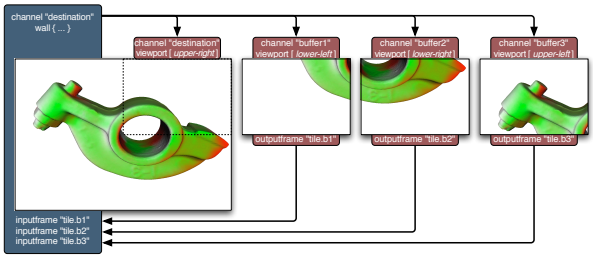


Figure 3: 2D Compound

Its disadvantage is that it relies on view frustum culling to reduce the amount of data submitted for rendering. Depending on the application data structure, the overlap of some primitives between individual tiles limits the scalability of this mode, typically to around eight graphics cards. Each node has to potentially hold the full database for rendering.

2D decompositions can be used by all types of applications, but should be combined with DB compounds to reduce the data per node, if possible. In most cases, a load_equalizer should be used to automatically adjust the tiling each frame, based on the current rendering load.

2D compounds in Equalizer are configured using the viewport parameter, using the values [x y width height] in normalized coordinates. The viewport defines the area of the parent (destination) channel to be rendered for each child. Each child compound uses an output frame, which is connected to an input frame on the destination channel. The destination channel can also be used as a source channel, in which case it renders in place and no output frame is needed.

2.2. DB or Sort-Last Compounds

DB, as shown in Figure 4[11], decomposes the rendered database so that all rendering units process a part of the scene in parallel. This mode is also known as sort-last, and is very similar to the data decomposition approach used by HPC applications.

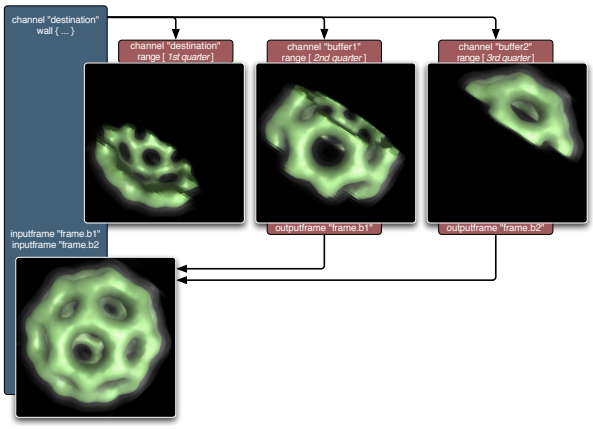


Figure 4: Database Compound

Volume rendering applications use an ordered alpha-based blending to composite the result image. The depth buffer information is used to composite the individual images correctly for polygonal data.

This mode provides very good scalability, since each rendering unit processes only a part of the database.

[11] 3D model courtesy of AVS, USA.

This allows to lower the requirements on all parts of the rendering pipeline: main memory usage, IO bandwidth, GPU memory usage, vertex processing and fill rate.

Unfortunately, the database recomposition has linear increasing IO requirements for the pixel transfer. Parallel compositing algorithms, such as direct-send, address this problem by keeping the per-node IO constant (see Figure 51).

The application has to partition the database so that the rendering units render only part of the database. Some OpenGL features do not work correctly (anti-aliasing) or need special attention (transparency, shadows).

The best use of database compounds is to divide the data to a manageable size, and then to use other decomposition modes to achieve further scalability. Volume rendering is one of the applications which can profit from database compounds.

DB compounds in Equalizer are configured using the range parameter, using the values [begin end] in normalized coordinates. The range defines the start and end point of the application's database to be rendered. The value has to be interpreted by the application's rendering code accordingly. Each child compound uses an output frame, which is connected to an input frame on the destination channel. For more than two contributing channels, it is recommended to configure streaming or parallel direct send compositing, as described in Section 7.2.9.

2.3. Stereo Compounds

Stereo compounds, as shown in Figure 5[12], assign each eye pass to individual rendering units. The resulting images are copied to the appropriate stereo buffer. This mode supports a variety of stereo modes, including active (quad-buffered) stereo, anaglyphic stereo and auto-stereo displays with multiple eye passes.

Due to the frame consistency between the eye views, this modes scales very well. The IO requirements for pixel transfer are small and constant. The number of rendering resources used by stereo compounds is limited by the number of eye passes, typically two.

Stereo compounds are used by all applications when rendering in stereo, and is often combined with other modes.

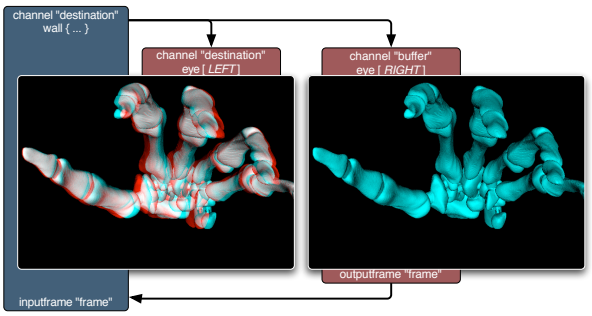


Figure 5: Stereo Compound

Eye compounds in Equalizer are configured using the eye parameter, limiting the child to render the [LEFT] or [RIGHT] eye. Each child compound uses an output frame, which is connected to an input frame on the destination channel. The destination channel can also be used to render an eye pass, in which case it renders in the correct stereo buffer and no output frame is needed.

2.4. DPlex Compounds

DPlex compounds assign full, alternating frames to individual rendering units. The resulting images are copied to the destination channel, and Equalizer load-balancing is used to ensure a steady framerate on the destination window. This mode is also known as time-multiplex or AFR.

[12] 3D model courtesy of Stereolithography Archive at Clemson University.

Due to the frame consistency between consecutive frames, this mode scales very well. The IO requirements for pixel transfer are small and constant.

DPlex requires a latency of at least n frames. This increased latency might be disturbing to the user, but it is often compensated by the higher frame rate. The frame rate typically increases linearly with the number of source channels, and therefore linearly with the latency.

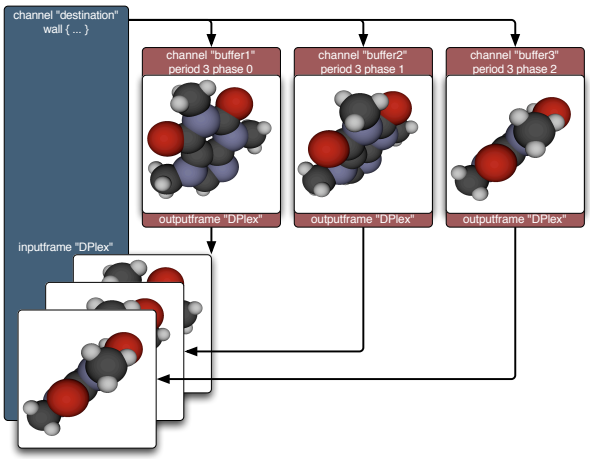


Figure 6: A DPlex Compound

DPlex compounds in Equalizer are configured using the period and phase parameter, limiting each child to render a subset of the frames. Each child compound uses an output frame, which is connected to an input frame on the destination channel. The destination channel uses a framerate_equalizer to smoothen the framerate.

2.5. Tile Compounds

Tile compounds are similar to 2D compounds. They decompose the rendering in screen-space, where each rendering unit pulls and processes regular tiles of the final view. Tile compounds are ideal for purely fill-limited applications such as volume rendering and raytracing.

Tile compounds have a low, constant IO overhead for the image transfers and can provide good scalability when used with fill-limited applications. Tile decomposition works transparently for all Equalizer-based applications.

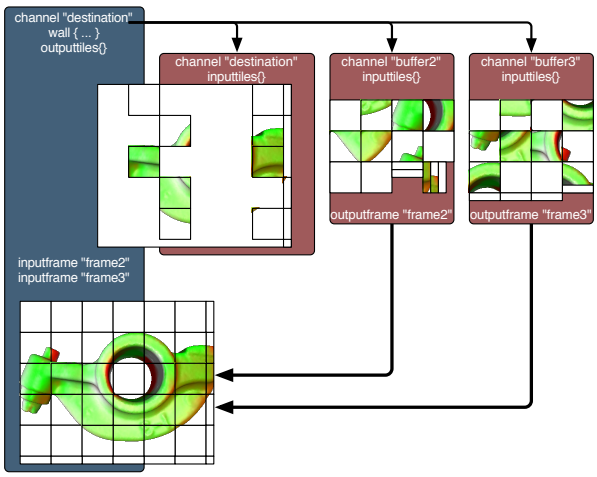


Figure 7: Tile Compound

Contrary to all other compounds, the work distribution is not decided before-hand using a push model, but each resource pulls work from a central work queue, until all tiles have been processed. Therefore the rendering is naturally load-balanced since all sources pull data on an as-needed basis. The queue implementation uses prefetching to hide the communication overhead of the central, distributed tile queue.

2.6. Pixel Compounds

Pixel compounds are similar to 2D compounds. While 2D compounds decompose the screen space into contiguous regions, pixel compounds assign one pixel of a regular kernel to each resource. The frusta of the source rendering units are modified so that each unit renders an evenly distributed subset of pixels, as shown in Figure 8[13]

As 2D compounds, pixel compounds have low, constant IO requirements for the pixel transfers during recomposition. They are naturally load-balanced for fill-limited operations, but do not scale geometry processing at all.

OpenGL functionality influenced by the raster position will not work correctly with pixel compounds, or needs at least special attention. Among them are: lines, points, sprites, glDrawPixels, glBitmap, glPolygonStipple. The application can query the current pixel parameters at runtime to adjust the rendering accordingly.

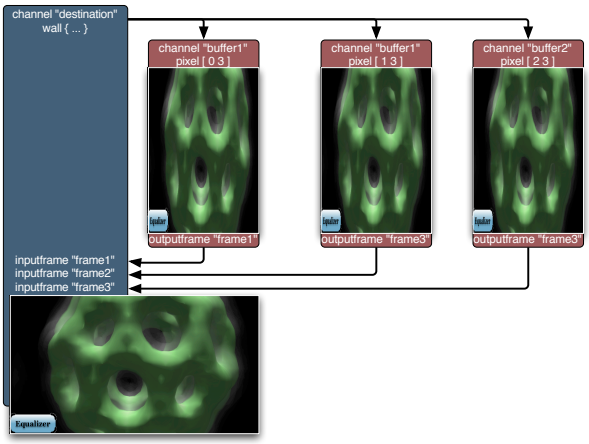


Figure 8: Pixel Compound

Pixel compounds work well for purely fill-limited applications. Techniques like view frustum culling do not reduce the rendered data, since each resource has approximately the same frustum. Pixel compounds are ideal for ray-tracing, which is highly fill-limited and needs the full database for rendering anyway. Volume rendering applications are also well suited for this mode, and should choose it over 2D compounds.

Pixel compounds in Equalizer are configured using the pixel parameter, using the values [x y width height] to configure the size and offset of the sampling kernel. The width and height of the sampling kernel define how many pixels are skipped in the x and y direction, respectively. The x and y offset define the index of the source channel within the kernel. They have to be smaller than the size of the kernel. Figure 9 illustrates these parameters, and Figure 10 shows some example kernels for a four-to-one pixel decomposition.

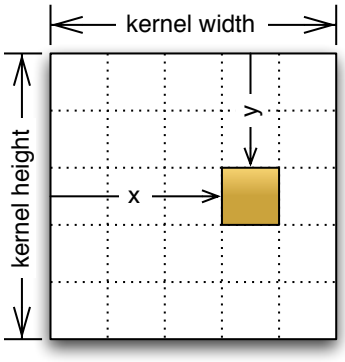


Figure 9: Pixel Compound Kernel

The destination channel can also be used as a source channel. Contrary to the other compound modes, it also has to use an output and corresponding input frame. During rendering, the frustum is 'squeezed' to configure the pixel decomposition. The destination channel can therefore not be rendered in place, like with the other compound modes.

[13] 3D model courtesy of AVS, USA.

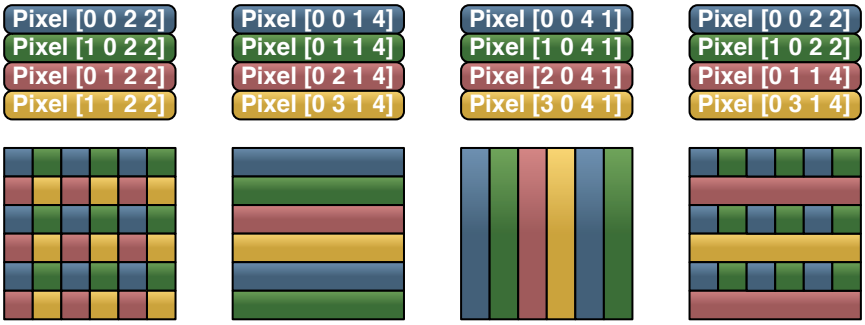


Figure 10: Example Pixel Kernels for a four-to-one Pixel Compound

2.7. Subpixel Compounds

Subpixel decomposes the rendering of multiple samples for one pixel, e.g., for anti-aliasing or depth-of-field rendering. The default implementation provides transparent, scalable software idle-antialiasing when configuring a subpixel compound.

Applications can use subpixel compounds to accelerate depth-of-field effects and software anti-aliasing, with potentially a different number of idle or non-idle samples per pixel.

As for the DB compound, the subpixel recomposition has linear increasing IO requirements for the pixel transfer, with the difference that only color information has to be transmitted.

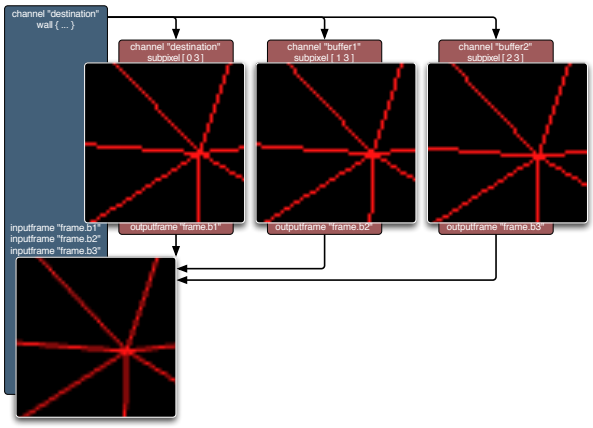


Figure 11: Subpixel Compound

Subpixel compounds are configured using the subpixel parameter, using the values [index size]. The index parameter corresponds to the current resource index and the size is the total number of resources used.

The index has to be smaller than the size. Figure 11 illustrates a three-way subpixel decomposition.

The destination channel can also be used as a source channel. As for the pixel compound, it has to use an output and corresponding input frame.

2.8. Automatic Runtime Adjustments

Some scalable rendering parameters are updated at runtime to provide optimal performance or influence other scalable rendering features. These adjustments are often referred to as load-balancing, but are called equalizers, since their functionality is not limited to load-balancing in Equalizer.

The server provides a number of equalizers, which automatically update certain parameters of compounds based on runtime information. They balance the load of 2D and DB compounds, optimally distribute render resources for multi-display

projection systems, adjust the resolution to provide a constant framerate or zoom images to allow monitoring of another view.

Equalizers are described in more detail in Section 3.11.8.

3. Configuring Equalizer Clusters

3.1. Auto-Configuration

3.1.1. Hardware Service Discovery

Equalizer uses the hwsd library for discovering local and remote GPUs as well as network interfaces. Based on this information, a typical configuration is dynamically compiled during the initialization of the application. The auto-configuration uses the same format as the static configuration files. It can be used to create template configurations by running a test application or the eqServer binary and using the generated configuration, saved as <session>.auto.eqc.

Please note that both hwsd and the hwsd ZeroConf module are optional and require hwsd and a ZeroConf implementation when Equalizer is compiled.

hwsd contains three components: a core library, local and remote discovery modules as well as a ZeroConf daemon. The daemon uses the appropriate module to query local GPUs and network interfaces to announce them using ZeroConf on the local network.

Equalizer uses the library with the dns_sd discovery module to gather the information announced by all daemons on the local network, as well as the local discovery modules for standalone auto-configuration. The default configuration is using all locally discovered GPUs and network interfaces.

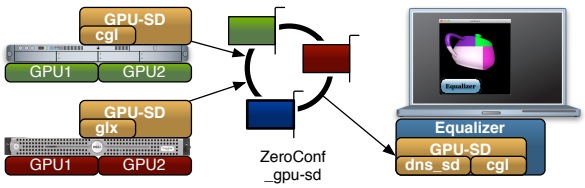


Figure 12: GPU discovery for auto-configuration

Figure 12 shows how hwsd is used to discover four remote GPUs on two different machines to use them to render a single view on a laptop.

3.1.2. Usage

On each node contributing to the configuration, install and start the hwsd daemon. If multiple, disjoint configurations are used on the same network, provide the session name as a parameter when starting the daemon. Verify that all GPUs and network interfaces are visible on the application host using the hw_sd_list tool. When starting the application, use the command-line parameter –eq-config:

- The default value is local which uses all local GPUs and network interfaces queried using the cgl, glx, or wgl GPU modules and the sys network module.
- –eq-config sessionname uses the dns_sd ZeroConf module of hwsd to query all GPUs and network interfaces in the subnet for the given session. The default session of the hwsd daemon is default. The found network interfaces are used to connect the nodes.
- –eq-config filename.eqc loads a static configuration from the given ASCII file. The following sections describe how to write configuration files.

The auto-configuration creates one display window on the local machine, and one off-screen channel for each GPU. The display window has one full-window channel used as an output channel for a single segment. It combines all GPUs into a scalability config with different layouts for each of the following scalability modes:

2D A dynamically load-balanced sort-first configuration using all GPUs as sources.

Simple A no-scalability configuration using only the display GPU for rendering.

Static DB A static sort-last configuration distributing the range evenly across all GPUs.

Dynamic DB A dynamically load-balanced sort-last configuration using all GPUs as sources.

DB Direct Send A direct send sort-last configuration using all GPUs as sources.

DB 2D A direct send sort-last configuration using all nodes together with a dynamically load-balanced sort-first configuration using local GPUs.

All suitable network interfaces are used to configure the nodes, that is, the launch command has to be able to resolve one hostname for starting the render client processes. Suitable interfaces have to be up and match optional given values which can be specified by the following command-line parameters:

–eq-config-flags <ethernet|infiniband> Limit the selection of network interfaces to one of those types.

–eq-config-prefixes <CIDR-prefixes> Limit the selection of network interfaces that match the given prefix.

3.2. Preparation

Before writing a configuration, it is useful to assemble the following information:

- A list of all **computers** in your rendering cluster, including the **IP addresses** of all network interfaces to be used.
- The number of **graphics cards** in each computer.
- The **physical dimensions** of the display system, if applicable. These are typically the bottom-left, bottom-right and top-left corner points of each display surface in meters.
- The relative coordinates of all the **segments** belonging to each display surface, and the graphics card **output** used for each segment. For homogeneous setups, it is often enough to know the number of rows and columns on each surface, as well as the overlap or underlap percentage, if applicable.
- The number of desired **application windows**. Application windows are typically destination windows for scalable rendering or 'control' windows paired with a view on a display system.
- **Characteristics** of the application, e.g., supported scalability modes and features.

3.3. Summary

Equalizer applications are configured at runtime by the Equalizer server. The server loads its configuration from a text file, which is a one-to-one representation of the configuration data structures at runtime.

For an extensive documentation of the file format please refer to Appendix B. This section gives an introduction on how to write configuration files.

A configuration consists of the declaration of the rendering resources, the description of the physical layout of the projection system, logical layouts on the projection canvases and an optional decomposition description using the aforementioned resources.

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, channels.

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

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

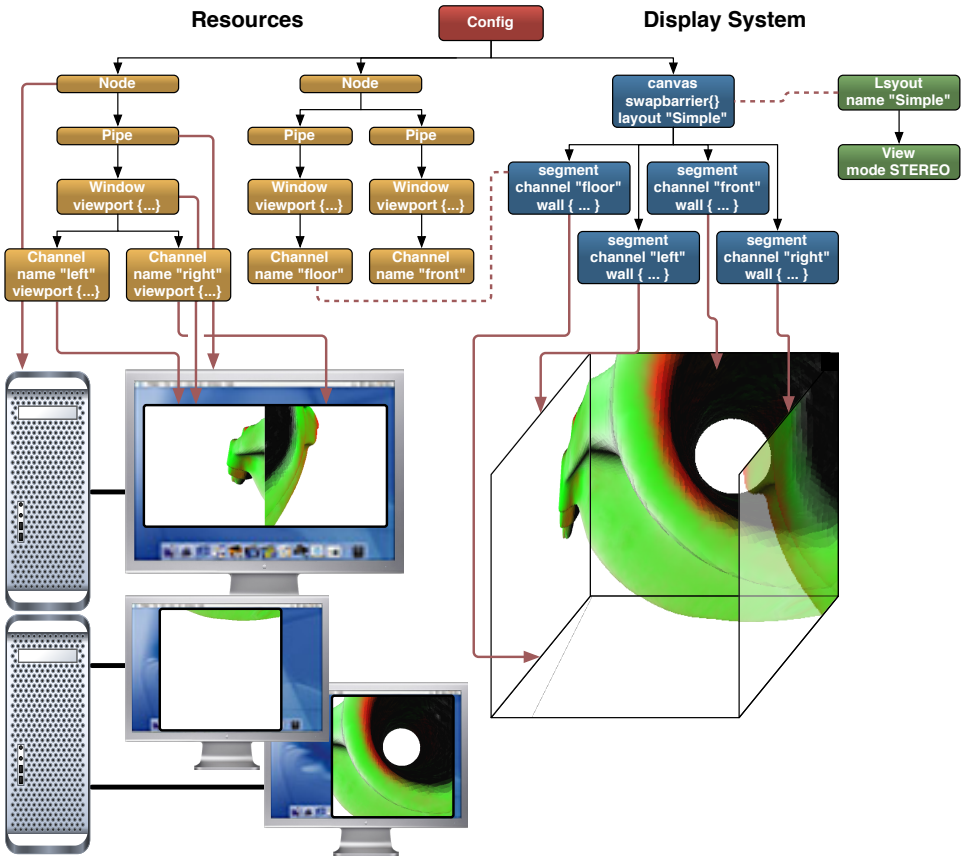


Figure 13: An Example Configuration

Figure 13 shows an example configuration for a four-side CAVE, running on two machines (nodes) using three graphics cards (pipes) with one window each to render to the four output channels connected to the projectors for each of the walls.

For testing and development purposes it is possible to use multiple instances for one resource, e.g. to run multiple render client nodes on one computer. For optimal performance during deployment, one node and pipe should be used for each computer and graphics card, respectively.

3.4. Node

For each machine in your cluster, create one node. Create one appNode for your application process. List all nodes, even if you are not planning to use them at first. Equalizer will only instantiate and access used nodes, that is, nodes which are referenced by an active compound.

In each node, list all connections through which this node is reachable. Typically a node uses only one connection, but it is possible to configure multiple connections if the machine and cluster is set up to use multiple, independent network interfaces. Make sure the configured hostname is reachable from all nodes. An IP address may be used as the hostname.

For cluster configurations with multiple nodes, configure at least one connection for the server. All render clients connect back to the server, for which this connection is needed.

The eq::Node class is the representation of a single computer in a cluster. One operating system process of the render client 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 application thread.

3.5. Pipe

For each node, create one pipe for each graphics card in the machine. Set the device number to the correct index. On operating systems using X11, e.g., Linux, also set the port number if your X-Server is running on a nonstandard port.

The eq::Pipe class is the abstraction of a graphics card (GPU), and uses one independent operating system thread for rendering. Non-threaded pipes are supported for integrating with thread-unsafe libraries, but have various performance caveats. They should only be used if using a different, synchronized rendering thread is not an option.

All pipe, window and channel task methods are executed from the pipe thread, or in the case of non-threaded pipes from the main application thread[14].

3.6. Window

Configure one window for each desired application window on the appNode. Configure one full-screen window for each display segment. Configure one off-screen window, typically a pbuffer, for each graphics card used as a source for scalable rendering. Provide a useful name to each on-screen window if you want to easily identify it at runtime.

Sometimes display segments cover only a part of the graphics card output. In this case it is advised to configure a non-fullscreen window without window decorations, using the correct window viewport.

The eq::Window class encapsulates a drawable and an OpenGL context. The drawable can be an on-screen window or an off-screen pbuffer or framebuffer object (FBO).

[14] see http://www.equalizergraphics.com/documents/design/nonthreaded.html

3.7. Channel

Configure one channel for each desired rendering area in each window. Typically one full-screen channel per window is used. Name the channel using a unique, easily identifiable name, e.g., 'source-1', 'control-2' or 'segment-2_3'.

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. In this case configure one channel for each segment, using the channel's viewport to configure its position relative to the window.

The eq::Channel class is the abstraction of an OpenGL viewport within its parent window. It is the entity executing the actual rendering. The channel's viewport is overwritten when it is rendering for another channel during scalable rendering.

3.8. Canvases

If you are writing a configuration for workstation usage you can skip the following sections and restart with Section 3.11.

Configure one canvas for each display surface. For planar surfaces, e.g., a display wall, configure a frustum. For non-planar surfaces, the frustum will be configured on each display segment.

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

Figure 14 illustrates the wall and projection frustum parameters.

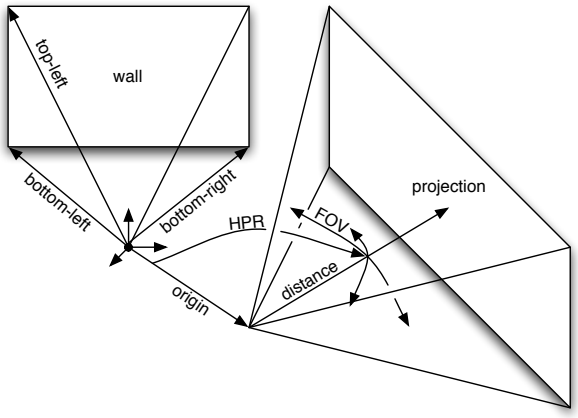


Figure 14: Wall and Projection Parameters

A canvas represents one physical projection surface, e.g., a PowerWall, a curved screen or an immersive installation. One configuration might drive multiple canvases, for example an immersive installation and an operator station.

A canvas consists of one or more segments. A planar canvas typically has a frustum description (see Section 3.11.3), which is inherited by the segments. Non-planar frusta are configured using the segment frusta. These frusta typically describe a physically correct display setup for Virtual Reality installations.

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

A canvas may have a swap barrier, which is used as the default swap barrier by all its segments to synchronize the video output.

Canvases provide a convenient way to configure projection surfaces. A canvas uses layouts, which describe logical views. Typically, each desktop window uses one canvas, one segment, one layout and one view.

3.8.1. Segments

Configure one segment for each display or projector of each canvas. Configure the viewport of the segment to match the area covered by the segment on the physical canvas. Set the output channel to the resource driving the described projector.

For non-planar displays, configure the frustum as described in Section 3.8. For passive stereo installations, configure one segment per eye pass, where the segment for the left and right eye have the same viewport. Set the eyes displayed by the segment, i.e., left or right and potentially cyclop.

To synchronize the video output, configure either a canvas swap barrier or a swap barrier on each segment to be synchronized.

When using software swap synchronization, swap-lock all segments using a swap barrier. All windows with a swap barrier of the same name synchronize their swap-buffers. Software swap synchronization uses a distributed barrier, and works on all hardware.

When using hardware swap synchronization, use swap barriers for all segment to be synchronized, setting NV_group and NV_barrier appropriately. The swap barrier name is ignored in this case. All windows of the same group on a single node synchronize their swap buffer. All groups of the same barrier synchronize their swap buffer across nodes. Please note that the driver typically limits the number of groups and barriers to one, and that multiple windows per swap group are not supported by all drivers. Hardware swap barriers require support from the OpenGL driver, and has been tested on NVIDIA Quadro GPUs with the G-Sync option. Please refer to your OpenGL driver documentation for details.

A segment represents one output channel of the canvas, e.g., a projector or an LCD. A segment has an output channel, which references the channel to which the display device is connected.

A segment covers a part of its parent canvas, which is configured using the segment viewport. The viewport is in normalized coordinates relative to the canvas. Segments might overlap (edge-blended projectors) or have gaps between each other (display walls, Figure 15[15]). The viewport is used to configure the segment's default frustum from the canvas frustum description, and to place layout views correctly.

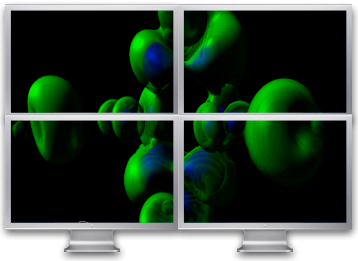


Figure 15: A Canvas using four Segments

3.8.2. Swap and Frame Synchronization

Canvases and segments may have a software or hardware swap barrier to synchronize the buffer swap of multiple channels. The swap barriers are inherited from the canvas to the segment ultimately to all compounds using a destination channel of the segment.

A software swap barrier is configured by giving it a name. Windows with a swap barrier of the same name synchronize with each other before executing the swap buffer task. Before entering the barrier, Window::finish is called to ensure that all OpenGL commands have been executed. Swap barrier names are only valid

[15]Dataset courtesy of VolVis distribution of SUNY Stony Brook, NY, USA.

within the compound tree, that is, a compound from one compound tree cannot be synchronized with a compound from another compound tree.

A hardware swap barrier uses a hardware component to synchronize the buffer swap of multiple windows. It guarantees that the swap happens at the same vertical retrace of all corresponding video outputs. It is configured by setting the NV_group and NV_barrier parameters. These parameters follow the NV_swap_group extension, which synchronizes all windows bound to the same group on a single machine, and all groups bound to the same barrier across systems.

Display synchronization uses different algorithms. Framelock synchronizes each vertical retrace of multiple graphic outputs using a hardware component. This is configured in the driver, independently of the application. Genlock synchronizes each horizontal and vertical retrace of multiple graphic outputs, but is not commonly used anymore for 3D graphics. Swap lock synchronizes the front and back buffer swap of multiple windows, either using a software solution based on network communication or a hardware solution based on a physical cable. It is independent of, but often used in conjunction with framelock.

Framelock is used to synchronize the vertical retrace in multi-display active stereo installations, e.g., for edge-blended projection systems or immersive installations. It is combined with a software or hardware swap barrier. Software barriers in this case cannot guarantee that the buffer swap of all outputs always happens with the same retrace. The time window for an output to miss the retrace for the buffer swap is however very small, and the output will simply swap on the next retrace, typically in 16 milliseconds.

Display walls made out of LCDs, monoscopic or passive stereo projection systems often only use a software swap barrier and no framelock. The display bezels make it very hard to notice the missing synchronization.

3.9. Layouts

Configure one layout for each configuration of logical views. Name the layout using a unique name. Often only one layout with a one view is used for all canvases.

Enable the layout on each desired canvas by adding it to the canvas. Since canvases reference layouts by name or index, layouts have to be configured before their respective canvases in the configuration file.

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 can be 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.

3.9.1. Views

Configure one view for each logical view in each layout. Set the viewport to position the view. Set the mode to stereo if appropriate.

A view is a logical view of the application data, in the sense used by the Model-View-Controller pattern. It can be a scene, viewing mode, viewing position, or any other representation of the application's data.

A view has a fractional viewport relative to its layout. A layout is often fully covered by its views, but this is not a requirement.

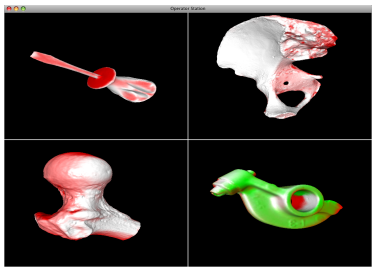


Figure 16: Layout with four Views

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 16 shows an example layout using four views on a single segment. Figure 3.9.1 shows a real-world setup of a single canvas with six segments using underlap, with a two-view layout activated. This configuration generates eight destination channels.

Figure 17: Display Wall using a six-Segment Canvas with a two-View Layout

3.10. Observers

Unless you have multiple tracked persons, or want to disable tracking on certain views, you can skip this section.

Configure one observer for each tracked person in the configuration. Most configurations have at most one observer. Assign the observer to all views which belong to this observer. Since the observer is referenced by its name or index, it has to be specified before the layout in the configuration file.

Views with no observer are not tracked. The config file loader will create one default observer and assign it to all views if the configuration has no observer.

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.

3.11. Compounds

Compound trees are used to describe how multiple rendering resources are combined to produce the desired output, especially how multiple GPUs are aggregated to increase the performance.

It is advised to study and understand the basic configuration files shipped with the Equalizer configuration, before attempting to write compound configurations. The auto-configuration code and command line program configTool, shipped with the Equalizer distribution, creates some standard configurations automatically. These are typically used as templates for custom configuration files.

For configurations using canvases and layouts without scalability, the configuration file loader will create the appropriate compounds. It is typically not necessary to write compounds for this use case.

The following subsection outlines the basic approach to writing compounds. The remaining subsections provide an in-depth explanation of the compound structure to give the necessary background for compound configuration.

3.11.1. Writing Compounds

The following steps are typically taken when writing compound configurations:

Root compound Define an empty top-level compound when synchronizing multiple destination views. Multiple destination views are used for multi-display systems, e.g., a PowerWall or CAVE. All windows used for one display surface should be swap-locked (see below) to provide a seamless image. A single destination view is typically used for providing scalability to a single workstation window.

Destination compound(s) Define one compound for each destination channel, either as a child of the empty group, or as a top-level compound. Set the destination channel by using the canvas, segment, layout and view name or index. The compound frustum will be calculated automatically based on the segment or view frustum. Note that one segment may created multiple view/segment channels, one for each view intersection of each layout used on the canvas. Only the compounds belonging to the active layout of a canvas are active at runtime.

Scalability If desired, define scalability for each of your destination compounds. Add one compound using a source channel for each contributor to the rendering. The destination channel may also be used as a source.

- **Decomposition** On each child compound, limit the rendering task of that child by setting the viewport, range, period and phase, pixel, subpixel, eye or zoom as desired.
- **Runtime Adjustments** A load_equalizer may be used on the destination compounds to set the viewport or range of all children each frame, based on the current load. A view_equalizer may be used on the root compound to assign resources to all destination compounds, which have to use load_equalizers. A framerate_equalizer should be used to smoothen the framerate of DPlex compounds. A DFR_equalizer may be used to set the zoom of a compound to achieve a constant framerate. One compound may have multiple equalizers, e.g., a load_equalizer and a DFR_equalizer for a 2D compound with a constant framerate.
- **Recomposition** For each source compound, define an output_frame to read back the result. Use this output frame as an input_frame on the destination compound. The frames are connected with each other by their name, which has to be unique within the root compound tree. For parallel compositing, describe your algorithm by defining multiple input and output frames across all source compounds.

3.11.2. Compound Channels

Each compound has a channel, which is used by the compound to execute the rendering tasks. One channel might be used by multiple compounds. Compounds are only active if their corresponding destination channel is active, that is, if the parent layout of the view which created the destination channel is active on at least one canvas.

Unused channels, windows, pipes and nodes are not instantiated during initialization. Switching an active layout may cause rendering resources to be stopped and started. The rendering tasks for the channels are computed by the server and send to the appropriate render client nodes at the beginning of each frame.

3.11.3. Frustum

Compounds have a frustum description to define the physical layout of the display environment. The frustum specification is described in Section 3.8. The frustum description is inherited by the children, therefore the frustum is defined on the topmost compound, typically by the corresponding segment.

3.11.4. Compound Classification

The channels of the leaf compounds in the compound tree are designated as source channels. The topmost channel in the tree is the destination channel. One compound tree might have multiple destination channels, e.g., for a swap-synchronized immersive installation.

All channels in a compound tree work for the destination channel. The destination channel defines the 2D pixel viewport rendered by all leaf compounds. The destination channel and pixel viewport cannot be overridden by child compounds.

3.11.5. Tasks

Compounds execute a number of tasks: clear, draw, assemble and readback. By default, a leaf compound executes all tasks and a non-leaf compound assemble and readback. A non-leaf compound will never execute the draw task.

A compound can be configured to execute a specific set of tasks, for example to configure the multiple steps used by binary-swap compositing.

3.11.6. Decomposition - Attributes

Compounds have attributes which configure the decomposition of the destination channel's rendering, which is defined by the viewport, frustum and database. A viewport decomposes the destination channel and frustum in screen space. A range tells the application to render a part of its database, and an eye rendering pass can selectively render different stereo passes. A pixel parameter adjusts the frustum so that the source channel renders an even subset of the parent's pixels. A subpixel parameter tells the source channels to render different samples for one pixel to perform anti-aliasing or depth-of-field rendering. Setting one or multiple attributes causes the parent's view to be decomposed accordingly. Attributes are cumulative, that is, intermediate compound attributes affect and therefore decompose the rendering of all their children.

3.11.7. Recomposition - Frames

Compounds use output and input frames to configure the recomposition of the resulting pixel data from the source channels. An output frame connects to an input frame of the same name. The selected frame buffer data is transported from the

output channel to the input channel. The assembly routine of the input channel will block on the availability of the output frame. This composition process is extensively described in Section 7.2.9. Frame names are only valid within the compound tree, that is, an output frame from one compound tree cannot be used as an input frame of another compound tree.

3.11.8. Adjustments - Equalizers

Equalizers are used to update compound parameters based on runtime data. They are attached to a compound (sub-)tree, on which they operate. The Equalizer distribution contains numerous example configuration files using equalizers.

Load Equalizer While pixel, subpixel and stereo compounds are naturally load-balanced, 2D and DB compounds often need load-balancing for optimal rendering performance.

Using a load equalizer is transparent to the application, and can be used with any application for 2D, and with most applications for DB load-balancing. Some applications do not support dynamic updates of the database range, and therefore cannot be used with DB load-balancing.

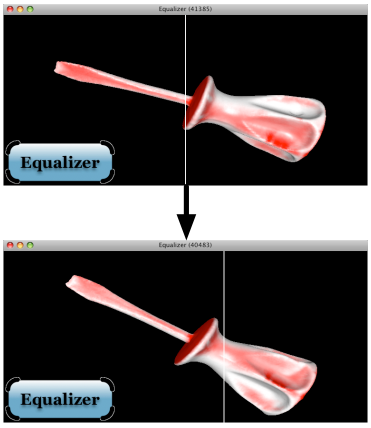


Figure 18: 2D Load-Balancing

Using a 2D or DB load-balancer will adjust the 2D split or database range automatically each frame. The 2D load-balancer exists in three flavors: 2D using tiles, VERTICAL using columns and HORIZONTAL using rows.

2D load-balancing increases the framerate over a static decomposition in virtually all cases. It works best if the application data is relatively uniformly distributed in screen-space. A damping parameter can be used to fine-tune the algorithm.

DB load-balancing is beneficial for applications which cannot precisely predict the load for their scene data, e.g., when the data is nonuniform. Volume rendering is a counterexample, where the data is uniform and a static DB decomposition typically results in a better performance.

View Equalizer Depending on the model position and data structure, each segment of a multi-display system has a different rendering load. The segment with the biggest load determines the overall performance when using a static assignment of resources to segments. The view equalizer analyzes the load of all segments, and adjusts the resource usage each frame. It equalizes the load on all segments of a view.

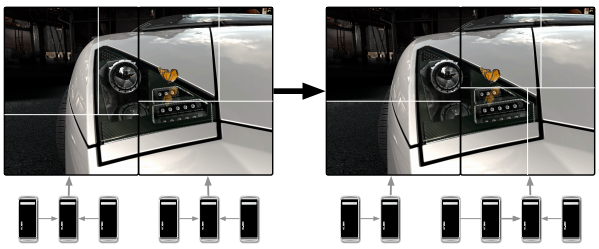


Figure 19: Cross-Segment Load-Balancing for two Segments using eight GPUs

Figure 19[16] illustrates this process. On the left side, a static assignment of resources to display segments is used. The right-hand segment has a higher load than the left-hand segment, causing sub-optimal performance. The configuration on the right uses a view equalizer, which assigns two GPUs to the left segment and four GPUs to the right segment, which leads to optimal performance for this model and camera position.

The view equalizer can also use resources from another display resource, if this resource has little rendering load by itself. It is therefore possible to improve the rendering performance of a multi-display system without any additional resources. This is particularly useful for installations with a higher number of displays where the rendering load is typically in a few segments only, e.g., for a CAVE.

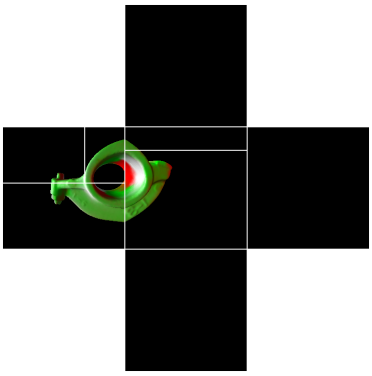


Figure 20: Cross-Segment Load-Balancing for a CAVE

Figure 20 shows cross-usage for a five-sided CAVE driven by five GPUs. The front and left segments show the model and have a significant rendering load. The view equalizer assigns the GPUs from the top, bottom and right wall for rendering the left and front wall in this configuration.

Cross-segment load-balancing is configured hierarchically. On the top compound level, a view equalizer assigns resources to each of its children, so that the optimal number of resources is used for each segment. On the next level, a load equalizer on each child computes the resource distribution within the segment, taking the resource usage given by the view equalizer into account.

Framerate Equalizer Certain configurations, in particular DPlex compounds, require a smoothing of the framerate at the destination channel, otherwise the framerate will become periodically faster and slower. Using a framerate equalizer will smoothen the swap buffer rate on the destination window for optimal user experience.

DFR Equalizer Dynamic Frame Resolution (DFR) trades rendering performance for visual quality. The rendering for a channel is done at a different resolution than the native channel resolution to keep the framerate constant. The DFR equalizer adjusts the zoom of a channel, based on the target and current framerate. It is typically used for fill-rate bound applications, such as volume rendering and ray-tracing.

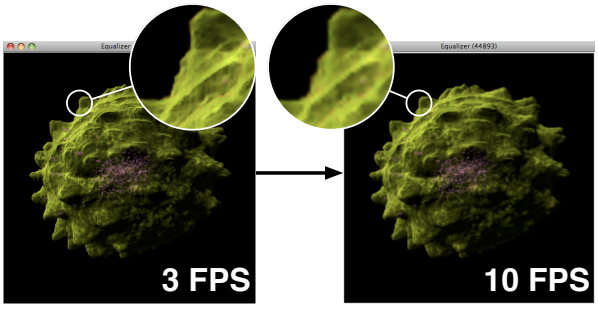


Figure 21: Dynamic Frame Resolution

[16]Image Copyright Realtime Technology AG, 2008

Figure 21[17] shows DFR for volume rendering. To achieve 10 frames per second, the model is rendered at a lower resolution, and upscaled to the native resolution for display. The rendering quality is slightly degraded, while the rendering performance remains interactive. When the application is idle, it renders a full-resolution view.

The dynamic frame resolution is not limited to subsampling the rendering resolution, it will also supersample the image if the source buffer is big enough. Upscaled rendering, which will down-sample the result for display, provides dynamic anti-aliasing at a constant framerate.

Monitor Equalizer The monitor equalizer allows the observation of another view, potentially made of multiple segments, in a different channel at a different resolution. This is typically used to reuse the rendering of a large-scale display on an operator station.

A monitor equalizer adjusts the frame zoom of the output frames used to observe the rendering, depending on the destination channel size. The output frames are downscaled on the GPU before readback, which results in optimal performance.

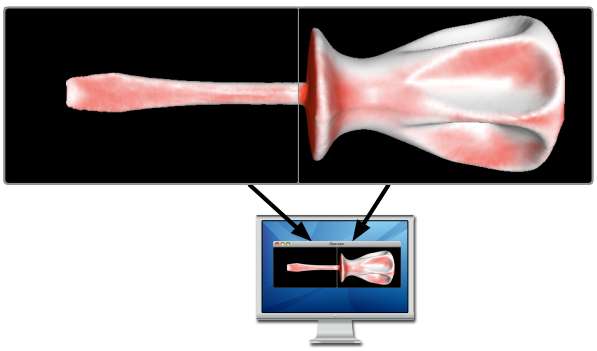


Figure 22: Monitoring a Projection Wall

Figure 22 shows a usage of the monitor equalizer. A two-segment display wall is driven by a separate control station. The rendering happens only on the display wall, and the control window receives the correctly downscaled version of the rendering.

4. Setting up a Visualization Cluster

This section covers the setup of a visualization cluster to run Equalizer applications. It does not cover basic cluster management and driver installation. A prerequisite to the following steps is a preinstalled cluster, including network and graphics card drivers.

4.1. Name Resolution

Pay attention that your name resolution works properly, that is, the output of the hostname command should resolve to the same, non-local IP address on all machines. If this is not the case, you will have to provide the public IP address for all processes, in the following way:

Server Specify the server IP as the hostname field in the connection description in the server section.

Application Specify the application IP as the hostname field in the connection description in the appNode section. If the application should not contribute to the rendering, set up an appNode without a pipe section.

[17] Data set courtesy of Olaf Ronneberger, Computer Science Institute, University of Freiburg, Germany

Render Clients Specify the client IPs as the hostname field in the connection description of each node section.

4.2. Server

The server may be started as a separate process or within the application process. If it is started separately, simply provide the desired configuration file as a parameter. It will listen on all network addresses, unless other connection parameters are specified in the configuration file. If the server is started within the application process, using the –eq-config parameter, you will have to specify a connection description for the server in the configuration file. Application-local servers do not create a listening socket by default for security reasons.

4.3. Starting Render Clients

Cluster configurations use multiple Equalizer nodes, where each node represents a separate process, typically on a different machine. These node processes have to be started for a visualization session, and need to communicate with each other.

Equalizer supports prelaunched render clients and automatic render client launching, if configured properly. Prelaunched render clients are started manually or by an external script on a predefined address. Auto-launched render client are started and stopped by the Equalizer server on demand.

The two mechanism can coexist. The server will first try to connect a prelaunched render client on the given connection descriptions for each node. If this fails, he will try to auto-launch the render client. If the render client does not connect back to the server within a certain timeout (default one minute), a failure to initialize the configuration is reported back to the application.

4.3.1. Prelaunched Render Clients

Prelaunched render clients are useful if setting up auto-launching is too time-consuming, e.g., on Windows which does not have a standard remote login procedure. The following steps are to be taken to use prelaunched render clients:

- Set the **connection** hostname and port parameters of each node in the configuration file.
- Start the **render clients** using the parameters –eq-client and –eq-listen, e.g., ./build/Linux/bin/eqPly –eq-client –eq-listen 192.168.0.2:1234. Pay attention to use the same connection parameters as in the configuration file.
- Start the **application**. If the server is running on the same machine and user as the application, the application will connect to it automatically. Otherwise use the –eq-server parameter to specify the server address.

The render clients will automatically exit when the config is closed. The eqPly example application implements the option -r to keep the render client processes resident.

4.3.2. Auto-launched Render Clients

To automatically launch the render clients, the server needs to know the name of the render client and the command to launch them without user interaction.

The name of the render client is automatically set to the name of the application executable. This may be changed programmatically by the application. Normally

it suffices to install the application in the same directory on all machines, ideally using a shared file system.

The default launch command is set to ssh, which is the most common solution for remote logins. To allow the server to launch the render clients without user interaction, password-less ssh needs to be set up. Please refer to the ssh documentation (cf. ssh-keygen and /.ssh/authorised_keys) and verify the functionality by logging in to each machine from the host running the server.

4.4. Debugging

If your configuration does not work, simplify it as much as possible first. Normally this means that there is one server, application and render client. Failure to launch a cluster configuration often is caused by one of the following reasons:

- A firewall is blocking network connections.
- The render client can't access the GPUs on the remote host. Set up your X-Server or application rights correctly. Log into the remote machine using the launch command and try to execute a simple application, e.g., glxinfo -display :0.1.
- The server does not find the prelaunched render client. Verify that the client is listening on the correct IP and port, and that this IP and port are reachable from the server host.
- The server cannot launch a render client. Check the server log for the launch command used, and try to execute a simple application from the server host using this launch command. It should run without user interaction. Check that the render client is installed in the correct path. Pay attention to the launch command quotes used to separate arguments on Windows. Check that the same software versions, including Equalizer, are installed on all machines.
- A client can't connect back to the application. Check the client log, this is typically caused by a misconfigured host name resolution.

Part II.
Programming Guide

This Programming Guide introduces Equalizer using a top-down approach, starting with a general introduction of the API in Section 5, followed by the simplified Sequel API in Section 6 which implements common use cases to deliver a large subset of the canonical Equalizer API introduced in Section 7. Section 8 introduces the separate Collage network library used as the foundation for the distributed execution and data synchronizing throughout Sequel and Equalizer.

5. Programming Interface

To modify an application for Equalizer, the programmer structures the source code so that the OpenGL rendering can be executed in parallel, potentially using multiple processes for cluster-based execution.

Equalizer uses a C++ programming interface. The API is minimally invasive. Equalizer imposes only a minimal, natural execution framework upon the application. It does not provide a scene graph, or interferes in any other way with the application's rendering code. The restructuring work enforced by Equalizer is the minimal refactoring needed to parallelize the application for scalable, distributed rendering.

The API documentation is available on the website or in the header files, and provides a comprehensive documentation on individual methods, types and other elements of the API. Methods marked with a specific version are part of the official, public API and have been introduced by this Equalizer version. Reasonable care is taken to not break API compatibility or change the semantics of these methods within future Equalizer versions of the same major revision. Any changes to the public API are documented in the release notes and the file CHANGES.txt.

In addition the official, public API Equalizer exposes a number of unstable methods and, where unavoidable, internal APIs. These are clearly marked in the API documentation. Unstable methods may be used by the programmer, but their interface or functionality may change in any future Equalizer version. The usage of internal methods is discouraged. Undocumented or unversioned methods should be considered as part of the unstable API.

5.1. Hello, World!

The eqHello example is a minimal application to illustrate the basic principle of any Equalizer application: The application developer has to implement a rendering method similar to the glutDisplayFunc in GLUT applications.

It can be run as a stand-alone application from the command line or using an explicit configuration file for a visualization cluster. In the stand-alone case, any Equalizer application, including eqHello, will automatically configure itself to use all graphics cards found on the local system for scalability.

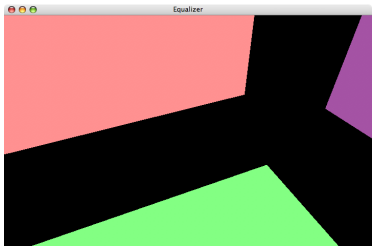


Figure 23: Hello, World!

The eqHello example uses Sequel, a thin layer on top of the canonical Equalizer programming interface. Section 6 introduces Sequel in detail, and Section 7.1 introduces the full scope of the Equalizer API.

The main eqHello function instantiates an application object, initializes it, starts the main loop and finally de-initializes the application:

```
int main( const int argc, char** argv )
{
    eqHello::ApplicationPtr app = new eqHello::Application;

    if( app->init( argc, argv, 0 ) && app->run( 0 ) && app->exit( ))
        return EXIT_SUCCESS;

    return EXIT_FAILURE;
}
```

The application object represents one process in the cluster. The primary application instance has the rendering loop and controls all execution. All other instances used for render client processes are passive and driven by Equalizer. The application is responsible for creating the renderers, of which one per GPU is used:

```
class Application : public seq::Application
{
public:
    virtual ~Application() {}
    virtual seq::Renderer* createRenderer() { return new Renderer( *this ); }
};
typedef lunchbox::RefPtr< Application > ApplicationPtr;
```

The renderer is responsible for executing the application's rendering code. One instance for each GPU is used. All calls to a single renderer are executed serially and therefore thread-safe.

In eqHello, the renderer draws six colored quads. The only change from a standard OpenGL application is the usage of the rendering context provided by Equalizer, most notably the frustum and viewport. The rendering context is described in detail in Section 7.1.8, and eqHello simply calls applyRenderContext which will execute the appropriate OpenGL calls.

After setting up lighting, the model is positioned using applyModelMatrix. For convenience, Sequel maintains one camera per view. The usage of this camera is purely optional, an application can implement its own camera model.

The actual OpenGL code, rendering six colored quads, is omitted here for brevity:

```
void eqHello::Renderer::draw( co::Object* frameData )
{
    applyRenderContext(); // set up OpenGL State

    const float lightPos[] = { 0.0f, 0.0f, 1.0f, 0.0f };
    glLightfv( GL_LIGHT0, GL_POSITION, lightPos );

    const float lightAmbient[] = { 0.2f, 0.2f, 0.2f, 1.0f };
    glLightfv( GL_LIGHT0, GL_AMBIENT, lightAmbient );

    applyModelMatrix(); // global camera

    // render six axis-aligned colored quads around the origin
```

5.2. Namespaces

The Equalizer software stack is modularized, layering gradually more powerful, but less generic APIs on top of each other. It furthermore relies on a number of required and optional libraries. Application developers are exposed to the following namespaces:

seq The core namespace for Sequel, the simple interface to the Equalizer client library.

eq The core namespace for the Equalizer client library. The classes and their relationship in this namespace closely model the configuration file format. The classes in the eq namespace are the main subject of this Programming Guide.Figure 25 provides an overview map of the most important classes in the Equalizer namespace, grouped by functionality.

eq::util The eq::util namespace provides common utility classes, which often simplify the usage of OpenGL functions. Most classes in this namespace are used by the Equalizer client library, but are usable independently from Equalizer for application development.

eq::admin The eq::admin namespace implements an administrative API to change the configurations of a running server. This admin API is not yet finalized and will very likely change in the future.

eq::fabric The eq::fabric namespace is the common data management and transport layer between the client library, the server and the administrative API. Most Equalizer client classes inherit from base classes in this namespace and have all their data access methods in these base classes.

co Collage is the network library used by Equalizer. It provides basic functionality for network communication, such as Connection and ConnectionSet, as well as higher-level functionality such as Node, LocalNode, Object and Serializable. Please refer to Section 8 for an introduction into the network layer, and to Section 7.1.3 for distributed objects.

lunchbox The lunchbox library provides C++ classes to abstract the underlying operating system and to implement common helper functionality for multi-threaded applications. Examples are lunchbox::Clock providing a high-resolution timer, or lunchbox::MTQueue providing a thread-safe, blocking FIFO. Classes in this namespace are fully documented in the API documentation on the Equalizer website, and are not subject of this Programming Guide.

hwloc, boost, vmmlib, hwsd External libraries providing manual and automatic thread affinity, serialization and the foundation for RSP multicast, vector and matrix mathematics as well as local and remote hardware (GPU, network interfaces) discovery, respectively. The hwloc and hwsd libraries are used only internally and are not exposed through the API.

eq::server The server namespace, implementing the functionality of the Equalizer server, which is an internal namespace not to be used by application developers. The eq::admin namespace enables run-time administration of Equalizer servers. The server does not yet expose a stable API.

The Equalizer examples are implemented in their own namespaces, e.g., eqPly or eVolve. They rely mostly on subclassing from the eq namespace, with the occasional usage of functionality from the eq::util, eq::fabric, co and lunchbox namespace. Figure 24 shows the namespaces and their layering.

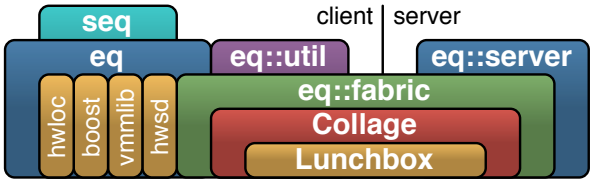


Figure 24: Namespaces

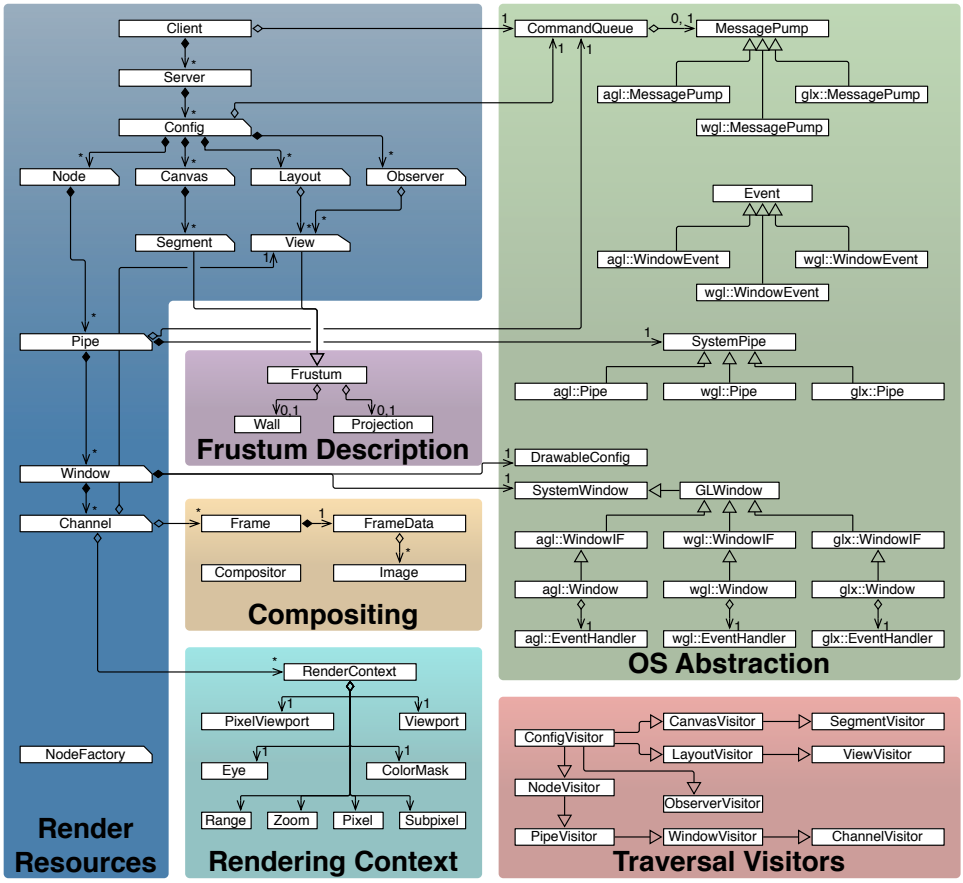


Figure 25: Equalizer client UML map

5.3. Task Methods

Methods called by the application have the form verb[Noun], whereas methods called by Equalizer ('Task Methods') have the form nounVerb. For example, the application calls Config::startFrame to render a new frame, which causes, among many other things, Node::frameStart to be called in all active render clients.

The application inherits from Equalizer classes and overrides virtual functions to implement certain functionality, e.g., the application's OpenGL rendering in eq::Channel::frameDraw. These task methods are similar in concept to C function callbacks. Section 7.1 will discuss the important task methods. A full list can be found on the website[18].

5.4. Execution Model and Thread Safety

Using threading correctly in OpenGL-based applications is easy with Equalizer. Equalizer creates one rendering thread for each graphics card. All task methods for a pipe, and therefore all OpenGL commands, are executed from this thread. This threading model follows the OpenGL 'threading model', which maintains a current context for each thread. If structured correctly, the application rarely has to take care of thread synchronization or protection of shared data.

[18] see http://www.equalizergraphics.com/documents/design/taskMethods.html

The main thread is responsible for maintaining the application logic. It reacts on user events, updates the data model and requests new frames to be rendered. It drives the whole application, as shown in Figure 26.

The rendering threads concurrently render the application's database. The database should be accessed in a read-only fashion during rendering to avoid threading problems. This is normally the case, for example all modern scene graphs use read-only render traversals, writing the GPU-specific information into a separate per-GPU data structure.

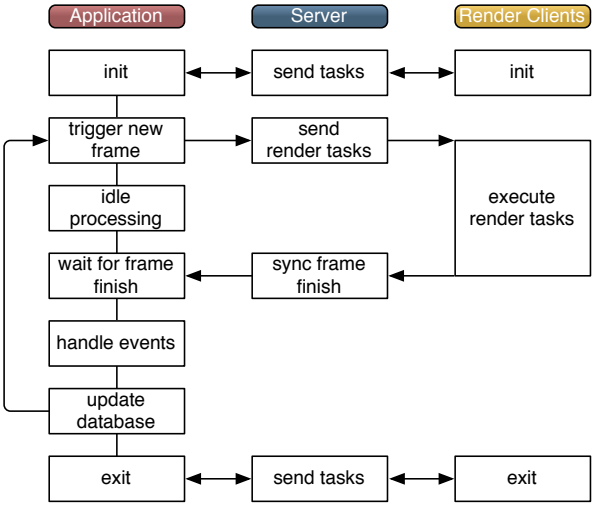


Figure 26: Simplified Execution Model

All rendering threads in the configuration run asynchronously to the application's main thread. Depending on the configuration's latency, they can fall n frames behind the last frame finished by the application thread. A latency of one frame is usually not perceived by the user, but can increase rendering performance substantially since operations can be better pipelined.

Rendering threads on a single node are synchronized when using the default thread model draw_sync. When a frame is finished, all local rendering threads are done drawing. Therefore the application can safely modify the data between the end of a frame and the beginning of a new frame. Furthermore, only one instance of the scene data has to be maintained within a process, since all rendering threads are guaranteed to draw the same frame.

This per-node frame synchronization does not inhibit latency across rendering nodes. Furthermore, advanced rendering software which multi-buffers the dynamic parts of the database can disable the per-node frame synchronization, as explained in Section 7.2.3. Some scene graphs implement multi-buffered data, and can profit from relaxing the local frame synchronization.

6. The Sequel Simple Equalizer API

In this section the source code of seqPly is used to introduce the Sequel API in detail, and relevant design decisions, caveats and other remarks are discussed. Sequel is conceived to lower the entry barrier into creating parallel rendering applications without sacrificing major functionality. It implements proven design patterns of Equalizer applications. Sequel does not prohibit the usage of Equalizer or Collage functionality, it simply makes it easier to use for the common use cases.

The seqPly parallel renderer provides a subset of features found in its cousin application, eqPly, introduced in the next section. It is more approachable, using approximately one tenth of the source code needed by eqPly due to the use of the Sequel abstraction layer and reduced functionality.

6.1. main Function

The main function is almost identical to eqHello. It instantiates an application object, initializes it, starts the main loop and finally de-initializes the application. The source code is not reproduced here due to its similarity with Section 5.1.

6.2. Application

The application object in Sequel represents one process in the cluster. The main application instance has the rendering loop and controls all execution. All other instances used for render client processes are passive and driven by Equalizer.

Sequel applications derive their application object from seq::Application and selectively override functionality. They have to implement createRenderer, as explained below. The seqPly application overrides init, exit, run and implements createRenderer.

The initialization and exit routines are overwritten to parse seqPly-specific command line options and to load and unload the requested model:

```
bool Application::init( const int argc, char** argv )
{
    const eq::Strings& models = _parseArguments( argc, argv );
    if( !seq::Application::init( argc, argv, 0 ))
        return false;

    _loadModel( models );
    return true;
}

bool Application::exit()
{
    _unloadModel();
    return seq::Application::exit();
}
```

Sequel manages distributed objects, simplifying their use. This includes registration, automatic creation and mapping as well as commit and synchronization of objects. One special object for initialization (not used in seqPly) and one for per-frame data are managed by Sequel, in addition to an arbitrary number of application-specific objects.

The objects passed to seq::Application::init and seq::Application::run are automatically distributed and instantiated on the render clients, and then passed to the respective task callback methods. The application may pass a 0 pointer if it does not need an object for initialization or per-frame data. Objects are registered with a type, and when automatically created, the createObject method on the application or renderer is used to create an instance based on this type.

The run method is overloaded to pass the frame data object to the Sequel application run loop. The object will be distributed and synchronized to all renderers:

```
bool Application::run()
{
    return seq::Application::run( &_frameData );
}
```

The application is responsible for creating renderers. Sequel will request one renderer for each GPU rendering thread. Sequel also provides automatic mapping and synchronization of distributed objects, for which the application has to provide a creation callback:

```
seq::Renderer* Application::createRenderer()
{
    return new Renderer( *this );
```

```
}

co::Object* Application::createObject( const uint32_t type )
{
    switch( type )
    {
      case seq::OBJECTTYPE_FRAMEDATA:
          return new eqPly::FrameData;

      default:
          return seq::Application::createObject( type );
    }
}
```

6.3. Renderer

The renderer is responsible for executing the application's rendering code. One instance for each GPU is used. All calls to a single renderer are executed serially and therefore thread-safe.

The seqPly rendering code uses the same data structure and algorithm as eqPly, described in Section 7.1.8. This renderer captures the GPU-specific data in a State object, which is created and destroyed during init and exit. The state captures also the OpenGL function table, which is available when init is called, but not yet during the constructor of the renderer:

```
bool Renderer::init( co::Object* initData )
{
    _state = new State( glewGetContext( ));
    return seq::Renderer::init( initData );
}

bool Renderer::exit()
{
    _state->deleteAll();
    delete _state;
    _state = 0;
    return seq::Renderer::exit();
}
```

The rendering code is similar to the typical OpenGL rendering code, except for a few modifications to configure the rendering. First, the render context is applied and lighting is set up. The render context, described in detail in Section 7.1.8, sets up the stereo buffer, 3D viewport as well as the projection and view matrices using the appropriate OpenGL calls. Applications can also retrieve the render context and apply the settings themselves:

```
    applyRenderContext();

    glLightfv( GL_LIGHT0, GL_POSITION, lightPosition );
    glLightfv( GL_LIGHT0, GL_AMBIENT,  lightAmbient  );
    glLightfv( GL_LIGHT0, GL_DIFFUSE,  lightDiffuse  );
    glLightfv( GL_LIGHT0, GL_SPECULAR, lightSpecular );

    glMaterialfv( GL_FRONT, GL_AMBIENT,    materialAmbient );
    glMaterialfv( GL_FRONT, GL_DIFFUSE,    materialDiffuse );
    glMaterialfv( GL_FRONT, GL_SPECULAR,   materialSpecular );
    glMateriali(  GL_FRONT, GL_SHININESS, materialShininess );
```

After the static light setup, the model matrix is applied to the existing view matrix, completing the modelview matrix and positioning the model. Sequel maintains a per-view camera, which is modified through mouse and keyboard events and determines the model matrix. Applications can overwrite this event handling and maintain their own camera model. Afterwards, the state is set up with the

projection-modelview matrix for view frustum culling, the DB range for sort-last rendering and the cull-draw traversal is executed, as described in Section 7.1.8:

```
applyModelMatrix();

glColor3f( .75f, .75f, .75f );

// Compute cull matrix
const eq::Matrix4f& modelM = getModelMatrix();
const eq::Matrix4f& view = getViewMatrix();
const eq::Frustumf& frustum = getFrustum();
const eq::Matrix4f projection = frustum.compute_matrix();
const eq::Matrix4f pmv = projection * view * modelM;
const seq::RenderContext& context = getRenderContext();

_state->setProjectionModelViewMatrix( pmv );
_state->setRange( &context.range.start );
_state->setColors( model->hasColors( ));

model->cullDraw( *_state );
```

7. The Equalizer Parallel Rendering Framework

The core Equalizer client library exposes the full feature set and flexibility to the application developer. New application development is encouraged to use the Sequel library, and inquire on the eq-dev mailing list when specific functionality is not available in Sequel. Only advanced and complex applications should be implemented using the Equalizer client library directly.

7.1. The eqPly Polygonal Renderer

In this section the source code of eqPly is used to introduce the Equalizer API in detail, and relevant design decisions, caveats and other remarks are discussed.

eqPly is a parallel renderer for polygonal data in the ply file format. It supports nearly all Equalizer features, and can be used to render on large-scale displays, immersive environments with head tracking and to render massive data sets using all scalable rendering features of Equalizer. It is a superset of seqPly, introduced in Section 6.

The eqPly example is shipped with the Equalizer distribution and serves as a reference implementation of an Equalizer-based application of medium complexity. It focuses on the example usage of core Equalizer features, not on advanced rendering features or visual quality.

Figure 27 shows how the most important Equalizer classes are used through inheritance by the eqPly example. All classes in the example are in the eqPly namespace to avoid type name ambiguities, in particular for the Window class which is frequently used as a type in the global namespace by windowing systems.

The eqPly classes fall into two categories: Subclasses of the rendering entities introduced in Section 3, and classes for distributing data.

The function and typical usage for each of the rendering entities is discussed in this section. Each of these classes inherits from a base class in the eq::fabric namespace, which implements data distribution for the entity. The fabric base classes are omitted in Figure 27.

The distributed data classes are helper classes based on co::Serializable or its base class co::Object. They illustrate the typical usage of distributed objects for static as well as dynamic, frame-specific data. Furthermore they are used for a basic scene graph distribution of the model data to the render client processes. Section 8 provides more background on the Collage network library.

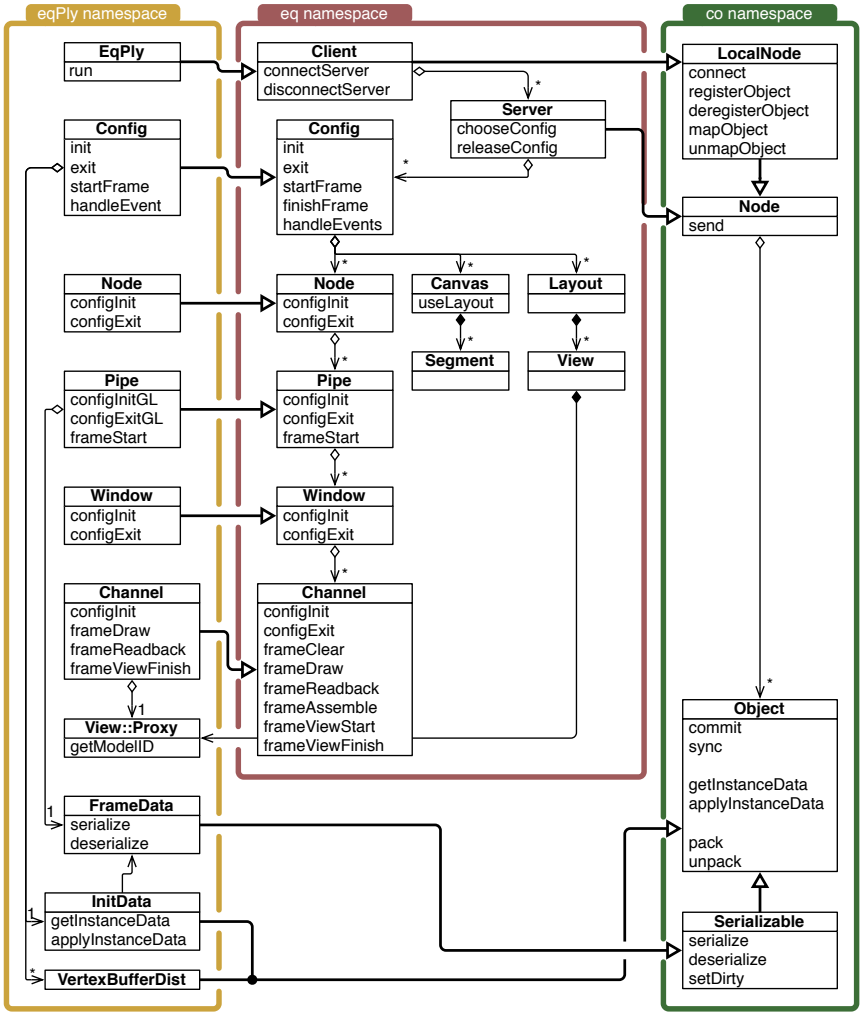


Figure 27: UML Diagram eqPly and relevant Equalizer Classes

7.1.1. main Function

The main function starts off with initializing the Equalizer library. The command line arguments are passed on to Equalizer. They are used to set certain default values based on Equalizer-specific options[19], e.g., the default server address. Furthermore, a NodeFactory is provided. The EQERROR macro, and its counterparts EQWARN, EQINFO and EQVERB allow selective debugging outputs with various logging levels:

```
int main( const int argc, char** argv )
{
    // 1. Equalizer initialization
    NodeFactory nodeFactory;
    eqPly::initErrors();

    if( !eq::init( argc, argv, &nodeFactory ))
    {
        LBERROR << "Equalizer init failed" << std::endl;
        return EXIT_FAILURE;
    }
```

[19] Equalizer-specific options always start with --eq-

The node factory is used by Equalizer to create the object instances of the configured rendering entities. Each of the classes inherits from the same type provided by Equalizer in the eq namespace. The provided eq::NodeFactory base class instantiates 'plain' Equalizer objects, thus making it possible to selectively subclass individual entity types, as it is done by eqHello. For each rendering resources used in the configuration, one C++ object will be created during initialization. Config, node and pipe objects are created and destroyed in the node thread, whereas window and channel objects are created and destroyed in the pipe thread:

```
class NodeFactory : public eq::NodeFactory
{
public:
    virtual eq::Config*  createConfig( eq::ServerPtr parent )
        { return new eqPly::Config( parent ); }
    virtual eq::Node*    createNode( eq::Config* parent )
        { return new eqPly::Node( parent ); }
    virtual eq::Pipe*    createPipe( eq::Node* parent )
        { return new eqPly::Pipe( parent ); }
    virtual eq::Window*  createWindow( eq::Pipe* parent )
        { return new eqPly::Window( parent ); }
    virtual eq::Channel* createChannel( eq::Window* parent )
        { return new eqPly::Channel( parent ); }
    virtual eq::View* createView( eq::Layout* parent )
        { return new eqPly::View( parent ); }
};
```

The second step is to parse the command line into the LocalInitData data structure. A part of it, the base class InitData, will be distributed to all render client nodes. The command line parsing is done by the LocalInitData class, which is discussed in Section 7.1.3:

```
// 2. parse arguments
eqPly::LocalInitData initData;
initData.parseArguments( argc, argv );
```

The third step is to create an instance of the application and to initialize it locally. The application is a subclass of eq::Client, which in turn is an co::LocalNode. The underlying Collage network library, discussed in Section 8, is a peer-to-peer network of co::LocalNodes. The client-server concept is implement the higher-level eq client namespace.

The local initialization of a node creates at least one local listening socket, which allows the eq::Client to communicate over the network with other nodes, such as the server and the rendering clients. The listening socket(s) can be configured using the –eq-listen command line parameter, by adding connections to the appNode in the configuration file, or by programmatically adding connection descriptions to the client before the local initialization:

```
// 3. initialization of local client node
lunchbox::RefPtr< eqPly::EqPly > client = new eqPly::EqPly( initData );
if( !client->initLocal( argc, argv ))
{
    LBERROR << "Can't init client" << std::endl;
    eq::exit();
    return EXIT_FAILURE;
}
```

Finally everything is set up, and the eqPly application is executed:

```
// 4. run client
const int ret = client->run();
```

After the application has finished, it is de-initialized and the main function returns:

```
    // 5. cleanup and exit
    client->exitLocal();

    LBASSERTINFO( client->getRefCount() == 1, client );
    client = 0;

    eq::exit();
    eqPly::exitErrors();
    return ret;
}
```

7.1.2. Application

In the case of eqPly, the application is also the render client. The eqPly executable has three runtime behaviors:

1. **Application**: The executable started by the user, the controlling entity of the rendering session.
2. **Auto-launched render client**: The typical render client, started by the server. The server starts the executable with special parameters, which cause Client::initLocal to never return. During exit, the server terminates the process. By default, the server starts the render client using ssh. The launch command can be used to configure another program to auto-launch render clients.
3. **Resident render client**: Manually prestarted render client, listening on a specified port for server commands. This mode is selected using the command-line option –eq-client and –eq-listen <address> to specify a well-defined listening address, and potentially -r to keep the client running across multiple runs[20].

Main Loop The application's main loop starts by connecting the application to an Equalizer server. If no server is specified, Client::connectServer tries first to connect to a server on the local machine using the default port. If that fails, it will create a server running within the application process using auto-configuration as described in Section 3.1.2. The command line parameter –eq-config can be used to specify a hwsd session or configuration file, and –eq-server to explicitly specify a server address.

```
int EqPly::run()
{
    // 1. connect to server
    eq::ServerPtr server = new eq::Server;
    if( !connectServer( server ))
    {
        LBERROR << "Can't open server" << std::endl;
        return EXIT_FAILURE;
    }
```

The second step is to ask the server for a configuration. The ConfigParams are a placeholder for later Equalizer implementations to provide additional hints and information to the server for auto-configuration. The configuration chosen by the server is created locally using NodeFactory::createConfig. Therefore it is of type eqPly::Config, but the return value is eq::Config, making the static_cast necessary:

```
    // 2. choose config
    eq::fabric::ConfigParams configParams;
    Config* config = static_cast<Config*>(server->chooseConfig( configParams ));
```

[20] see http://www.equalizergraphics.com/documents/design/residentNodes.html

```
if( !config )
{
    LBERROR << "No matching config on server" << std::endl;
    disconnectServer( server );
    return EXIT_FAILURE;
}
```

Finally it is time to initialize the configuration. For statistics, the time for this operation is measured and printed. During initialization the server launches and connects all render client nodes, and calls the appropriate initialization task methods, as explained in later sections. Config::init returns after all nodes, pipes, windows and channels are initialized.

The return value of Config::init depends on the configuration robustness attribute. This attribute is set by default, allowing configurations to launch even when some entities failed to initialize. If set, Config::init always returns true. If deactivated, it returns true only if all initialization task methods were successful. In any case, Config::getError only returns ERROR_NONE if all entities have initialized successfully.

The EQLOG macro allows topic-specific logging. The numeric topic values are specified in the respective log.h header files, and logging for various topics is enabled using the environment variable EQ_LOG_TOPICS:

```
// 3. init config
lunchbox::Clock clock;

config->setInitData( _initData );
if( !config->init( ))
{
    LBWARN << "Error during initialization: " << config->getError()
           << std::endl;
    server->releaseConfig( config );
    disconnectServer( server );
    return EXIT_FAILURE;
}
if( config->getError( ))
    LBWARN << "Error during initialization: " << config->getError()
           << std::endl;

LBLOG( LOG_STATS ) << "Config init took " << clock.getTimef() << " ms"
                   << std::endl;
```

When the configuration was successfully initialized, the main rendering loop is executed. It runs until the user exits the configuration, or when a maximum number of frames has been rendered, specified by a command-line argument. The latter is useful for benchmarks. The Clock is reused for measuring the overall performance. A new frame is started using Config::startFrame and a frame is finished using Config::finishFrame.

When a new frame is started, the server computes all rendering tasks and sends them to the appropriate render client nodes. The render client nodes dispatch the tasks to the correct node or pipe thread, where they are executed in order of arrival.

Config::finishFrame blocks on the completion of the frame current - latency. The latency is specified in the configuration file, and allows several outstanding frames. This allows overlapping execution in the node processes and pipe threads and minimizes idle times.

By default, Config::finishFrame also synchronizes the completion of all local rendering tasks for the current frame. This facilitates porting of existing rendering codes, since the database does not have to be multi-buffered. Applications such as eqPly, which do not need this per-node frame synchronization, can disable it as explained in Section 7.2.3:

```
// 4. run main loop
```

```
uint32_t maxFrames = _initData.getMaxFrames();
int lastFrame = 0;

clock.reset();
while( config->isRunning( ) && maxFrames-- )
{
    config->startFrame();
    if( config->getError( ))
        LBWARN << "Error during frame start: " << config->getError()
               << std::endl;
    config->finishFrame();
```

Figure 28 shows the execution of the rendering tasks of a 2-node 2D compound without latency and with a latency of one frame. The asynchronous execution pipelines certain rendering operations and hides imbalances in the load distribution, resulting in an improved framerate. For example, we have observed a speedup of 15% on a five-node rendering cluster when using a latency of one frame instead of no latency[21]. A latency of one or two frames is normally not perceived by the user. The statistics overlay is explained in detail in Section 7.2.11.

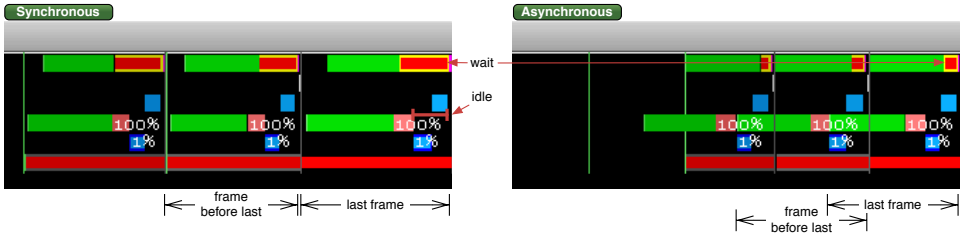


Figure 28: Synchronous and Asynchronous Execution

When playing a camera animation, eqPly prints the rendering performance once per animation loop for benchmarking purposes:

```
if( config->getAnimationFrame() == 1 )
{
    const float time = clock.resetTimef();
    const size_t nFrames = config->getFinishedFrame() - lastFrame;
    lastFrame = config->getFinishedFrame();

    LBLOG( LOG_STATS ) << time << " ms for " << nFrames << " frames @ "
                       << ( nFrames / time * 1000.f) << " FPS)"
                       << std::endl;
}
```

eqPly uses event-driven execution, that is, it only request new rendering frames if an event or animation requires an update. The eqPly::Config maintains a dirty state, which is cleared after a frame has been started, and set when an event causes a redraw. Furthermore, when an animation is running or head tracking is active, the config always signals the need for a new frame.

If the application detects that it is currently idle, all pending commands are gradually flushed, while still looking for a redraw event. Then it waits and handles one event at a time, until a redraw is needed:

```
while( !config->needRedraw( )) // wait for an event requiring redraw
{
    if( hasCommands( )) // execute non-critical pending commands
    {
        processCommand();
        config->handleEvents(); // non-blocking
    }
```

[21] http://www.equalizergraphics.com/scalability.html

```
            else  // no pending commands, block on user event
            {
                const eq::EventICommand& event = config->getNextEvent();
                if( !config->handleEvent( event ))
                    LBVERB << "Unhandled " << event << std::endl;
            }
        }
        config->handleEvents(); // process all pending events
```

When the main rendering loop has finished, Config::finishAllFrames is called to catch up with the latency. It returns after all outstanding frames have been rendered, and is needed to provide an accurate measurement of the framerate:

```
    const uint32_t frame = config->finishAllFrames();
    const float time = clock.resetTimef();
    const size_t nFrames = frame - lastFrame;
    LBLOG( LOG_STATS ) << time << " ms for " << nFrames << " frames @ "
                       << ( nFrames / time * 1000.f) << " FPS)" << std::endl;
```

The remainder of the application code cleans up in the reverse order of initialization. The config is exited, released and the connection to the server is closed:

```
    // 5. exit config
    clock.reset();
    config->exit();
    LBLOG( LOG_STATS ) << "Exit took " << clock.getTimef() << " ms" <<std::endl;

    // 6. cleanup and exit
    server->releaseConfig( config );
    if( !disconnectServer( server ))
        LBERROR << "Client::disconnectServer failed" << std::endl;

    return EXIT_SUCCESS;
}
```

Render Clients In the second and third use case of the eqPly, when the executable is used as a render client, Client::initLocal never returns. Therefore the application's main loop is never executed. To keep the client resident, the eqPly example overrides the client loop to keep it running beyond one configuration run:

```
void EqPly::clientLoop()
{
    do
    {
        eq::Client::clientLoop();
        LBINFO << "Configuration run successfully executed" << std::endl;
    }
    while( _initData.isResident( )); // execute at least one config run
}
```

7.1.3. Distributed Objects

Equalizer provides distributed objects which facilitate the implementation of data distribution in a cluster environment. Distributed objects are created by subclassing from co::Serializable or co::Object. The application programmer implements serialization and deserialization of the distributed data. Section 8.4 covers distributed objects in detail.

Distributed objects can be static (immutable) or dynamic. Dynamic objects are versioned. The eqPly example uses static distributed objects to provide initial data and the model to all rendering nodes, as well as a versioned object to provide frame-specific data such as the camera position to the rendering methods.

InitData - a Static Distributed Object The InitData class holds a couple of parameters needed during initialization. These parameters never change during one configuration run, and are therefore static.

On the application side, the class LocalInitData subclasses InitData to provide the command line parsing and to set the default values. The render nodes only instantiate the distributed part in InitData.

A static distributed object has to implement getInstanceData and applyInstanceData to serialize and deserialize the object's distributed data. These methods provide an output or input stream as a parameter, which abstracts the data transmission and can be used like a std::stream.

The data streams implement efficient buffering and compression, and automatically select the best connection, i.e., multicast where available, for data transport. They perform no type checking or transformation on the data. It is the application's responsibility to exactly match the order and types of variables during serialization and de-serialization.

Custom data type serializers can be implemented by providing the appropriate serialization functions. No pointers should be directly transmitted through the data streams. For pointers, the corresponding object is typically a distributed object as well, and its identifier and potentially version is transmitted in place of its pointer.

For InitData, serialization in getInstanceData and de-serialization in applyInstanceData is performed by streaming all member variables to or from the provided data streams:

```
void InitData::getInstanceData( co::DataOStream& os )
{
    os << _frameDataID << _windowSystem << _renderMode << _useGLSL << _invFaces
       << _logo << _roi;
}

void InitData::applyInstanceData( co::DataIStream& is )
{
    is >> _frameDataID >> _windowSystem >> _renderMode >> _useGLSL >> _invFaces
       >> _logo >> _roi;
    LBASSERT( _frameDataID != 0 );
}
```

FrameData - a Versioned Distributed Object Versioned objects have to override getChangeType to indicate how they want to have changes to be handled. All types of versioned objects currently implemented have the following characteristics:

- The master instance of the object generates new versions for all slaves. These versions are continuous, starting at co::VERSION_FIRST. It is possible to commit on slave instances, but special care has to be taken to handle possible conflicts. Section 8.4.4 covers slave object commits in detail.
- Slave instance versions can only be advanced, that is, sync(version) with a version smaller than the current version will fail.
- Newly mapped slave instances are mapped to the oldest available version by default, or to the version specified when calling mapObject.

Upon commit the delta data from the previous version is sent to all mapped slave instances. The data is queued on the remote node, and is applied when the application calls sync to synchronize the object to a new version. The sync method might block if a version has not yet been committed or is still in transmission.

Not syncing a mapped, versioned object creates a memory leak. The method Object::notifyNewHeadVersion is called whenever a new version is received by the

node. The notification is send from the command thread, which is different from the node main thread. The object should not be synced from this method, but instead a message may be send to the application, which then takes the appropriate action. The default implementation asserts when too many versions have been queued to detect memory leaks during development.

Besides the instance data (de-)serialization methods used to map an object, versioned objects may implement pack and unpack to serialize or de-serialize the changes since the last version. If these methods are not implemented, their default implementation forwards the (de-)serialization request to getInstanceData and applyInstanceData, respectively.

The creation of distributed, versioned objects is simplified when using co::Serializable, which implements one common way of tracking data changes in versioned objects. The concept of a dirty bit mask is used to mark parts of the object for serialization, while preserving the capability to inherit objects. Other ways of implementing change tracking, e.g., using incarnation counters, can still be implemented by using co::Object which leaves all flexibility to the developer. Figure 29 shows the relationship between co::Serializable and co::Object.

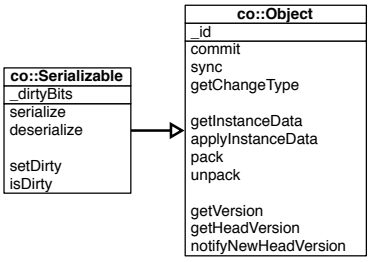


Figure 29: co::Serializable and co::Object

The FrameData is sub-classed from Serializable, and consequently tracks its changes by setting the appropriate dirty bit whenever it is changed. The serialization methods are called by the co::Serializable with the dirty bit mask needed to serialize all data, or with the dirty bit mask of the changes since the last commit. The FrameData only defines its own dirty bits and serialization code:

```
        /** The changed parts of the data since the last pack(). */
        enum DirtyBits
        {
            DIRTY_CAMERA   = co::Serializable::DIRTY_CUSTOM << 0,
            DIRTY_FLAGS    = co::Serializable::DIRTY_CUSTOM << 1,
            DIRTY_VIEW     = co::Serializable::DIRTY_CUSTOM << 2,
            DIRTY_MESSAGE = co::Serializable::DIRTY_CUSTOM << 3,
        };

void FrameData::serialize( co::DataOStream& os, const uint64_t dirtyBits )
{
    co::Serializable::serialize( os, dirtyBits );
    if( dirtyBits & DIRTY_CAMERA )
        os << _position << _rotation << _modelRotation;
    if( dirtyBits & DIRTY_FLAGS )
        os << _modelID << _renderMode << _colorMode << _quality << _ortho
           << _statistics << _help << _wireframe << _pilotMode << _idle
           << _compression;
    if( dirtyBits & DIRTY_VIEW )
        os << _currentViewID;
    if( dirtyBits & DIRTY_MESSAGE )
        os << _message;
}

void FrameData::deserialize( co::DataIStream& is, const uint64_t dirtyBits )
{
    co::Serializable::deserialize( is, dirtyBits );
    if( dirtyBits & DIRTY_CAMERA )
        is >> _position >> _rotation >> _modelRotation;
    if( dirtyBits & DIRTY_FLAGS )
        is >> _modelID >> _renderMode >> _colorMode >> _quality >> _ortho
           >> _statistics >> _help >> _wireframe >> _pilotMode >> _idle
```

```
            >> _compression;
    if( dirtyBits & DIRTY_VIEW )
        is >> _currentViewID;
    if( dirtyBits & DIRTY_MESSAGE )
        is >> _message;
}
```

Scene Data Some applications rely on a shared filesystem to access the data, for example when out-of-core algorithms are used. Other applications prefer to load the data only on the application process, and use distributed objects to synchronize the scene data with the render clients.

eqPly chooses the second approach, using static distributed objects to distribute the model loaded by the application. It can be easily extended to versioned objects to support dynamic data modifications.

The kD-tree data structure and rendering code for the model is strongly separated from Equalizer, and kept in the separate namespace mesh. It can also be used in other rendering software, for example in a GLUT application. To keep this separation while implementing data distribution, an external 'mirror' hierarchy is constructed aside the kD-tree. This hierarchy of VertexBufferDist nodes is responsible for cloning the model data on the remote render clients.

The identifier of the model's root object of this distributed hierarchy is passed as part of the InitData for the default model, or as part of the View for each logical view. It is used on the render clients to map the model when it is needed for rendering.

Figure 30 shows the UML hierarchy of the model and distribution classes. Section 8.4 illustrates other approaches to employ distributed objects for data distribution and synchronization.

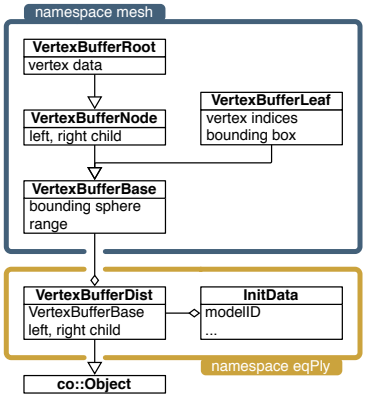


Figure 30: Scene Data in eqPly

Each VertexBufferDist object corresponds to one node of the model's data tree. It is serializing the data for this node. Furthermore, it mirrors the kD-tree by having a VertexBufferDist child for each child of its corresponding tree node. During serialization, the identifier of these children is sent to the remote nodes, which reconstruct the mirror distribution hierarchy and model data tree based on this data.

The serialization function getInstanceData sends all the data needed to reconstruct the model tree: the object identifiers of its children, vertex data for the tree root and vertex indices for the leaf nodes, as well as the bounding sphere and database range of each node. The deserialization function applyInstanceData retrieves the data in multiple steps, and constructs the model tree on the fly based on this information. It is omitted here for brevity:

```
void VertexBufferDist::getInstanceData( co::DataOStream& os )
{
    LBASSERT( _node );
    os << _isRoot;

    if( _left && _right )
    {
        os << _left->getID() << _right->getID();

        if( _isRoot )
        {
            LBASSERT( _root );
```

```
            const mesh::VertexBufferData& data = _root->_data;

            os << data.vertices << data.colors << data.normals << data.indices
               << _root->_name;
        }
    }
    else
    {
        os << co::UUID() << co::UUID();

        LBASSERT( dynamic_cast< const mesh::VertexBufferLeaf* >( _node ));
        const mesh::VertexBufferLeaf* leaf =
            static_cast< const mesh::VertexBufferLeaf* >( _node );

        os << leaf->_boundingBox[0] << leaf->_boundingBox[1]
           << uint64_t( leaf->_vertexStart ) << uint64_t( leaf->_indexStart )
           << uint64_t( leaf->_indexLength ) << leaf->_vertexLength;
    }

    os << _node->_boundingSphere << _node->_range;
}
```

Applications distributing a dynamic scene graph use the frame data instead of the init data as the entry point to their scene graph data structure. Figure 31 shows one possible implementation, where the identifier and version of the scene graph root are transported using the frame data. The scene graph root then serializes and deserializes his immediate children by transferring their identifier and current version, similar to the static distribution done by eqPly.

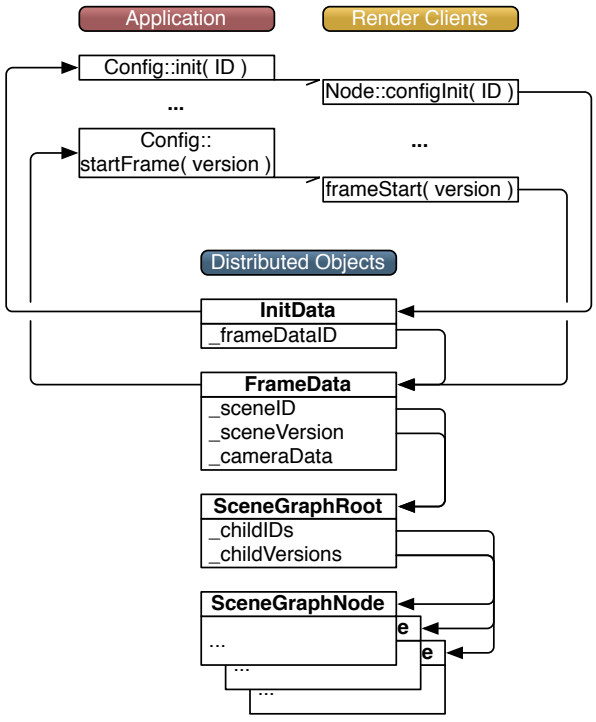


Figure 31: Scene Graph Distribution

The objects are still created by the application, and then registered or mapped with the session to distribute them. When mapping objects in a hierarchical data structure, their type often has to be known to create them. Equalizer does not currently provide object typing, this has to be done by the application, either implicitly in the current implementation context, or by transferring a type identifier. In eqPly, object typing is implicit since it is well-defined which object is mapped in which context.

7.1.4. Config

The eq::Config class is driving the application's rendering, that is, it is responsible for updating the data based on received events, requesting new frames to be rendered and to provide the render clients with the necessary data.

Initialization and Exit The config initialization happens in parallel, that is, all config initialization tasks are transmitted by the server at once and their completion is synchronized afterwards.

The tasks are executed by the node and pipe threads in parallel. The parent's initialization methods are always executed before any child initialization method. This parallelization allows a speedy startup on large-scale graphics clusters. On the other hand, it means that initialization functions are called even if the parent's initialization has failed. Figure 32 shows a sequence diagram of the config initialization.

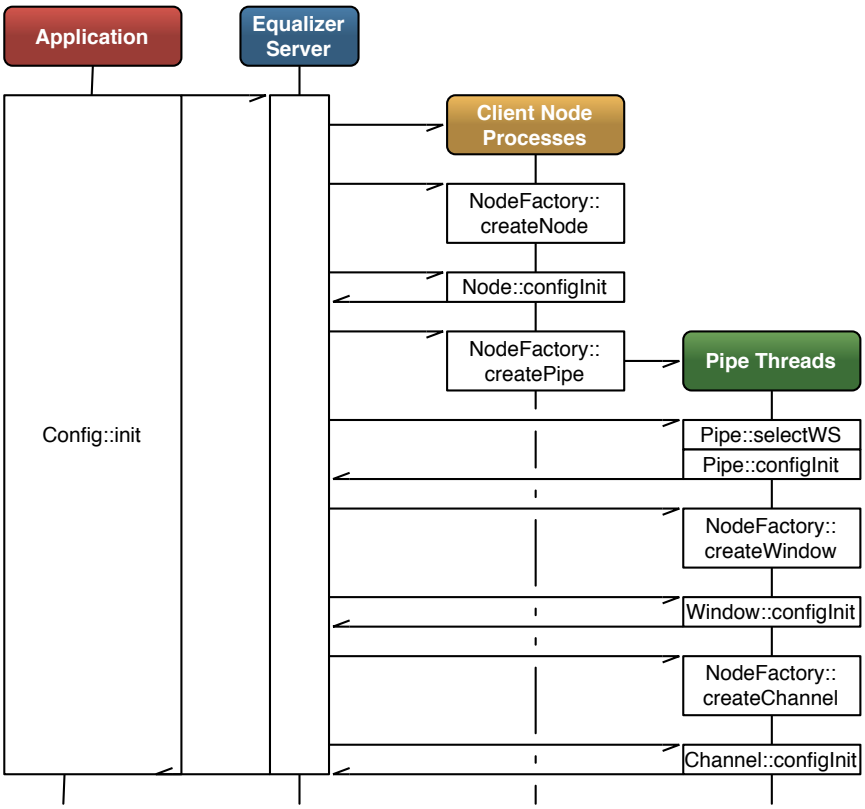


Figure 32: Config Initialization Sequence

The eqPly::Config class holds the master versions of the initialization and frame data objects. Both are registered with the eq::Config. The configuration forwards the registration to the local client node and augments the object registration for buffered objects.

First, it configures the objects to retain its data latency+1 commits, which corresponds to the typical use case where objects are committed once per frame. This allows render clients, which often are behind the application process, to map objects with an old version. This does not necessarily translate into increased memory usage, since new versions are only created when the object was dirty during commit.

Second, it retains the data for buffered objects data for latency frames after their deregistration. This allows to map the object on a render client, even after it has been deregistered on the application node. This does delay the deallocation of the buffered object data by latency frames.

The identifier of the initialization data is transmitted to the render client nodes using the initID parameter of eq::Config::init. The identifier of the frame data is transmitted using the InitData.

Equalizer will pass this identifier to all configInit calls of the respective objects:

```
bool Config::init()
{
    if( !_animation.isValid( ))
        _animation.loadAnimation( _initData.getPathFilename( ));

    // init distributed objects
    if( !_initData.useColor( ))
        _frameData.setColorMode( COLOR_WHITE );

    _frameData.setRenderMode( _initData.getRenderMode( ));
    registerObject( &_frameData );
    _frameData.setAutoObsolete( getLatency( ));

    _initData.setFrameDataID( _frameData.getID( ));
    registerObject( &_initData );

    // init config
    if( !eq::Config::init( _initData.getID( )))
```

After a successful initialization, the models are loaded and registered for data distribution. When idle, Equalizer will predistribute object data during registration to accelerate the mapping of slave instances. Registering the models after Config::init ensures that the render clients are running and can cache the data:

```
    _loadModels();
    _registerModels();
```

The exit function of the configuration stops the render clients by calling eq::Config::exit, and then de-registers the initialization and frame data objects:

```
bool Config::exit()
{
    const bool ret = eq::Config::exit();
    _deregisterData();
    _closeAdminServer();

    // retain model & distributors for possible other config runs, dtor deletes
    return ret;
}
```

Frame Control The rendering frames are issued by the application main loop. The eqPly::Config overrides startFrame to update its data, commit a new version of the frame data object, and then requests the rendering of a new frame using the current frame data version. This version is passed to the rendering callbacks and will be used by the rendering threads to synchronize the frame data to the state belonging to the current frame. This ensures that all frame-specific data, e.g., the camera position, is used consistently to generate the frame:

```
uint32_t Config::startFrame()
{
    _updateData();
    const eq::uint128_t& version = _frameData.commit();

    _redraw = false;
    return eq::Config::startFrame( version );
}
```

The update of the per-frame shared data consist of calculating the camera position based on the current navigation mode, and determining the idle state for rendering. When idle, eqPly performs anti-aliasing to gradually reduce aliasing effects in the rendering. The idle state is tracked by the application and used by the rendering callbacks to jitter the frusta, accumulate and display the results, as described in Section 7.2.10:

```
void Config::_updateData()
{
    // update camera
    if( _animation.isValid( ))
    {
        const eq::Vector3f&  modelRotation = _animation.getModelRotation();
        const CameraAnimation::Step& curStep = _animation.getNextStep();

        _frameData.setModelRotation( modelRotation );
        _frameData.setRotation( curStep.rotation );
        _frameData.setCameraPosition( curStep.position );
    }
    else
    {
        if( _frameData.usePilotMode())
            _frameData.spinCamera( -0.001f * _spinX, -0.001f * _spinY );
        else
            _frameData.spinModel( -0.001f * _spinX, -0.001f * _spinY, 0.f );

        _frameData.moveCamera( 0.0f, 0.0f, 0.001f * _advance );
    }

    // idle mode
    if( isIdleAA( ))
    {
        LBASSERT( _numFramesAA > 0 );
        _frameData.setIdle( true );
    }
    else
        _frameData.setIdle( false );

    _numFramesAA = 0;
}
```

Event Handling Events are sent by the render clients to the application using eq::Config::sendEvent. At the end of the frame, Config::finishFrame calls Config::handleEvents to perform the event handling. The default implementation processes all pending events by calling Config::handleEvent for each of them.

Since eqPly uses event-driven execution, the config maintains a dirty state to know when a redraw is needed.

The eqPly example implements Config::handleEvent to provide the various reactions to user input, most importantly camera updates based on mouse events. The camera position has to be handled correctly regarding latency, and is therefore saved in the frame data.

The event handling code reproduced here is just showing the handling of one type of event. A detailed description on how to customize event handling can be found in Section 7.2.1:

```
        case eq::Event::CHANNEL_POINTER_WHEEL:
        {
            _frameData.moveCamera( -0.05f * event->data.pointerWheel.yAxis,
                                   0.f,
                                   0.05f * event->data.pointerWheel.xAxis );
            _redraw = true;
            return true;
        }
```

Model Handling Models in eqPly are static, and therefore the render clients only need to map one instance of the model per node. The mapped models are shared by all pipe render threads, which access them read-only.

Multiple models can be loaded in eqPly. A configuration has a default model, stored in InitData, and one model per view, stored and distributed using the View.

The loaded models are evenly distributed over the available views of the configuration, as shown in Figure 16.

The channel acquires the model during rendering from the config, using the model identifier from its current view, or from the frame data if no view is configured.

The per-process config instance maintains the mapped models, and lazily maps new models, which are registered by the application process. Since the model loading may be called concurrently from different pipe render threads, it is protected by a mutex:

```
const Model* Config::getModel( const eq::uint128_t& modelID )
{
    if( modelID == 0 )
        return 0;

    // Protect if accessed concurrently from multiple pipe threads
    const eq::Node* node = getNodes().front();
    const bool needModelLock = (node->getPipes().size() > 1);
    lunchbox::ScopedWrite _mutex( needModelLock ? &_modelLock : 0 );

    const size_t nModels = _models.size();
    LBASSERT( _modelDist.size() == nModels );

    for( size_t i = 0; i < nModels; ++i )
    {
        const ModelDist* dist = _modelDist[ i ];
        if( dist->getID() == modelID )
            return _models[ i ];
    }

    _modelDist.push_back( new ModelDist );
    Model* model = _modelDist.back()->loadModel( getApplicationNode(),
                                                 getClient(), modelID );
    LBASSERT( model );
    _models.push_back( model );

    return model;
}
```

Layout and View Handling For layout and model selection, eqPly maintains an active view and canvas. The identifier of the active view is stored in the frame data, which is used by the render client to highlight it using a different background color. The active view can be selected by clicking into a view, or by cycling through all views using a keyboard shortcut.

The model of the active view can be changed using a keyboard shortcut. The model is view-specific, and therefore the model identifier for each view is stored on the view, which is used to retrieve the model on the render clients.

View-specific data is not limited to a model. Applications can choose to make any application-specific data view-specific, e.g., cameras, rendering modes or annotations. A view is a generic concept for an application-specific view on data, eqPly is simply using different models to illustrate the concept:

```
void Config::_switchCanvas()
{
    const eq::Canvases& canvases = getCanvases();
    if( canvases.empty( ))
        return;

    _frameData.setCurrentViewID( eq::UUID( ));

    if( !_currentCanvas )
    {
        _currentCanvas = canvases.front();
```

```
        return;
    }

    eq::CanvasesCIter i = stde::find( canvases, _currentCanvas );
    LBASSERT( i != canvases.end( ));

    ++i;
    if( i == canvases.end( ))
        _currentCanvas = canvases.front();
    else
        _currentCanvas = *i;
    _switchView(); // activate first view on canvas
}

void Config::_switchView()
{
    const eq::Canvases& canvases = getCanvases();
    if( !_currentCanvas && !canvases.empty( ))
        _currentCanvas = canvases.front();

    if( !_currentCanvas )
        return;

    const eq::Layout* layout = _currentCanvas->getActiveLayout();
    if( !layout )
        return;

    const View* view = _getCurrentView();
    const eq::Views& views = layout->getViews();
    LBASSERT( !views.empty( ));

    if( !view )
    {
        _frameData.setCurrentViewID( views.front()->getID( ));
        return;
    }

    eq::ViewsCIter i = std::find( views.begin(), views.end(), view );
    if( i != views.end( ))
        ++i;
    if( i == views.end( ))
        _frameData.setCurrentViewID( eq::UUID( ));
    else
        _frameData.setCurrentViewID( (*i)->getID( ));
}
```

The layout of the canvas with the active view can also be dynamically switched using a keyboard shortcut. The first canvas using the layout is found, and then the next layout of the configuration is set on this canvas.

Switching a layout causes the initialization and de-initialization task methods to be called on the involved channels, and potentially windows, pipes and nodes. This operation might fail, which may cause the config to stop running.

Layout switching is typically used to change the presentation of views at runtime. The source code omitted for brevity.

7.1.5. Node

For each active render client, one eq::Node instance is created on the appropriate machine. Nodes are only instantiated on their render client processes, i.e., each process will only have one instance of the eq::Node class. The application process might also have a node class, which is handled in exactly the same way as the render client nodes. The application and render clients might use a different node factory, instantiating a different types of eq::Config... eq::Channel.

All dynamic data is multi-buffered in eqPly. During initialization, the eqPly::Node relaxes the thread synchronization between the node and pipe threads, unless the configuration file overrides this. Section 7.2.3 provides a detailed explanation of thread synchronization modes in Equalizer.

During node initialization the static, per-config data is mapped to a local instance using the identifier passed from Config::init. No pipe, window or channel tasks methods are executed before Node::configInit has returned:

```
bool Node::configInit( const eq::uint128_t& initID )
{
    // All render data is static or multi-buffered, we can run asynchronously
    if( getIAttribute( IATTR_THREAD_MODEL ) == eq::UNDEFINED )
        setIAttribute( IATTR_THREAD_MODEL, eq::ASYNC );

    if( !eq::Node::configInit( initID ))
        return false;

    Config* config = static_cast< Config* >( getConfig( ));
    if( !config->loadData( initID ))
    {
        setError( ERROR_EQPLY_MAPOBJECT_FAILED );
        return false;
    }
    return true;
}
```

The actual mapping of the static data is done by the config. The config retrieves the distributed InitData. The object is directly unmapped since it is static, and therefore all data has been retrieved during :

```
bool Config::loadData( const eq::uint128_t& initDataID )
{
    if( !_initData.isAttached( ))
    {
        const uint32_t request = mapObjectNB( &_initData, initDataID,
                                              co::VERSION_OLDEST,
                                              getApplicationNode( ));
        if( !mapObjectSync( request ))
            return false;
        unmapObject( &_initData ); // data was retrieved, unmap immediately
    }
    else // appNode, _initData is registered already
    {
        LBASSERT( _initData.getID() == initDataID );
    }
    return true;
}
```

7.1.6. Pipe

All task methods for a pipe and its children are executed in a separate thread. This approach optimizes GPU usage, since all tasks are executed serially and therefore do not compete for resources or cause OpenGL context switches. Multiple GPU threads run in parallel with each other.

The pipe uses an eq::SystemPipe, which abstracts and manages window-system-specific code for the GPU, e.g., an X11 Display connection for the glX pipe system.

Initialization and Exit Pipe threads are not explicitly synchronized with each other in eqPly due to the use of the async thread model. Pipes might be rendering different frames at any given time. Therefore frame-specific data has to be allocated for each pipe thread, which is only the frame data in eqPly. The frame data is a

member variable of the eqPly::Pipe, and is mapped to the identifier provided by the initialization data:

```
bool Pipe::configInit( const eq::uint128_t& initID )
{
    if( !eq::Pipe::configInit( initID ))
        return false;

    Config*         config      = static_cast<Config*>( getConfig( ));
    const InitData& initData    = config->getInitData();
    const eq::uint128_t&  frameDataID = initData.getFrameDataID();

    return config->mapObject( &_frameData, frameDataID );
}
```

The initialization in eq::Pipe does the GPU-specific initialization by calling configInitSystemPipe. which is window-system-dependent. On AGL the display ID is determined, and on glX the display connection is opened.

The config exit function is similar to the config initialization. The frame data is unmapped and GPU-specific data is de-initialized by eq::Config::exit:

```
bool Pipe::configExit()
{
    eq::Config* config = getConfig();
    config->unmapObject( &_frameData );

    return eq::Pipe::configExit();
}
```

Window System Equalizer supports multiple window system interfaces, at the moment glX/X11, WGL and AGL/Carbon. Some operating systems, and therefore some Equalizer versions, support multiple window systems concurrently.

Each pipe might use a different window system for rendering, which is determined before Pipe::configInit by Pipe::selectWindowSystem. The default implementation of selectWindowSystem uses the first supported window system.

The eqPly examples allows selecting the window system using a command line option. Therefore the implementation of selectWindowSystem is overwritten and returns the specified window system, if supported:

```
eq::WindowSystem Pipe::selectWindowSystem() const
{
    const Config* config = static_cast<const Config*>( getConfig( ));
    return config->getInitData().getWindowSystem();
}
```

Carbon/AGL Thread Safety Parts of the Carbon API used for window and event handling in the AGL window system are not thread safe. The application has to call eq::Global::enterCarbon before any thread-unsafe Carbon call, and eq::Global::leaveCarbon afterwards. These functions should be used only during window initialization and exit, not during rendering. For implementation reasons enterCarbon might block up to 50 milliseconds. Carbon calls in the window event handling routine Window::processEvent are thread-safe, since the global carbon lock is set in this method. Please contact the Equalizer developer mailing list if you need to use Carbon calls on a per-frame basis.

Frame Control All task methods for a given frame of the pipe, window and channel entities belonging to the thread are executed in one block, starting with Pipe::frameStart and finished by Pipe::finishFrame. The frame start callback is therefore the natural place to update all frame-specific data to the version belonging to the frame.

In eqPly, the version of the only frame-specific object FrameData is passed as the per-frame id from Config::startFrame to the frame task methods. The pipe uses this version to update its instance of the frame data to the current version, and unlocks its child entities by calling startFrame:

```
void Pipe::frameStart( const eq::uint128_t& frameID, const uint32_t frameNumber)
{
    eq::Pipe::frameStart( frameID, frameNumber );
    _frameData.sync( frameID );
}
```

7.1.7. Window

The Equalizer window abstracts an OpenGL drawable and a rendering context. When using the default window initialization functions, all windows of a pipe share the OpenGL context. This allows reuse of OpenGL objects such as display lists and textures between all windows of one pipe.

The window uses an eq::SystemWindow, which abstracts and manages window-system-specific handles to the drawable and context, e.g., an X11 window XID and GLXContext for the glX window system.

The window class is the natural place for the application to maintain all data specific to the OpenGL context.

Window System Interface The particulars of creating a window and OpenGL context depend on the window system used. One can either use the implementation provided by the operating system, e.g., AGL, WGL or glX, or some higher-level toolkit, e.g., Qt.

All window-system specific functionality is implemented by a specialization of eq::SystemWindow. The SystemWindow class defines the minimal interface to be implemented for a new window system. Each Window uses one SystemWindow during execution. This separation allows an easy implementation and adaption to another window system or application.

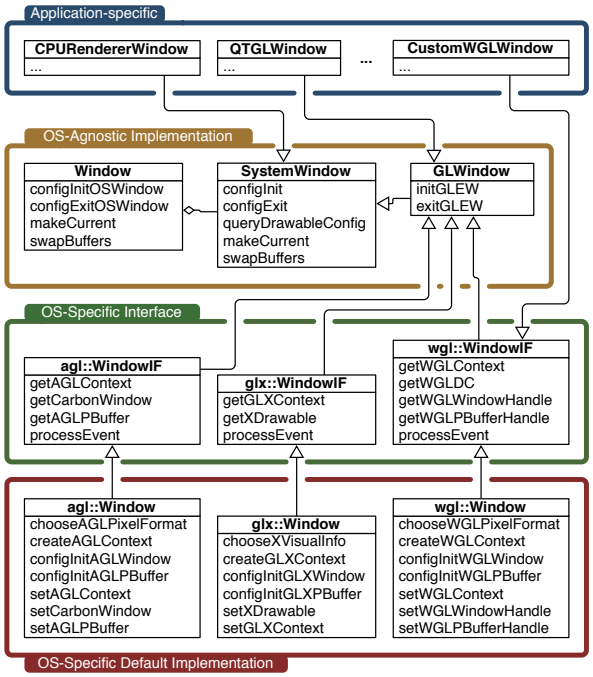


Figure 33: SystemWindow UML Class Hierarchy

Equalizer provides a generic interface and implementation for the three most common window systems through the OpenGL specific eq::GLWindow class: AGL, WGL and glX. The interfaces define the minimal functionality needed to reuse other window system specific classes, for example the AGL, WGL and glX event handlers. The separation of the OpenGL calls from the SystemWindow permits to implement window systems which don't use any OpenGL context and therefore to use a different renderer. The implementation

derived from these interfaces provides a sample implementation which honors all configurable window attributes.

Initialization and Exit The initialization sequence uses multiple, override-able task methods. The main task method configInit calls first configInitSystemWindow, which creates and initializes the SystemWindow for this window. The SystemWindow initialization code is implementation specific. If the SystemWindow was initialized successfully, configInit calls configInitGL, which performs the generic OpenGL state initialization. The default implementation sets up some typical OpenGL state, e.g., it enables the depth test. Most nontrivial applications do override this task method.

The SystemWindow initialization takes into account various attributes set in the configuration file. Attributes include the size of the various frame buffer planes (color, alpha, depth, stencil) as well as other framebuffer attributes, such as quad-buffered stereo, doublebuffering, fullscreen mode and window decorations. Some of the attributes, such as stereo, doublebuffer and stencil can be set to eq::AUTO, in which case the Equalizer default implementation will test for their availability and enable them if possible.

For the window-system specific initialization, eqPly uses the default Equalizer implementation. The eqPly window initialization only overrides the OpenGL-specific initialization function configInitGL to initialize a state object and an overlay logo. This function is only called if an OpenGL context was created and made current:

```
bool Window::configInitGL( const eq::uint128_t& initID )
{
    if( !eq::Window::configInitGL( initID ))
        return false;

    glLightModeli( GL_LIGHT_MODEL_LOCAL_VIEWER, 1 );
    glEnable( GL_CULL_FACE ); // OPT - produces sparser images in DB mode
    glCullFace( GL_BACK );

    LBASSERT( !_state );
    _state = new VertexBufferState( getObjectManager( ));

    const Config*    config   = static_cast< const Config* >( getConfig( ));
    const InitData& initData = config->getInitData();

    if( initData.showLogo( ))
        _loadLogo();

    if( initData.useGLSL() )
        _loadShaders();

    return true;
}
```

The state object is used to handle the creation of OpenGL objects in a multipipe, multithreaded execution environment. It uses the object manager of the eq::Window, which is described in detail in Section 7.1.7.

The logo texture is loaded from the file system and bound to a texture ID used later by the channel for rendering. A code listing is omitted, since the code consists of standard OpenGL calls and is not Equalizer-specific.

The window exit happens in the reverse order of the initialization. First, configExitGL is called to de-initialize OpenGL, followed by configExitSystemWindow which de-initializes the drawable and context and deletes the SystemWindow allocated in configInitSystemWindow.

The window OpenGL exit function of eqPly de-allocates all OpenGL objects. The object manager does not delete the object in its destructor, since it does not know if an OpenGL context is still current.

```
bool Window::configExitGL()
{
    if( _state && !_state->isShared( ))
        _state->deleteAll();

    delete _state;
    _state = 0;

    return eq::Window::configExitGL();
}
```

Object Manager The object manager is, strictly speaking, not a part of the window. It is mentioned here since the eqPly window uses an object manager.

The state object in eqPly gathers all rendering state, which includes an object manager for OpenGL object allocation.

The object manager (OM) is a utility class and can be used to manage OpenGL objects across shared contexts. Typically one OM is used for each set of shared contexts of a single GPU.

Each eq::Window has an object manager with the key type const void*, for as long as it is initialized. Each window can have a shared context window. The OM is shared with this shared context window. The shared context window is set by default to the first window of each pipe, and therefore the OM will be shared between all windows of a pipe. The same key is used by all contexts to get the OpenGL name of an object, thus reusing of the same object within the same share group. The method eq::Window::setSharedContextWindow can be used to set up a different context sharing.

eqPly uses the window's object manager in the rendering code to obtain the OpenGL objects for a given data item. The address of the data item to be rendered is used as the key.

For the currently supported types of OpenGL objects please refer to the API documentation on the Equalizer website. For each object, the following functions are available:

supportsObjects() returns true if the usage for this particular type of objects is supported. For objects available in OpenGL 1.1 or earlier, this function is not implemented.

getObject(key) returns the object associated with the given key, or FAILED.

newObject(key) allocates a new object for the given key. Returns FAILED if the object already exists or if the allocation failed.

obtainObject(key) convenience function which gets or obtains the object associated with the given key. Returns FAILED only if the object allocation failed.

deleteObject(key) deletes the object.

7.1.8. Channel

The channel is the heart of the application's rendering code, it executes all task methods needed to update the configured views. It performs the various rendering operations for the compounds. Each channel has a set of task methods to execute the clear, draw, readback and assemble stages needed to render a frame.

Initialization and Exit During channel initialization, the near and far planes are set to reasonable values to contain the whole model. During rendering, the near and far planes are adjusted dynamically to the current model position:

```
bool Channel::configInit( const eq::uint128_t& initID )
{
    if( !eq::Channel::configInit( initID ))
        return false;

    setNearFar( 0.1f, 10.0f );
    _model = 0;
    _modelID = 0;
    return true;
}
```

Rendering The central rendering routine is Channel::frameDraw. This routine contains the application's OpenGL rendering code, which uses the contextual information provided by Equalizer. As most of the other task methods, frameDraw is called in parallel by Equalizer on all pipe threads in the configuration. Therefore the rendering must not write to shared data, which is the case for all major scene graph implementations.

In eqPly, the OpenGL context is first set up using various apply convenience methods from the base Equalizer channel class. Each of the apply methods uses the corresponding get methods and then calls the appropriate OpenGL functions. It is also possible to just query the values from Equalizer using the get methods, and use them to set up the OpenGL state appropriately, for example by passing the parameters to the renderer used by the application.

For example, the implementation for eq::Channel::applyBuffer does set up the correct rendering buffer and color mask, which depends on the current eye pass and possible anaglyphic stereo parameters:

```
void eq::Channel::applyBuffer()
{
    glReadBuffer( getReadBuffer( ));
    glDrawBuffer( getDrawBuffer( ));

    const ColorMask& colorMask = getDrawBufferMask();
    glColorMask( colorMask.red, colorMask.green, colorMask.blue, true );
}
```

The contextual information has to be used to render the view as expected by Equalizer. Failure to use certain information will result in incorrect rendering for some or all configurations. The channel render context consist of:

Buffer The OpenGL 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 The two-dimensional pixel viewport restricting the rendering area within the channel. For correct operations, both glViewport and glScissor have to be used. The pixel viewport is influenced by the destination channel's viewport definition and compound viewports set for sort-first/2D decompositions.

Frustum The same frustum parameters as defined by glFrustum. Typically the frustum used to set up the OpenGL projection matrix. The frustum is influenced by the destination channel's view definition, compound viewports, head matrix and the current eye pass. If the channel has a subpixel parameter, the frustum will be jittered before it is applied. Please refer to Section 7.2.10 for more information.

Head Transformation A transformation matrix positioning the frustum. This is typically an identity matrix and is used for off-axis frusta 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. It is influenced by the compound range attribute.

The rendering first checks a number of preconditions, such as if the rendering was interrupted by a reset and if the idle anti-aliasing is finished. Then the near and far planes are re-computed, before the rendering context is applied:

```
void Channel::frameDraw( const eq::uint128_t& frameID )
{
    if( stopRendering( ))
        return;

    _initJitter();
    if( _isDone( ))
        return;

    Window* window = static_cast< Window* >( getWindow( ));
    VertexBufferState& state = window->getState();
    const Model* oldModel = _model;
    const Model* model = _getModel();

    if( oldModel != model )
        state.setFrustumCulling( false ); // create all display lists/VBOs

    if( model )
        _updateNearFar( model->getBoundingSphere( ));

    eq::Channel::frameDraw( frameID ); // Setup OpenGL state
```

The frameDraw method in eqPly calls the frameDraw method from the parent class, the Equalizer channel. The default frameDraw method uses the apply convenience functions to setup the OpenGL state for all render context information, except for the range which will be used later during rendering:

```
void eq::Channel::frameDraw( const uint128_t& frameID )
{
    applyBuffer();
    applyViewport();

    glMatrixMode( GL_PROJECTION );
    glLoadIdentity();
    applyFrustum();

    glMatrixMode( GL_MODELVIEW );
    glLoadIdentity();
    applyHeadTransform();
}
```

After the basic view setup, a directional light is configured, and the model is positioned using the camera parameters from the frame data. The camera parameters are transported using the frame data to ensure that all channels render a given frame using the same position.

Three different ways of coloring the object are possible: Using the colors of the mode, using a unique per-channel color to demonstrate the decomposition as shown in Figure 34, or using solid white for anaglyphic stereo. The model colors are per-vertex and are set during rendering, whereas the unique per-channel color is set in frameDraw for the whole model:

```
glLightfv( GL_LIGHT0, GL_POSITION, lightPosition );
glLightfv( GL_LIGHT0, GL_AMBIENT,  lightAmbient  );
glLightfv( GL_LIGHT0, GL_DIFFUSE,  lightDiffuse  );
glLightfv( GL_LIGHT0, GL_SPECULAR, lightSpecular );

glMaterialfv( GL_FRONT, GL_AMBIENT,   materialAmbient );
glMaterialfv( GL_FRONT, GL_DIFFUSE,   materialDiffuse );
glMaterialfv( GL_FRONT, GL_SPECULAR,  materialSpecular );
glMateriali(  GL_FRONT, GL_SHININESS, materialShininess );

const FrameData& frameData = _getFrameData();
glPolygonMode( GL_FRONT_AND_BACK,
               frameData.useWireframe() ? GL_LINE : GL_FILL );

const eq::Vector3f& position = frameData.getCameraPosition();

glMultMatrixf( frameData.getCameraRotation().array );
glTranslatef( position.x(), position.y(), position.z() );
glMultMatrixf( frameData.getModelRotation().array );

if( frameData.getColorMode() == COLOR_DEMO )
{
    const eq::Vector3ub color = getUniqueColor();
    glColor3ub( color.r(), color.g(), color.b() );
}
else
    glColor3f( .75f, .75f, .75f );
```

Finally the model is rendered. If the model was not loaded during node initialization, a quad is drawn in its place:

```
if( model )
    _drawModel( model );
else
{
    glNormal3f( 0.f, -1.f, 0.f );
    glBegin( GL_TRIANGLE_STRIP );
        glVertex3f(  .25f, 0.f,  .25f );
        glVertex3f( -.25f, 0.f,  .25f );
        glVertex3f(  .25f, 0.f, -.25f );
        glVertex3f( -.25f, 0.f, -.25f );
    glEnd();
}
```

To draw the model, a helper class for view frustum culling is set up, using the view frustum from Equalizer (projection and view matrix) and the camera position (model matrix) from the frame data. The frustum helper computes the six frustum planes from the projection and modelView matrices. During rendering, the bounding spheres of the model are tested against these planes to determine the visibility with the frustum.

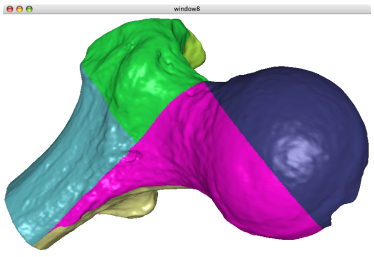


Figure 34: Destination View of a DB Compound using Demonstrative Coloring

Furthermore, the render state from the window and the database range from the channel is obtained. The render state manages display list or VBO allocation:

```
void Channel::_drawModel( const Model* scene )
{
    Window* window = static_cast< Window* >( getWindow( ));
    VertexBufferState& state = window->getState();
    const FrameData& frameData = _getFrameData();
```

```
if( frameData.getColorMode() == COLOR_MODEL && scene->hasColors( ))
    state.setColors( true );
else
    state.setColors( false );
state.setChannel( this );

// Compute cull matrix
const eq::Matrix4f& rotation = frameData.getCameraRotation();
const eq::Matrix4f& modelRotation = frameData.getModelRotation();
eq::Matrix4f position = eq::Matrix4f::IDENTITY;
position.set_translation( frameData.getCameraPosition());

const eq::Frustumf& frustum = getFrustum();
const eq::Matrix4f projection = useOrtho() ? frustum.compute_ortho_matrix():
                                             frustum.compute_matrix();
const eq::Matrix4f& view = getHeadTransform();
const eq::Matrix4f model = rotation * position * modelRotation;

state.setProjectionModelViewMatrix( projection * view * model );
state.setRange( &getRange().start);

const eq::Pipe* pipe = getPipe();
const GLuint program = state.getProgram( pipe );
if( program != VertexBufferState::INVALID )
    glUseProgram( program );

scene->cullDraw( state );
```

The model data is spatially organized in a 3-dimensional kD-tree[22] for efficient view frustum culling. When the model is loaded by Node::configInit, it is preprocessed into the kD-tree. During this preprocessing step, each node of the tree gets a database range assigned. The root node has the range [0, 1], its left child [0, 0.5] and its right child [0.5, 1], and so on for all nodes in the tree. The preprocessed model is saved in a binary format for accelerating subsequent loading.

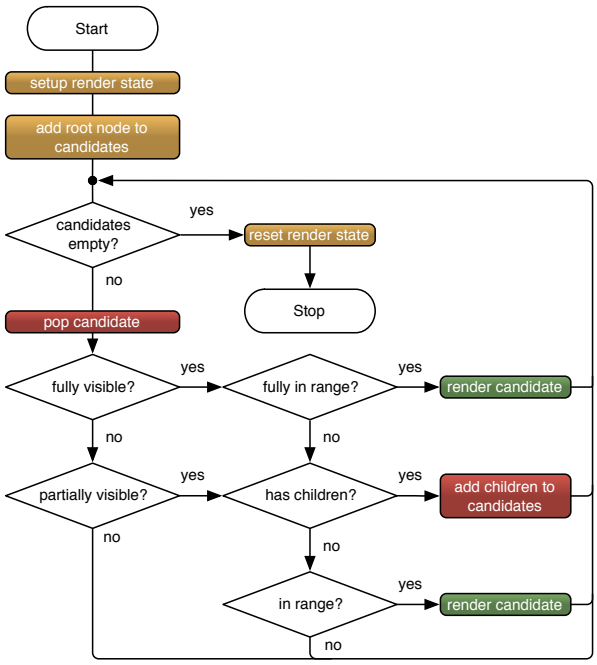


Figure 35: Main Render Loop

The rendering loop maintains a list of candidates to render, which initially contains the root node. Each candidate of this list is tested for full visibility against the frustum and range, and rendered if visible. It is dropped if it is fully invisible or fully out of range. If it is partially visible or partially in range, the children of the node are added to the candidate list.

Figure 35 shows a flow chart of the rendering algorithm, which performs efficient view frustum and range culling.

[22] http://en.wikipedia.org/wiki/Kd-tree

The actual rendering uses display lists or vertex buffer objects. These OpenGL objects are allocated using the object manager. The rendering is done by the leaf nodes, which are small enough to store the vertex indices in a short value for optimal performance with VBOs. The leaf nodes reuse the objects stored in the object manager, or create and set up new objects if it was not yet set up. Since one object manager is used per thread (pipe), this allows a thread-safe sharing of the compiled display lists or VBOs across all windows of a pipe.

The main rendering loop is implemented in VertexBufferRoot::cullDraw(), and not duplicated here.

Assembly Like most applications, eqPly uses most of the default implementation of the frameReadback and frameAssemble task methods. To implement an optimization and various customizations, frameReadback is overwritten. eqPly does not need the alpha channel on the destination view. The output frames are flagged to ignore alpha, which allows the compressor to drop 25% of the data during image transfer. Furthermore, compression can be disabled and the compression quality can be changed at runtime to demonstrate the impact of compression on scalable rendering:

```
void Channel::frameReadback( const eq::uint128_t& frameID )
{
    if( stopRendering() || _isDone( ))
        return;

    const FrameData& frameData = _getFrameData();
    const eq::Frames& frames = getOutputFrames();
    for( eq::FramesCIter i = frames.begin(); i != frames.end(); ++i )
    {
        eq::Frame* frame = *i;
        // OPT: Drop alpha channel from all frames during network transport
        frame->setAlphaUsage( false );

        if( frameData.isIdle( ))
            frame->setQuality( eq::Frame::BUFFER_COLOR, 1.f );
        else
            frame->setQuality( eq::Frame::BUFFER_COLOR, frameData.getQuality());

        if( frameData.useCompression( ))
            frame->useCompressor( eq::Frame::BUFFER_COLOR, EQ_COMPRESSOR_AUTO );
        else
            frame->useCompressor( eq::Frame::BUFFER_COLOR, EQ_COMPRESSOR_NONE );
    }

    eq::Channel::frameReadback( frameID );
}
```

The frameAssemble method is overwritten for the use of Subpixel compound with idle software anti-aliasing, as described in Section 7.2.10.

7.2. Advanced Features

This section discusses important features not covered by the previous eqPly section. Where possible, code examples from the Equalizer distribution are used to illustrate usage of the specific feature. Its purpose is to provide information on how to address a typical problem or use case when developing an Equalizer-based application.

7.2.1. Event Handling

Event handling requires flexibility. On one hand, the implementation differs slightly for each operating and window system due to conceptual differences in the specific

implementation. On the other hand, each application and widget set has its own model on how events are to be handled. Therefore, event handling in Equalizer is customizable at any stage of the processing, to the extreme of making it possible to disable all event handling code in Equalizer. In this aspect, Equalizer substantially differs from GLUT, which imposes an event model and hides most of the event handling in glutMainLoop.

The default implementation provides a convenient, easily accessible event framework, while allowing all necessary customizations. It gathers all events from all node processes in the main thread of the application, so that the developer only has to implement Config::processEvent to update its data based on the preprocessed, generic keyboard and mouse events. It is very easy to use and similar to a GLUT-based implementation.

Threading Events are received and processed by the pipe thread a window belongs to. For AGL, Equalizer internally forwards the events from the main thread, where it is received, to the appropriate pipe thread. This model allows window and channel modifications which are naturally thread-safe, since they are executed from the corresponding render thread and therefore cannot interfere with rendering operations.

Message Pump To dispatch events, Equalizer 'pumps' the native events. On WGL and GLX, this happens on each thread with windows, whereas on AGL it happens on the main thread and on each pipe thread. By default, Equalizer pumps these events automatically for the application in-between executing task methods.

The method Pipe::createMessagePump is called by Equalizer during application and pipe thread initialization before Pipe::configInit to create a message pump for the given pipe. For AGL, this affects the node thread and pipe threads, since the node thread message pump needs to dispatch the events to the pipe thread event queue. Custom message pumps may be implemented, and it is valid to return no message pump to disable message dispatch for the respective pipe.

If the application disables message pumping in Equalizer, it has to make sure the events are processed, as it often done by external widget sets such as Qt.

Event Data Flow Events are received by an event handler. The event handler finds the eq::SystemWindow for the event. It then creates a generic Event, which holds the event data in an independent format. The original native event and this generic Event form the SystemWindowEvent, which is passed to the concrete SystemWindow for processing.

The purpose of the SystemWindow processing method, processEvent, is to perform window-system specific event processing. For example, AGLWindow::processEvent calls aglUpdateContext whenever a resize event is received. For further, generic processing, the Event is passed on to Window::processEvent. This Event no longer contains the native event.

Window::processEvent is responsible for handling the event locally and for translating it into a generic ConfigEvent. Pointer events are translated and dispatched to the channel under the

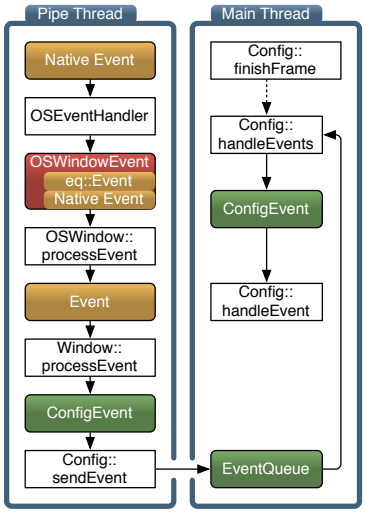


Figure 36: Event Processing

mouse pointer. The window or channel processEvent method perform local updates such as setting the pixel viewport before forwarding the event to the application main loop. If the event was processed, processEvent has to return true. If false is returned to the event handler, the event will be passed to the previously installed, window-system-specific event handling function.

After local processing, events are send using Config::sendEvent to the application node. On reception, they are queued in the application thread. After a frame has been finished, Config::finishFrame calls Config::handleEvents. The default implementation of this method provides non-blocking event processing, that is, it calls Config::handleEvent for each queued event. By overriding handleEvents, event-driven execution can easily be implemented.

Figure 36 shows the overall data flow of an event.

Default Implementation Equalizer provides an AGLEventHandler, GLXEventHandler and WGLEventHandler, which handle events for an AGLWindowIF, GLXWindowIF and WGLWindowIF, respectively. Figure 37 illustrates the class hierarchy for event processing.

The concrete implementation of these window interfaces is responsible for setting up and de-initializing event handling.

Carbon events issued for AGL windows are initially received by the node main thread, and automatically dispatched to the pipe thread. The pipe thread will dispatch the event to the appropriate event handler. One AGLEventHandler per window is used, which is created during AGLWindow::configInit. The event handler installs a Carbon event handler for all important events. The event handler uses an AGLWindowEvent to pass the Carbon EventRef to AGLWindowIF::processEvent. During window exit, the installed Carbon handler is removed when the window's event handler is deleted. No event handling is set up for pbuffers.

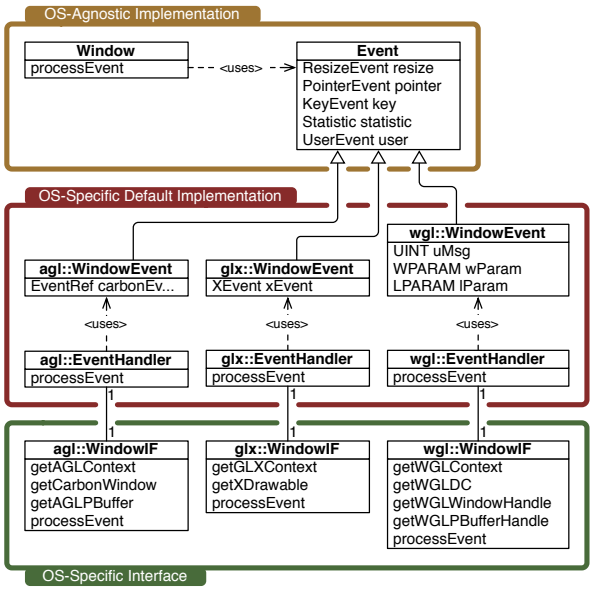


Figure 37: UML Class Diagram for Event Handling

For each GLX window, one GLXEventHandler is allocated. FBOs and pbuffers are handled in the same way as window drawables. The event dispatch finds the corresponding event handler for each received event, which is then used to process the event in a fashion similar to AGL. The GLXWindowEvent passes the XEvent to GLXWindowIF::processEvent.

Each WGLWindow allocates one WGLEventHandler when the window handle is set. The WGLEventHandler passes the native event parameters uMsg, wParam and lParam to WGLWindowIF::processEvent as part of the WGLWindowEvent. No event handling is set up for pbuffers.

Custom Events in eqPixelBench The eqPixelBench example is a benchmark program to measure the pixel transfer rates from and to the framebuffer of all channels within a configuration. It uses custom config events to send the gathered data to the application. It is much simpler than the eqPly example since it does not provide any useful rendering or user interaction.

The rendering routine of eqPixelBench in Channel::frameDraw loops through a number of pixel formats and types. For each of them, it measures the time to readback and assemble a full-channel image. The format, type, size and time is recorded in a config event, which is sent to the application. The new custom event types are defined as user events:

```
enum ConfigEventType
{
    READBACK = eq::Event::USER,
    ASSEMBLE,
    START_LATENCY
};
```

The Config::sendEvent method provides an eq::EventOCommand to which additional data can be appended. The event output command is derived from the Collage co::DataOStream which provides a convenient std::ostream-like interface to send data between nodes. The event is sent when the command looses its scope, that is, immediately after the following call in eqPixelBench::Channel:

```
getConfig()->sendEvent( type )
    << msec << name << area << formatType << dataSizeGPU << dataSizeCPU;
```

Each event has a type which is used to identify it by the config processing function. On the application end, Config::handleEvent receives an eq::EventICommand, which provides deserialization capabilities of the received data. The underlying co::DataIStream does perform endian conversion if the endianess of the sending and receiving nodes does not match. The event data is decoded and printed in a nicely formatted way:

```
bool Config::handleEvent( eq::EventICommand command )
{
    switch( command.getEventType( ))
    {
    case READBACK:
    case ASSEMBLE:
    case START_LATENCY:
    {
        switch( command.getEventType( ))
        {
        case READBACK:
            std::cout << "readback";
            break;
        case ASSEMBLE:
            std::cout << "assemble";
            break;
        case START_LATENCY:
        default:
            std::cout << "         ";
        }

        const float msec = command.get< float >();
        const std::string& name = command.get< std::string >();
        const eq::Vector2i area = command.get< eq::Vector2i >();
        const std::string& formatType = command.get< std::string >();
        const uint64_t dataSizeGPU = command.get< uint64_t >();
        const uint64_t dataSizeCPU = command.get< uint64_t >();

        std::cout << " \"" << name << "\" " << formatType
                  << std::string( 32-formatType.length(), ' ' ) << area.x()
                  << "x" << area.y() << ": ";
```

7.2.2. Error Handling

All Equalizer entities use an error code to report error conditions during various operations. This error code is reported back from the render processes to the application config instance. The last error is propagated from the failed resource to the config object, where it can be queried by the application using Config::getError.

Each error emitted by Equalizer code has a textual description. This string is automatically used for printing an Error on an std::ostream, and can be queried from the fabric::ErrorRegistry, which is accessible from fabric::Global.

Applications can register additional error codes and strings. The eVolve example uses this to report if required OpenGL extensions are missing. The registration of new error codes is not thread-safe, that is, no other thread should use the error registry when it is modified. It is therefore strongly advised to register application-specific errors before eq::init and clear them after eq::exit:

```
int main( const int argc, char** argv )
{
    // 1. Equalizer initialization
    NodeFactory nodeFactory;
    eVolve::initErrors();

    if( !eq::init( argc, argv, &nodeFactory ))

  ...

    eq::exit();
    eVolve::exitErrors();
    return ret;
}
```

When the application returns false from a configInit task method due to an application-specific error, it should set an error code using setError. Application-specific errors can have any value equal or greater than eq::ERROR_CUSTOM:

```
    /** Defines errors produced by eVolve. */
    enum Error
    {
        ERROR_EVOLVE_ARB_SHADER_OBJECTS_MISSING = eq::ERROR_CUSTOM,
        ERROR_EVOLVE_EXT_BLEND_FUNC_SEPARATE_MISSING,
        ERROR_EVOLVE_ARB_MULTITEXTURE_MISSING,
        ERROR_EVOLVE_LOADSHADERS_FAILED,
        ERROR_EVOLVE_LOADMODEL_FAILED,
        ERROR_EVOLVE_MAPOBJECT_FAILED
    };
```

During initialization, eVolve may use these error codes:

```
bool Window::configInitGL( const eq::uint128_t& initID )
{
    Pipe*     pipe     = static_cast<Pipe*>( getPipe() );
    Renderer* renderer = pipe->getRenderer();

    if( !renderer )
        return false;

    if( !GLEW_ARB_shader_objects )
    {
        setError( ERROR_EVOLVE_ARB_SHADER_OBJECTS_MISSING );
        return false;
    }
```

It is not required to register an error string for each application-specific error. Registering a string will however cause error printing to use this string instead of using only the numerical error value. Applications may also redefine existing error strings to their convenience, e.g., for internationalization purposes:

```
namespace
{
struct ErrorData
{
    const uint32_t code;
    const std::string text;
};

ErrorData _errors[] = {
    { ERROR_EVOLVE_ARB_SHADER_OBJECTS_MISSING,
      "GL_ARB_shader_objects extension missing" },
    { ERROR_EVOLVE_EXT_BLEND_FUNC_SEPARATE_MISSING,
      "GL_ARB_shader_objects extension missing" },
    { ERROR_EVOLVE_ARB_MULTITEXTURE_MISSING,
      "GL_ARB_shader_objects extension missing" },
    { ERROR_EVOLVE_LOADSHADERS_FAILED, "Can't load shaders" },
    { ERROR_EVOLVE_LOADMODEL_FAILED, "Can't load model" },
    { ERROR_EVOLVE_MAPOBJECT_FAILED,
      "Mapping data from application process failed" },

    { 0, "" } // last!
};
}

void initErrors()
{
    eq::fabric::ErrorRegistry& registry = eq::fabric::Global::getErrorRegistry();

    for( size_t i=0; _errors[i].code != 0; ++i )
        registry.setString( _errors[i].code, _errors[i].text );
}

void exitErrors()
{
    eq::fabric::ErrorRegistry& registry = eq::fabric::Global::getErrorRegistry();

    for( size_t i=0; _errors[i].code != 0; ++i )
        registry.eraseString( _errors[i].code );
}
```

7.2.3. Thread Synchronization

Equalizer applications use multiple, potentially asynchronous execution threads. The default execution model is designed on making the porting of existing applications as easy as possible, as described in Section 5.4. The default, per-node thread synchronization provided by Equalizer can be relaxed by advanced applications to gain better performance through higher asynchronicity.

Threads The application or node main thread is the primary thread of each process and executes the main function. The application and render clients initialize the local node for communications with other nodes, including the server, using Client::initLocal. The client derives from co::LocalNode which does provide most of the communication logic‘.

During this initialization, Collage creates and manages two threads for communication, the receiver thread and the command thread. Normally no application code is executed from these two threads.

The receiver thread manages the network connections to other nodes and receives data. It dispatches the received data either to the application threads, or to the command thread.

The command thread processes internal requests from other nodes, for example during co::Object mapping. In some special cases the command thread executes

application code, for example when a remote node maps a static or unbuffered object, Object::getInstanceData is called from the command thread.

The receiver and command thread are terminated when the application stops network communications using Client::exitLocal.

During config initialization, one pipe thread is created for each pipe. The pipe threads execute all render task methods for this pipe, and therefore executes the application's rendering code. All pipe threads are terminated during Config::exit. Since a layout switch on a canvas may involve different resources, pipe threads may be started and stopped dynamically at runtime. Before such an update, Equalizer will always finish all pending rendering operations to ensure that all resources are idle.

During compositing, readback and tranmission threads are created lazy on the first image readback and transmission. Performing readback, compression and transmission of images asynchronously pipelines these operations with subsequent rendering commands, which increases overall performance. Equalizer creates one thread per pipe to finalize an asynchronous readback and one thread per node to compress and transmit the images to other nodes. Both threads are only visible to transfer and compression plugins, not to any other application code.

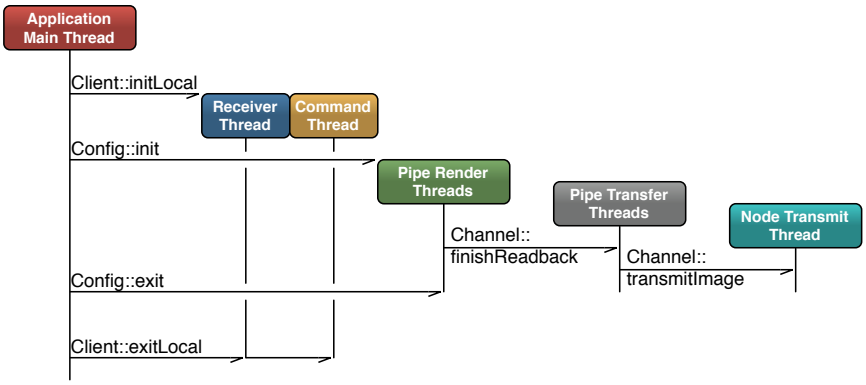


Figure 38: Threads within one Node Process

Figure 38 provides an overview on all the threads used by Equalizer and Collage. The rest of this section discusses the thread synchronization between the main thread and the pipe threads.

Thread Synchronization Models Equalizer supports three threading models, which can be set programmatically by the application or through the configuration file format. Applications typically hard-code their threading model. The file format is commonly used to change the threading model for benchmarking and experimentation using test applications.

The following thread synchronization models are implemented:

ASYNC: No synchronization happens between the pipe render threads, except for synchronizing the finish of frame current-latency. The eqPly and eVolve Equalizer examples activate this threading model by setting it in Node::configInit. This synchronization model provides the best performance and should be used by all applications which multi-buffer all dynamic, frame-specific data.

DRAW_SYNC: Additionally to the synchronization of the async thread model, all local render threads are synchronized, so that the draw operations happen synchronously with the node main loop. Compositing, swap barriers and

buffer swaps happen asynchronously. This model allows to use the same database for rendering, and safe modifications of this database are possible from the node thread, since the pipe threads do not execute any rendering tasks between frames. This is the default threading model. This threading model should be used by applications which keep one copy of the scene graph per node.

LOCAL_SYNC: Additionally to the synchronization of the async thread model, all local frame operations, including readback, assemble and swap buffer are synchronized with the node main loop. This threading model should be used by applications which need to access non-buffered, frame-specific data after rendering, e.g., during Channel::frameAssemble.

Figure 39 illustrates the synchronization and task execution for the thread synchronization models. Please note that the thread synchronization synchronizes all pipe render threads on a **single** node with the node's main thread. The per-node frame synchronization does not break the asynchronous execution across nodes.

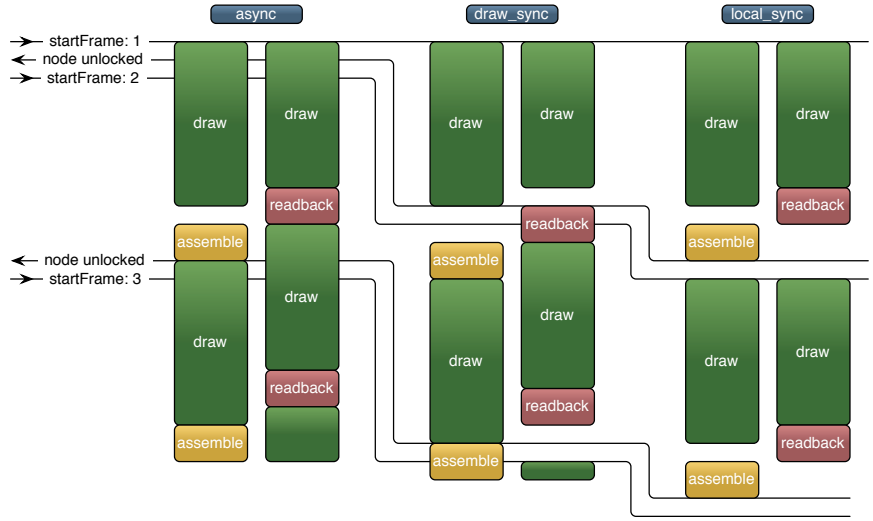


Figure 39: Async, draw_sync and local_sync Thread Synchronization Models

An implication of the draw_sync and local_sync models is that the application node cannot issue a new frame until it has completed all its draw tasks. For larger cluster configurations it is therefore advisable to assign only assemble operations to the application node, allowing it to run asynchronous to the rendering nodes. If the machine running the application process should also contribute to rendering, a second node on the same host can be used to perform off-screen draw and readback operations for the application node process.

DPlex Compounds DPlex decomposition requires multiple frames to be rendered concurrently. Applications using the thread synchronization models draw_sync (the default) or local_sync have to use one render client process per GPU to benefit from DPlex task decomposition.

Non-threaded pipes should not be used for DPlex source and destination channels. Applications using the local_sync thread model cannot benefit from DPlex if the application node uses a DPlex source or destination channel.

Applications using the async thread synchronization model can fully profit from DPlex using multiple render threads on a multi-GPU system. For these applications,

all render threads run asynchronously and can render different frames at the same time.

Synchronizing the draw operations between multiple pipe render threads, and potentially the application thread, breaks DPlex decomposition. At any given time, only one frame can be rendered from the same process. The speedup of DPlex relies however on the capability to render different frames concurrently.

If one process per GPU is configured, draw-synchronous applications can scale the performance using DPlex compounds. The processes are not synchronized with each other, since each process keeps its own version of the scene data.

Thread Synchronization in Detail The application has extended control over the task synchronization during a frame. Upon Config::startFrame, Equalizer invokes the frameStart task methods of the various entities. The entities unlock all their children by calling startFrame, e.g., Node::frameStart has to call Node::startFrame to unlock the pipe threads. Note that certain startFrame calls, e.g., Window::startFrame, are currently empty since the synchronization is implicit due to the sequential execution within the thread.

Figure 40 illustrates the local frame synchronization. Each entity uses waitFrameStarted to block on the parent's startFrame, e.g., Pipe::frameStart calls Node::waitFrameStarted to wait for the corresponding Node::startFrame. This explicit synchronization allows to update non-critical data before synchronizing with waitFrameStarted, or after unlocking using startFrame. Figure 40 illustrates this synchronization model.

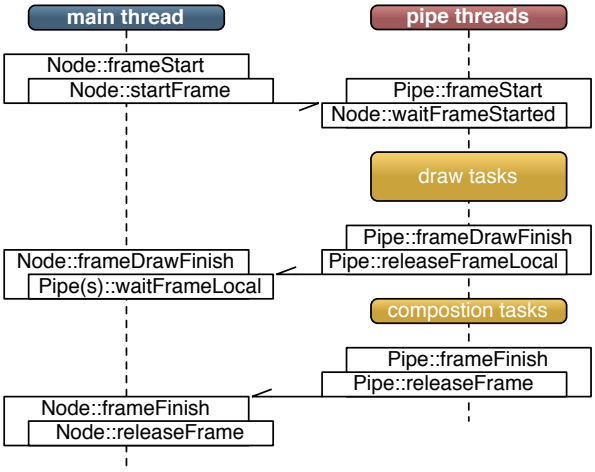


Figure 40: Per-Node Frame Synchronization

At the end of the frame, two similar sets of synchronization methods are used. The first set synchronizes the local execution, while the second set synchronizes the global execution.

The local synchronization consists of releaseFrameLocal to unlock the local frame, and of waitFrameLocal to wait for the unlock. For the default synchronization model sync_draw, Equalizer uses the task method frameDrawFinish which is called on each resource after the last Channel::frameDraw invocation for this frame. Consequently, Pipe::frameDrawFinish calls Pipe::releaseFrameLocal to signal that it is done drawing the current frame, and Node::frameDrawFinish calls Pipe::waitFrameLocal for each of its pipes to block the node thread until the current frame has been drawn.

The second, global synchronization is used for the frame completion during Config::finishFrame, which causes frameFinish to be called on all entities, passing the oldest frame number, i.e., frame current-latency. The frameFinish task methods have to call releaseFrame to signal that the entity is done with the frame. The release causes the parent's frameFinish to be invoked, which is synchronized internally. Once all Node::releaseFrame have been called, Config::finishFrame returns.

Figure 41 outlines the synchronization for the application, node and pipe classes for an application node and one render client when using the default draw_sync

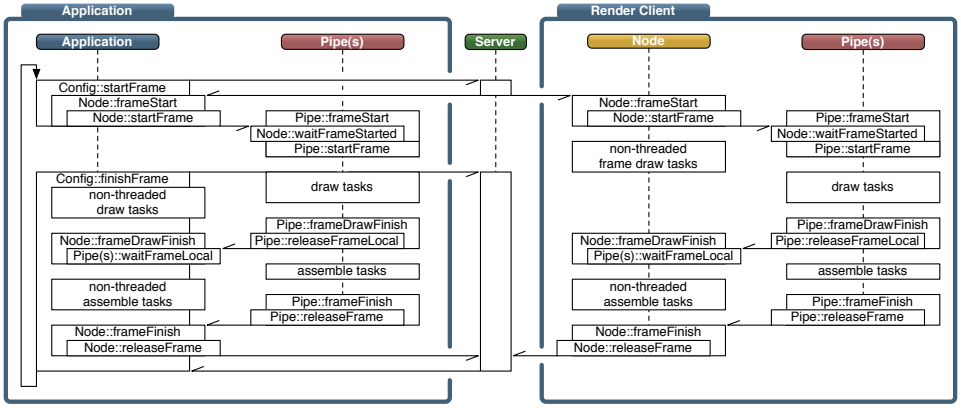


Figure 41: Synchronization of Frame Tasks

thread model. Please note that Config::finishFrame does block until the current frame has been released locally and until the frame current - latency has been released by all nodes. The window and channel synchronization are similar and omitted for simplicity.

It is absolutely vital for the execution that Node::startFrame and Node::releaseFrame are called, respectively. The default implementations of the node task methods do take care of that.

7.2.4. OpenGL Extension Handling

Equalizer uses GLEW[23] for OpenGL extension handling, particularly the GLEW_MX implementation providing multi-context support. The build system favors an existing GLEW_MX installation, but will fall back to a builtin implementation. Applications should use eq/client/gl.h to include the proper GLEW headers. If the preprocessor define EQ_IGNORE_GLEW is set, no GLEW headers will be included into application code by any Equalizer header file.

GLEW uses a function table called GLEWContext to store function pointers for non-standard OpenGL functions. This table is initialized once per OpenGL context by retrieving the pointers through a system-specific method. OpenGL functions are then redefined using a macro which retrieves the GLEWContext using glewGetContext, looking up the corresponding function pointer in this table and calling the function.

Each eq::GLWindow, which is the SystemWindow base class for all OpenGL system windows, has a GLEWContext. This context can be obtained by using glewGetContext on the eq::Window or eq::Channel. Equalizer (re-)initializes the GLEW context whenever a new OpenGL context is set.

Extended OpenGL functions called from a GLWindow, window or channel instance can be called directly. GLEW will call the object's glewGetContext to obtain the correct context:

```
void eqPly::Channel::_drawModel( const Model* model )
{
    ...
    glUseProgram( program );
    ...
}
```

[23] http://glew.sourceforge.net

Functions called from another place need to define a macro or function glewGetContext that returns the pointer to the GLEWContext of the appropriate window, e.g., as done by the eqPly kd-tree rendering classes:

```
// state has GLEWContext* from window
#define glewGetContext state.glewGetContext

/*  Set up rendering of the leaf nodes.  */
void VertexBufferLeaf::setupRendering( VertexBufferState& state,
                                       GLuint* data ) const
{
    ...
    glBindBuffer( GL_ARRAY_BUFFER, data[VERTEX_OBJECT] );
    glBufferData( GL_ARRAY_BUFFER, _vertexLength * sizeof( Normal ),
                  &_globalData.normals[_vertexStart], GL_STATIC_DRAW );
    ...
}
```

The WGL and GLX pipe manage a WGLEWContext and GLXEWContext, respectively. These context are useful if extended wgl or glX functions are used during window initialization. The GLEW context structures are initialized using a temporary OpenGL context, created using the proper display device of the pipe.

7.2.5. Window System Integration

Communicating with GPUs, creating windows and handling events is operating system dependent in OpenGL. Equalizer abstracts the specifities behind the eq::WindowSystemIF interface and provides an implemenation for glX/X11, AGL/Carbon and WGL. This interface class defines a factory to instantiate SystemPipe, SystemWindow and MessagePump. Its constructor registers the available instances used at runtime, that is, the class should be instantiated exactly once per process by the implementation.

The SystemPipe abstracts GPU-specific handling, most notably the implementation does query the display resolution and sets it on its eq::Pipe during initialization. It also contains a GLXEWContext and WGLEWContext dispatch table for the glX and WGL window system, respectively.

The SystemWindow interface externalizes the details of the windowing API from the eq::Window implementation and facilitates the integration with new windowing APIs and custom applications. The system window implements the core functionality for Equalizer to interface with the underlying window system and is described in detail below.

The MessagePump ensures that OS events are processed and is called by Equalizer from the main and render threads regularly. Typically it only needs to be customized when integrating a totally new window system.

Equalizer provides sample implementations for the supported window systems in the agl, glx and wgl subfolders. These sample implementations are intended to be sub-classed and various steps in the window initialization can be overwritten and customized.

An application typically chooses to subclass the sample implementation if only minor tweaks are needed for integration. For major changes or new window systems, it is often easier to subclass directly from SystemWindow or GLWindow and implement the abstract methods of this interface class.

The method Window::configInitSystemWindow is used to instantiate and initialize the SystemWindow implementation during config initialization. After a successful SystemWindow initialization, Window::configInitGL is called for the generic OpenGL state setup.

Since window initialization is notoriously error-prone and hard to debug in an distributed application, the sample implementation propagates the reason for errors

from the render clients back to the application. The Pipe and Window classes have a setError method, which is used to set an error code. This string is passed to the Config instance on the application node, where it can be retrieved using getError. The Section 7.2.2 explains error handling in more detail.

The sample implementations agl::Window, glx::Window and wgl::Window all have similar, override-able methods for all sub-tasks. This allows partial customization, without the need of rewriting tedious window initialization code, e.g., the OpenGL pixel format selection. Figure 33 shows the UML class hierarchy for the system window implementations.

Drawable Configuration OpenGL drawables have a multitude of buffer modes. A drawable might be single-buffered, double-buffered or quad-buffered, have auxiliary image planes such as stencil, accumulation and depth buffer or multisampling.

The OpenGL drawable is configured using window attributes. These attributes are used by the method choosing the pixel format (or visual in X11 speak) to select the correct drawable configuration.

Window attributes can either be configured through the configuration file (see Appendix B), or programmatically. In the configuration file, modes are selected which are not application-specific, for example stereo formats for active stereo displays.

Applications which require certain drawable attributes can set the corresponding window attribute hint during window initialization. The Equalizer volume rendering example, eVolve, is such an example. It does need alpha planes for rendering and compositing. The window initialization of eVolve sets the attribute before calling the default initialization method of Equalizer:

```
bool Window::configInit( const eq::uint128_t& initID )
{
    // Enforce alpha channel, since we need one for rendering
    setIAttribute( IATTR_PLANES_ALPHA, 8 );

    return eq::Window::configInit( initID );
}
```

AGL Window Initialization AGL initialization happens in three steps: choosing a pixel format, creating the context and creating a drawable.

Most AGL and Carbon calls are not thread-safe. The Equalizer methods calling these functions use Global::enterCarbon and Global::leaveCarbon to protect the API calls. Please refer to Section 7.1.6 for more details.

The pixel format is chosen based on the window's attributes. Some attributes set to auto, e.g., stereo, cause the method first to request the feature and then to back off and retry if it is not available. The pixel format returned by chooseAGLPixelFormat has to be destroyed using destroyAGLPixelFormat. When no matching pixel format is found, chooseAGLPixelFormat returns 0 and the AGL window initialization returns with a failure.

The context creation also uses the global Carbon lock. Furthermore, it sets up the swap buffer synchronization with the vertical retrace, if enabled by the corresponding window attribute hint. Again the window initialization fails if the context could not be created.

The drawable creation method configInitAGLDrawable calls either configInitAGL-Fullscreen, configInitAGLWindow or configInitAGLPBuffer

The top-level AGL window initialization code therefore looks as follows:

```
bool Window::configInit()
{
    AGLPixelFormat pixelFormat = chooseAGLPixelFormat();
```

```
    if( !pixelFormat )
        return false;

    AGLContext context = createAGLContext( pixelFormat );
    destroyAGLPixelFormat ( pixelFormat );
    setAGLContext( context );

    if( !context )
        return false;

    makeCurrent();
    initGLEW();
    return configInitAGLDrawable();
}
```

GLX Window Initialization GLX initialization is very similar to AGL initialization. Again the steps are: choose frame buffer configuration (pixel format), create OpenGL context and then create drawable. The only difference is that the data returned by chooseGLXFBConfig has to be freed using XFree:

```
bool Window::configInit()
{
    GLXFBConfig* fbConfig = chooseGLXFBConfig();
    if( !fbConfig )
    {
        setError( ERROR_SYSTEMWINDOW_PIXELFORMAT_NOTFOUND );
        return false;
    }

    GLXContext context = createGLXContext( fbConfig );
    setGLXContext( context );
    if( !context )
    {
        XFree( fbConfig );
        return false;
    }

    const bool success = configInitGLXDrawable( fbConfig );
    XFree( fbConfig );

    if( !success || !_xDrawable )
    {
        if( getError() == ERROR_NONE )
            setError( ERROR_GLXWINDOW_NO_DRAWABLE );
        return false;
    }

    makeCurrent();
    initGLEW();
    _initSwapSync();
    if( getIAttribute( eq::Window::IATTR_HINT_DRAWABLE ) == FBO )
        configInitFBO();

    return success;
}
```

WGL Window Initialization The WGL initialization requires another order of operations compared to AGL or GLX. The following functions are used to initialize a WGL window:

1. initWGLAffinityDC is used to set up an affinity device context, which might be needed for window creation. The WGL window tracks potentially two device context handles, one for OpenGL context creation (the affinity DC), and one for swapBuffers (the window's DC).

2. chooseWGLPixelFormat chooses a pixel format based on the window attributes. If no device context is given, it uses the system device context. The chosen pixel format is set on the passed device context.

3. configInitWGLDrawable creates the drawable. The device context passed to configInitWGLDrawable is used to query the pixel format and is used as the device context for creating a pbuffer. If no device context is given, the display device context is used. On success, it sets the window handle. Setting a window handle also sets the window's device context.

4. createWGLContext creates an OpenGL rendering context using the given device context. If no device context is given, the window's device context is used. This function does not set the window's OpenGL context.

The full configInitWGL task method, including error handling and cleanup, looks as follows:

```
bool Window::configInit()
{
    if( !initWGLAffinityDC( ))
    {
        setError( ERROR_WGL_CREATEAFFINITYDC_FAILED );
        return false;
    }

    const int pixelFormat = chooseWGLPixelFormat();
    if( pixelFormat == 0 )
    {
        exitWGLAffinityDC();
        return false;
    }

    if( !configInitWGLDrawable( pixelFormat ))
    {
        exitWGLAffinityDC();
        return false;
    }

    if( !_wglDC )
    {
        exitWGLAffinityDC();
        setWGLDC( 0, WGL_DC_NONE );
        setError( ERROR_WGLWINDOW_NO_DRAWABLE );
        return false;
    }

    HGLRC context = createWGLContext();
    if( !context )
    {
        configExit();
        return false;
    }

    setWGLContext( context );
    makeCurrent();
    initGLEW();
    _initSwapSync();
    if( getIAttribute( eq::Window::IATTR_HINT_DRAWABLE ) == FBO )
        return configInitFBO();

    return true;
}
```

7.2.6. Stereo and Immersive Rendering

Equalizer fully supports immersive rendering for Virtual Reality by implementing multiple tracked observers, head-mounted displays (HMD), flexible focus distance and asymmetric eye positions. Equalizer optionally supports tracking devices using the VRPN or OpenCV libraries.

An Equalizer configuration contains a number of observers. Each observer represents one tracked entity. Most immersive configurations have one observer, but it is possible to support multiple tracked viewers in the same configuration, e.g., to use two HMDs.

Each observer has its own head matrix, eye positions and focus information for tracking. Typically each observer receives tracking data from a different device. The observer may set the name of a VRPN tracking device or the index of the OpenCV camera to be used to track this observer. The VRPN tracker is expected to deliver tracking data in the correct coordinate system, that is, using meter units with the same origin as the frustum descriptions in the Equalizer configuration file. The OpenCV tracker is limited to 2.5D tracking due to the limited amount of information gained by face detection.

Stereo Rendering Figure 42(a) illustrates a monoscopic view frustum. The viewer is positioned at the origin of the global coordinate system, and the frustum is completely symmetric. This is the typical view frustum for non-stereoscopic applications.

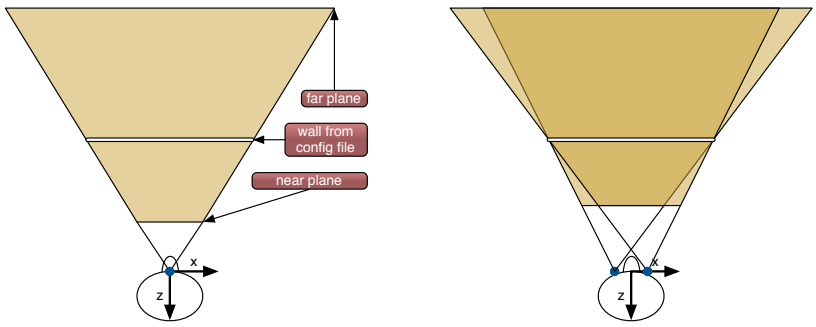


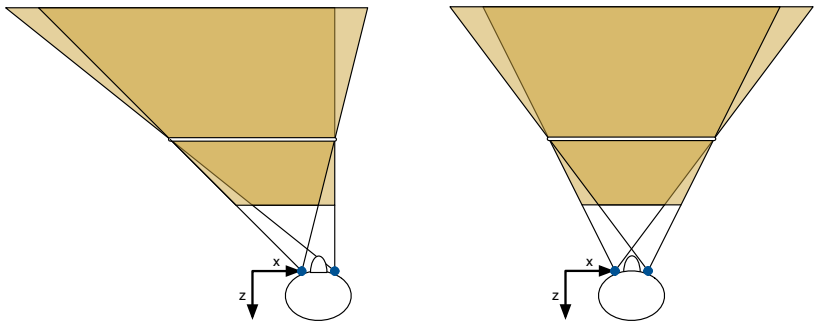
Figure 42: Monoscopic(a) and Stereoscopic(b) Frusta

In stereo rendering, the scene is rendered twice, with the two frustum origins 'moved' to the position of the left and right eye, as shown in Figure 42(b). The stereo frusta are asymmetric. The stereo convergence plane is the same as the projection surface, unless specified otherwise using the focus distance API (see Section 7.2.6).

Note that while stereo rendering is often implemented using the simpler toe-in method, Equalizer implements the correct approach using asymmetric frusta.

Immersive Rendering In immersive visualization, the observer is tracked in and the view frusta are adapted to the viewer's position and orientation, as shown in Figure 43(a). The transformation *origin* → *viewer* is set by the integrated tracking code or by the application using Observer::setHeadMatrix, which is used by the server to compute the absolute eye positions, and consequently the view frusta.

Tracking events are often delivered asynchronously by an external source. The recommended way is to emit an OBSERVER_MOTION event, which has to contain



(a) (b)

Figure 43: Tracked(a) and HMD(b) Immersive Frusta

the observer identifier and a Matrix4f head matrix. Equalizer optionally implements head tracking using VRPN or OpenCV, and uses this mechanism to inject the asynchronously computed tracking matrix:

```
config->sendEvent( Event::OBSERVER_MOTION ) << originator << head;
```

This event will be dispatched to the given observer instance in the application process during the next Config::handleEvents. The observer will update its head matrix based on the event data:

```
switch( command.getEventType( ))
{
case Event::OBSERVER_MOTION:
    return setHeadMatrix( command.get< Matrix4f >( ));
}
```

Projection surfaces which are not X/Y-planar create frusta which are not oriented along the Z axis, as shown in Figure 44(a). These frusta are positioned using the channel's head transformation, which can be retrieved using Channel::getHeadTransform.

For head-mounted displays (HMD), the tracking information is used to move the frusta with the observer, as shown in Figure 43(b). This results in different projections compared to normal tracking with fixed projection screens. This difference is transparent to Equalizer applications, only the configuration file uses a different wall type for HMDs.

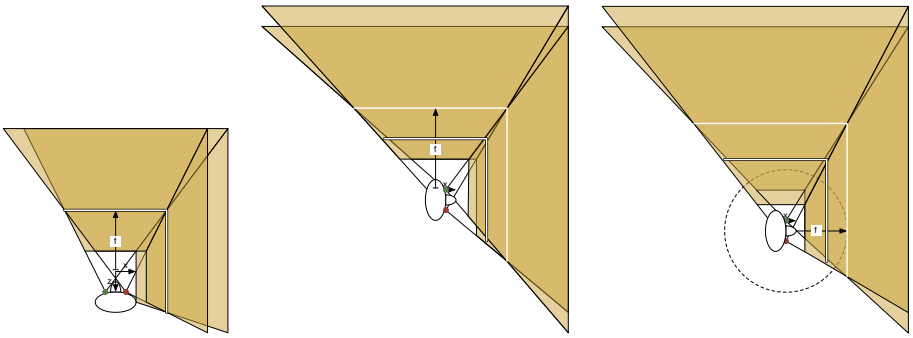
Focus Distance The focus distance, also called stereo convergence, is the Z distance in which the left and right eye frusta converge. A plane parallel to the near plane positioned in the focus distance creates the same 2D image for both eyes.

The frustum calculation up to Equalizer version 1.0 places the stereo convergence on the projection surface, as shown in Figure 44(a). The focus distance is therefore the distance between the origin and the middle of the projection surface. This is how almost all Virtual Reality software handles the focal plane.

In Equalizer 1.2 and later the focus distance and mode can be configured and changed at runtime for each observer. This allows applications to expose the focal plane in their user interface, or to automatically calculate it based on the scene and view direction.

The default focus mode fixed implements the algorithm used by Equalizer 1.0. This mode ignores the focus distance setting. The focus modes relative_to_origin and relative_to_observer use the focus distance parameter to dynamically change the stereo convergence.

The focus distance calculation relative to the origin allows to change the focus independent of the observer position by separating the projection surface from the

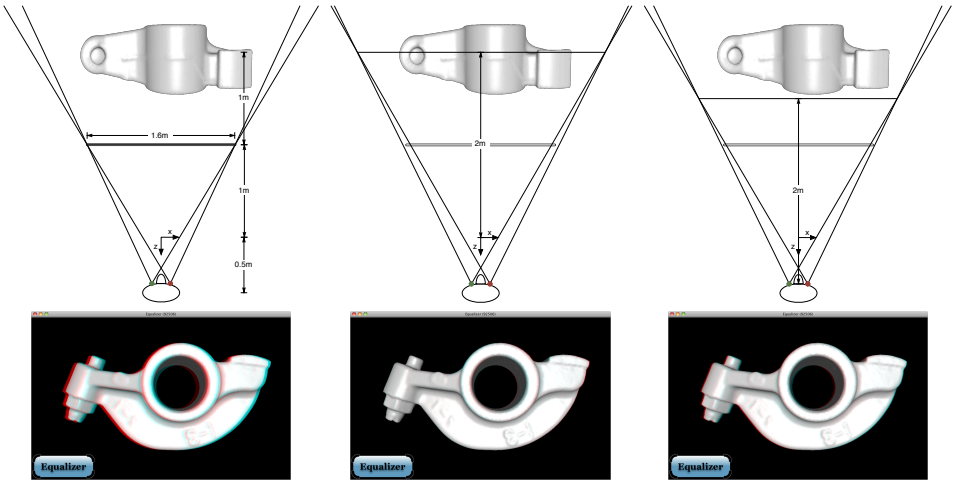


(a) (b) (c)

Figure 44: Fixed(a) and dynamic focus distance relative to origin(b) and observer(c)

stereo convergence plane. The convergence plane of the first wall in the negative Z direction is moved to be at the given focus distance, as shown in Figure 44(b). All other walls are moved by the same relative amount. The movement is made from the view of the central eye, thus leaving the mono frustum unchanged. Figure 44(b) shows the new logical 'walls' used for frustum calculations in white, while the physical projection from Figure 44(a) is still visible.

The focus distance calculation relative to the observer is similar to the origin algorithm, but it keeps the closest wall in the observer's view direction at the given focus distance, as shown in Figure 44(c). When the observer moves forward, the focal plane moves forward as well. Consequently, when the observer looks in a different direction, a different object in the scene is focused, as indicated by the dotted circle in Figure 44(c).



(a) (b) (c)

Figure 45: Fixed(a), relative to origin(b) and observer(c) focus distance examples

Figure 45 shows an example for the three focus distance modes. The configured wall is one meter behind the origin, the model two meters behind and the observer is half a meter in front of the origin. The focus distance was set to two meters.

Application-specific Scaling All Equalizer units in the configuration file and API are configured in meters. This convention allows the reuse of configurations across multiple applications. When visualizing real-world objects, e.g., for architectural visualizations, it guarantees that they appear realistic and full immersion into the visualization can be achieved.

Certain applications want to visualize objects in immersive environments in a scale different from their natural size, e.g., astronomical simulations. Each model, and therefore each view, might have a different scale. Applications can declare this scale as part of the eq::View, which will be applied to the virtual environment by Equalizer. Common metric scale factors are provided as constants.

7.2.7. Layout API

The Layout API provides an abstraction for render surfaces (Canvas and Segment) and the arrangement of rendering areas on them (Layout and View). Its functionality has been described in Section 3.8 and Section 3.9. This section focuses on how to use the Layout API programmatically.

The application has read access to all canvases, segment, layouts and views of the configuration. The render client has access to the current view in the channel task methods. The layout entities can be sub-classed using the NodeFactory. Currently the layout of a canvas, the frustum and stereo mode of a view as well as the view's user data object can be changed at runtime.

Subclassing and Data Distribution Layout API entities (Canvas, Segment, Layout, View) are sub-classed like all other Equalizer entities using the NodeFactory. Equalizer registers the master instance of these entities on the server node. Mutable parameters, e.g., the active layout of a canvas, are distributed using slave object commits (cf. Section 8.4.4). Application-specific data can be attached to a view using a distributable UserData object. Figure 46 shows the UML class hierarchy for the eqPly::View.

Equalizer commits dirty layout entities at the beginning of each Config::startFrame, and synchronizes the slave instances on the render clients correctly with the current frame.

The render clients can access a slave instance of the view using Channel::getView. When called from one of the frame task methods, this method will return the view of the current destination channel for which the task method is executed. Otherwise it returns the channel's native view, if it has one. Only destination channels of an active canvas have a native view.

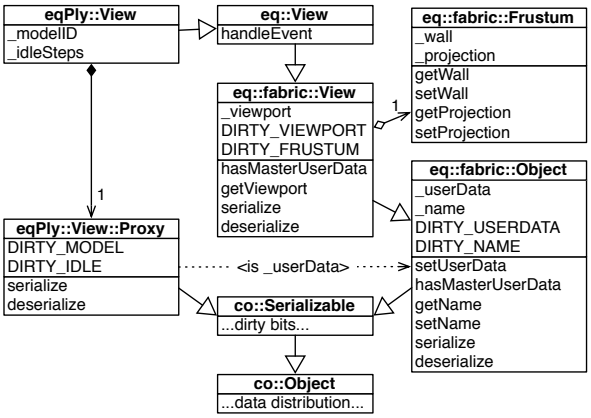


Figure 46: UML Hierarchy of eqPly::View

The most common entity to subclass is the View, since the application often amends it with view-specific application data. A view might have a distributable user data object, which has to inherit from co::Object to be committed and synchronized with the associated view.

Externalizing the data distribution in a UserData object is necessary since the server holds the master instance of a view. The server contains no application code, and would not be able to (de-)serialize the application data of a view. Instead, the user data object has its master and slave instances only in application processes, and the server only handles the identifier and version of this object.

In eqPly, the application-specific data is the model identifier and the number of anti-aliasing steps to be rendered when idle. This data is distributed by a View::Proxy object which serves as the view's user data. The proxy defines the necessary dirty bits and serializes the data:

```
/** The changed parts of the view. */
enum DirtyBits
{
    DIRTY_MODEL = co::Serializable::DIRTY_CUSTOM << 0,
    DIRTY_IDLE  = co::Serializable::DIRTY_CUSTOM << 1
};

    if( dirtyBits & DIRTY_MODEL )
        os << _view->_modelID;
    if( dirtyBits & DIRTY_IDLE )
        os << _view->_idleSteps;
}

void View::Proxy::deserialize( co::DataIStream& is, const uint64_t dirtyBits )
{
    if( dirtyBits & DIRTY_MODEL )
        is >> _view->_modelID;
    if( dirtyBits & DIRTY_IDLE )
    {
        is >> _view->_idleSteps;
        if( isMaster( ))
            setDirty( DIRTY_IDLE ); // redistribute slave settings
    }
}

void View::setModelID( const lunchbox::uint128_t& id )
```

The eqPly::View sets its Proxy as the user data object in the constructor. By default, the master instance of the view's user data is on the application instance of the view. This may be changed by overriding hasMasterUserData. The proxy object registration, mapping and synchronization is fully handled be the fabric layer, no further handling has to be done by the application:

```
View::View( eq::Layout* parent )
        : eq::View( parent )
        , _proxy( this )
        , _idleSteps( 0 )
{
    setUserData( &_proxy );
}

void View::setModelID( const lunchbox::uint128_t& id )
{
    if( _modelID == id )
        return;

    _modelID = id;
    _proxy.setDirty( Proxy::DIRTY_MODEL );
}
```

Run-time Layout Switch The application can use a different layout on a canvas. This will cause the running entities to be updated on the next frame. At a minimum, this means the channels involved in the last layout on the canvas are de-initialized,

that is configExit and NodeFactory::releaseChannel is called, and channels involved in the new layout are initialized. If a layout does not cover fully a canvas, the layout switch can also cause the (de-)initialization of windows, pipes and nodes.

Due to the entity (de-)-initialization and the potential need to initialize view-specific data, e.g., a model, a layout switch is relatively expensive and will stall eqPly for about a second.

Initializing an entity can fail. If a failure occurs and runtime reliability is not active, the server will exit the whole configuration, and send an EXIT event to the application node. The exit event will cause the application to exit, since it resets the config's running state.

Run-time Stereo Switch Similar to switch a layout, the stereo mode of each view can be switched at runtime. This causes all destination channels of the view to update the cyclop eye or the left and right eye.

The configuration contains stereo information in three places: the view, the segment and the compound. The view defines which stereo mode is active: mono or stereo. This setting can be done in the configuration file or programmatically.

The segment has an eye attribute in which defines which eyes are displayed by this segment. This is typically all eyes for active stereo projections and the left or right eye for passive stereo. The cyclop eye for passive stereo can either be set on a single segment or both, depending if the second projector is active during monoscopic rendering. The default setting enables all eyes for a segment.

The compound has an eye attribute defining which eyes it is capable of updating. This allows to specify different compounds for the same channel, depending on the stereo mode. One use case is to use one GPU each for updating a stereo destination channel in stereo mode, and using a 2D compound with the two GPUs in mono mode. Figure 47 illustrates this example. The coloring in mono mode is to illustrate the 2D decomposition. The default setting for the compound eye attributes is all eyes.

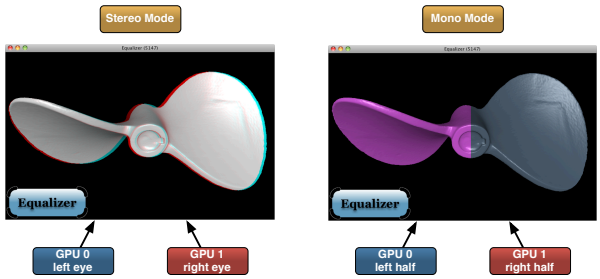


Figure 47: Using two different decompositions during stereo and mono rendering

Frustum Updates Frustum parameters can be changed at runtime for views and segments by the application. View frusta are typically changed for non-fullscreen application windows and multi-view layouts, where the rendering is not meant to be viewed in real-world size in an immersive environment. A typical use case is changing the field-of-view of the rendering.

Segment frusta are changed when the display system changes at runtime, for example by moving a tracked LCD through a virtual world.

The view and segment are derived from eq::Frustum (Figure 46), and the application process can set the wall or projection parameters at runtime. For a description of wall and projection parameters please refer to Section 3.11.3. The new data will be effective for the next frame. The frustum of a view overrides the underlying frustum of the segments.

The default Equalizer event handling is using the view API to maintain the aspect ratio of destination channels after a window resize. Without updating the wall or projection description, the rendering would become distorted.

When a window is resized, a CHANNEL_RESIZE event is generated. If the corresponding channel has a view, Channel::processEvent sends a VIEW_RESIZE event to the application. This event contains the identifier of the view. The config event is dispatched to View::handleEvent on the application thread. Using the original size and wall or projection description of the view, a new wall or projection is computed, keeping the aspect ratio and the height of the frustum constant. This new frustum is automatically applied by Equalizer at the next config frame.

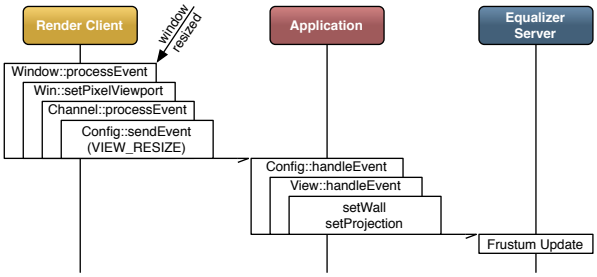
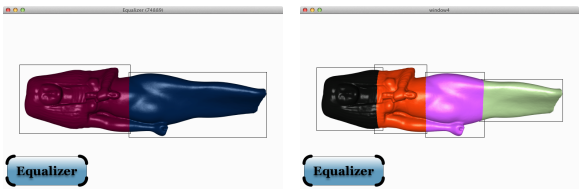


Figure 48: Event Flow during a View Update

Figure 48 shows a sequence diagram of such a view update.

7.2.8. Region of Interest

Motivation Regions of interest (ROI) define which part of the framebuffer was updated by the application. They allow Equalizer to perform important optimizations during scalable rendering.



(a) (b)

Figure 49: ROI for a two-way(a) and four-way DB(b) compound

The first optimization concerns the compositing operation. The declared ROI allows Equalizer to restrict the readback, compression, network transmission and assembly to only the relevant pixels. This is particularly important for DB compounds, where less screen space on each channel is covered as resources are added to the decomposition. Figure 49 illustrates this for a two-way and four-way decomposition. Declaring the ROI alleviates the increasing compositing cost as resources are added to a DB compound.

For 2D compounds, the same optimization is applied, but has a smaller impact on the compositing performance. Figure 50 illustrates the ROI for a four-way 2D compound.

The second optimization is important for load-balanced 2D compounds. The 2D load equalizer uses internal timing statistics to form a 2D load grid for computing the split of the next frame. Without ROI, an even load within each tile has to be assumed. With ROI, an even load within the declared, smaller region of interest can be used. This causes a smaller error in the load estimation, and therefore a more accurate load prediction.

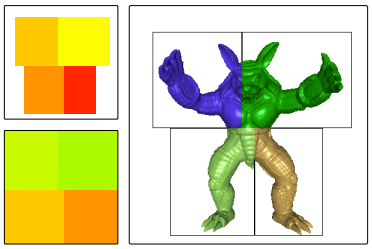


Figure 50: ROI for 2D load balancing

Figure 50 illustrates this load grid for a four-way 2D compound with ROI (top) and without ROI (bottom).

ROI in eqPly The application should declare its regions of interest during rendering. This declaration can be very fine-grained, e.g., on each leaf node of a scene graph. Equalizer will track and optimize multiple regions automatically. The current implementation merges all regions of a single channel into one region for compositing and load-balancing. Later Equalizer versions may use different, more optimal, heuristics based on the application-declared regions.

Each leaf node of the kd-tree used in eqPly declares its region of interest when it is rendered. The region is calculated by projecting the bounding box into screen space and normalizing the resulting screen space rectangle:

```
void VertexBufferLeaf::draw( VertexBufferState& state ) const
{
    if( state.stopRendering( ))
        return;

    state.updateRegion( _boundingBox );
...
void VertexBufferState::updateRegion( const BoundingBox& box )
{
    const Vertex corners[8] = { Vertex( box[0][0], box[0][1], box[0][2] ),
                                Vertex( box[1][0], box[0][1], box[0][2] ),
                                Vertex( box[0][0], box[1][1], box[0][2] ),
                                Vertex( box[1][0], box[1][1], box[0][2] ),
                                Vertex( box[0][0], box[0][1], box[1][2] ),
                                Vertex( box[1][0], box[0][1], box[1][2] ),
                                Vertex( box[0][0], box[1][1], box[1][2] ),
                                Vertex( box[1][0], box[1][1], box[1][2] ) };

    Vector4f region(  std::numeric_limits< float >::max(),
                      std::numeric_limits< float >::max(),
                     -std::numeric_limits< float >::max(),
                     -std::numeric_limits< float >::max( ));

    for( size_t i = 0; i < 8; ++i )
    {
        const Vertex corner = _pmvMatrix * corners[i];
        region[0] = std::min( corner[0], region[0] );
        region[1] = std::min( corner[1], region[1] );
        region[2] = std::max( corner[0], region[2] );
        region[3] = std::max( corner[1], region[3] );
    }

    // transform region of interest from [ -1 -1 1 1 ] to normalized viewport
    const Vector4f normalized( region[0] * .5f + .5f,
                               region[1] * .5f + .5f,
                               ( region[2] - region[0] ) * .5f,
                               ( region[3] - region[1] ) * .5f );

    declareRegion( normalized );
...
```

The declareRegion is eventually forwarded to eq::Channel::declareRegion.

7.2.9. Image Compositing for Scalable Rendering

Two task methods are responsible for collecting and compositing the result image during scalable rendering. Scalable rendering is a use case of parallel rendering, where multiple channels are contributing to a single view. This requires reading

back the pixel data from the source GPU and assembling it on the destination GPU.

Channels producing one or more outputFrames use Channel::frameReadback to read the pixel data from the frame buffer. The channels receiving one or multiple inputFrames use Channel::frameAssemble to assemble the pixel data into the frame-buffer. Equalizer takes care of the network transport of frame buffer data between nodes.

Normally the programmer does not need to interfere with the image compositing. Changes are sometimes required at a high level, for example to order the input frames or to optimize the readback. The following sections describe the image compositing API in Equalizer.

Compression Plugins Compression plugins allow the creation of runtime-loadable modules for image compression. Equalizer will search predefined directories during eq::init for dynamic shared objects (DSO) containing compression libraries (EqualizerCompressor*.dll on Windows, libEqualizerCompressor*.dylib on Mac OS X, libEqualizerCompressor*.so on Linux).

The interface to a compression DSO is a C API, which allows to maintain binary compatibility across Equalizer versions. Furthermore, the definition of an interface facilitates the creation of new compression codecs for developers.

Please refer to the Equalizer API documentation on the website for the full specification for compression plugins. The Lunchbox and Equalizer DSOs double as compression plugins and implement a set of compression engines, which can be used as a reference implementation.

Each compression DSO may contain multiple compression engines. The number of compressors in the DSO is queried by Equalizer using EqCompressGetNumCompressors.

For each compressor, EqCompressorGetInfo is called to retrieve the information about the compressor. The information contains the API version the DSO was written against, a unique name of the compressor, the type of input data accepted as well as information about the compressor's speed, quality and compression ratio.

Each image transported over the network allocates its own compressor or decompressor instance. This allows compressor implementations to maintain information in a thread-safe manner. The handle to a compressor or decompressor instance is a void pointer, which typically hides a C++ object instantiated by the compression DSO.

A unit test is delivered with Equalizer which runs all compressors against a set of images and provides performance information to calculate the compressor characteristics.

Parallel Direct Send Compositing To provide a motivation for the design of the image compositing API, the direct send parallel compositing algorithm is introduced in this section. Other parallel compositing algorithms, e.g. binary-swap, can also be expressed through an Equalizer configuration file.

Direct send has two important properties: an algorithmic complexity of O(1) for each node, that is, the compositing cost per node is constant as resources are added, and the capability to perform total ordering during compositing, e.g, to back-to-front sort all contributions of a 3D volume rendering correctly.

The main idea behind direct send is to parallelize the costly recomposition for database (sort-last) decomposition. With each additional source channel, the amount of pixel data to be composited grows linearly. When using the simple approach of compositing all frames on the destination channel, this channel quickly becomes the

bottleneck in the system. Direct send distributes this workload evenly across all source channels, and thereby keeps the compositing work per channel constant.

In direct send compositing, each rendering channel is also responsible for the sort-last composition of one screen-space tile. It receives the framebuffer pixels for its tile from all the other channels. The size of one tile decreases linearly with the number of source channels, which keeps the total amount of pixel data per channel constant.

After performing the sort-last compositing, the color information is transferred to the destination channel, similarly to a 2D (sort-first) compound. The amount of pixel data for this part of the compositing pipeline also approaches a constant value, i.e., the full frame buffer.

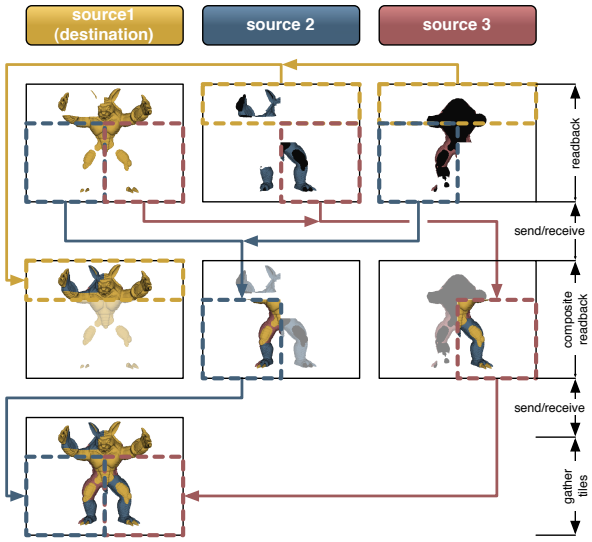


Figure 51: Direct Send Compositing

Figure 51 illustrates this algorithm for three channels. The Equalizer website contains a presentation[24] explaining and comparing this algorithm to the binary-swap algorithm.

The following operations have to be possible to perform this algorithm:

- Selection of color and/or depth frame buffer attachments
- Restricting the read-back area to a part of the rendered area
- Positioning the pixel data correctly on the receiving channels

Frame, Frame Data and Images An eq::Frame references an eq::FrameData. The frame data is the object connecting output with input frames. Output and input frames with the same name within the same compound tree will reference the same frame data.

The frame data is a holder for images and additional information, such as output frame attributes and pixel data availability.

An eq::Image holds a two-dimensional snapshot of the framebuffer and can contain color and/or depth information.

The frame synchronization through the frame data allows the input frame to wait for the pixel data to become ready, which is signaled by the output frame after readback.

Furthermore, the frame data transports the inherited range of the output frame's compound. The range can be used to compute the assembly order of multiple input frames, e.g., for sorted-blend compositing in volume rendering applications.

The offset of input and output frames characterizes the position of the frame data relative to the framebuffer, that is, the **window's** lower-left corner. For output frames this is the position of the channel relative to the window.

[24] http://www.equalizergraphics.com/documents/EGPGV07.pdf

For output frames, the frame data's pixel viewport is the area of the frame buffer to read back. It will transport the offset from the source to the destination channel, that is, the frame data pixel viewport for input frames position the pixel data on the destination. This has the effect that a partial framebuffer readback will end up in the same place in the destination channels.

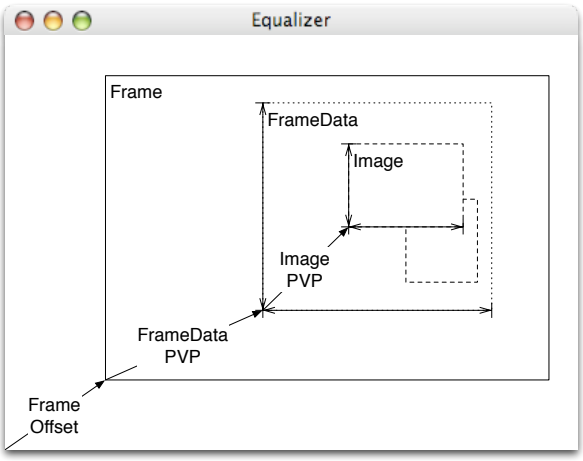


Figure 52: Hierarchy of Assembly Classes

The image pixel viewport signifies the region of interest that will be read back. The default readback operation reads back one image using the full pixel viewport of the frame data.

Figure 52 illustrates the relationship between frames, frame data and images.

The Compositor The Compositor class gathers a set of static functions which implement the various compositing algorithms and low-level optimizations. Figure 53 provides a top-down functional overview of the various compositor functions.

On a high level, the compositor combines multiple input frames using 2D tiling, depth-compositing for polygonal data or sorted, alpha-blended compositing for semi-transparent volumetric data. These operations composite either directly all images on the GPU, or use a CPU-based compositor and then transfer the preintegrated result to the GPU. The high-level entry points automatically select the best algorithm. The CPU-based compositor uses OpenMP to accelerate its operation.

On the next lower level, the compositor provides functionality to composite a single frame, either using 2D tiling (possibly with blending for alpha-blended compositing) or depth-based compositing.

The per-frame compositing in turn relies on the per-image compositing functionality, which automatically decides on the algorithm to be used (2D or depth-based). The concrete per-image assembly operation uses OpenGL operations to composite the pixel data into the framebuffer, potentially using GLSL for better performance.

Custom Assembly in eVolve The eVolve example is a scalable volume renderer. It uses 3D texture-based volume rendering, where the volume is intersected by view-aligned slices. The slices are rendered back-to-front and blended to produce the final image, as shown in Figure 54(b)[25].

When using 2D (sort-first) or stereo decompositions, no special programming is needed to achieve good scalability, as eVolve is mostly fill-limited and therefore scales nicely in these modes.

The full power of scalable volume rendering is however in DB (sort-last) compounds, where the full volume is divided into separate bricks. Each of the bricks is rendered like a separate volume. For recomposition, the RGBA frame buffer data resulting from these render passes then has to be assembled correctly.

Conceptually, the individual volume bricks of each of the source channels produces pixel data which can be handled like one big 'slice' through the full texture.

[25]Volume Data Set courtesy of: SFB-382 of the German Research Council (DFG)

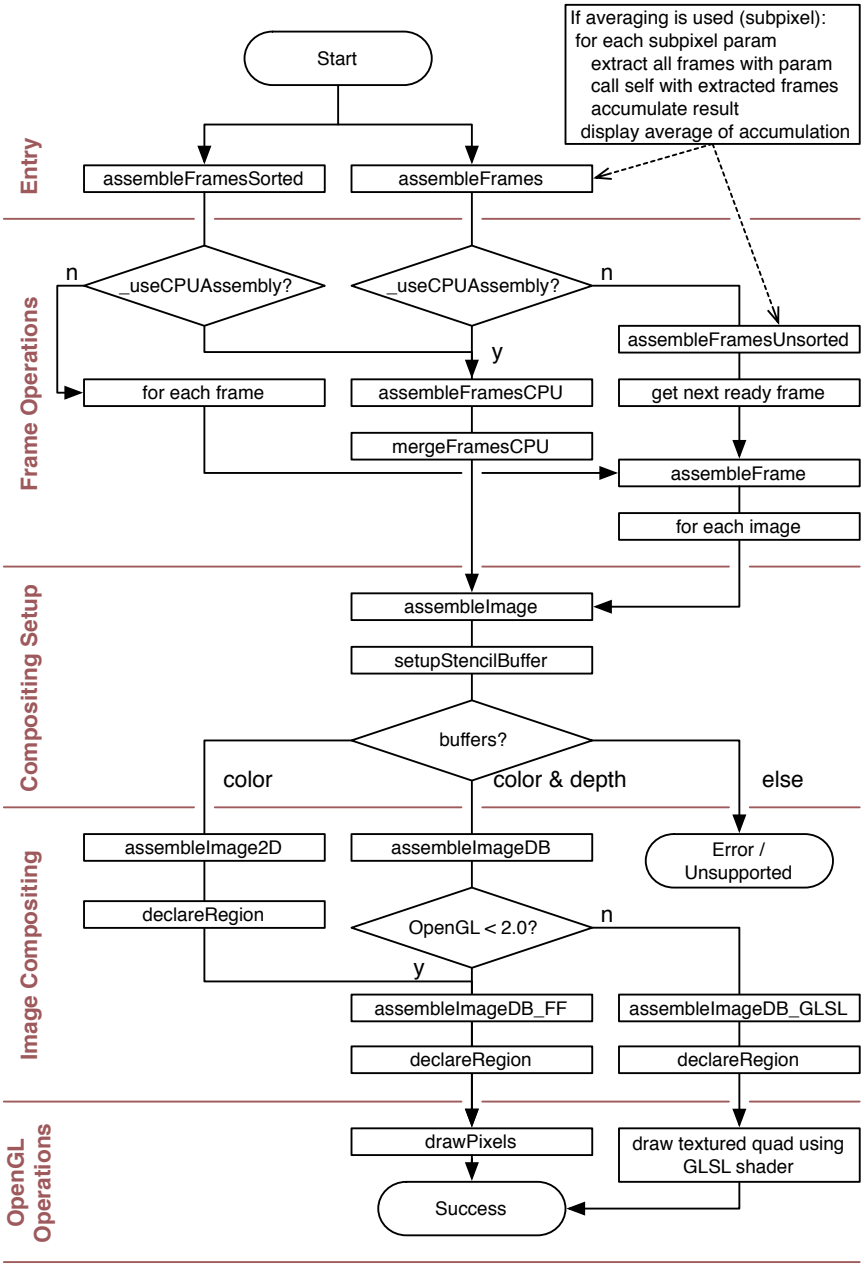
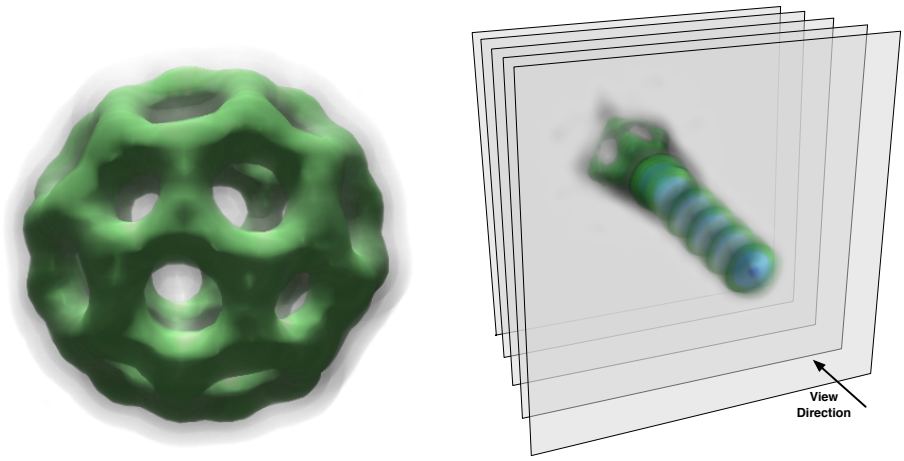


Figure 53: Functional Diagram of the Compositor

Therefore they have to be blended back-to-front in the same way as the slice planes are blended during rendering.

Database decomposition has the advantage of scaling any part of the volume rendering pipeline: texture and main memory (smaller bricks for each channel), fill rate (less samples per channel) and IO bandwidth for time-dependent data (less data update per time step and channel). Since the amount of texture memory needed for each node decreases linearly, sort-last rendering makes it possible to render data sets which are not feasible to visualize with any other approach.

For recomposition, the 2D frame buffer contents are blended to form a seamless picture. For correct blending, the frames are ordered in the same back-to-front

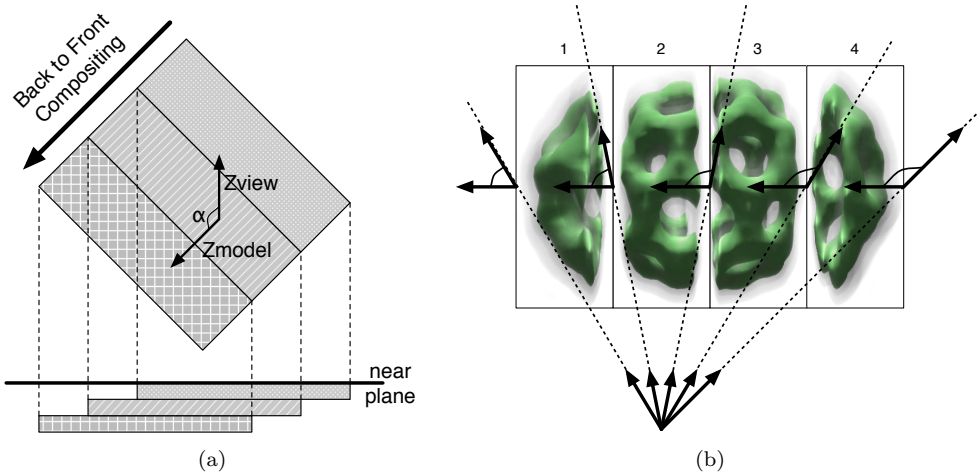


(a) (b)

Figure 54: Final Result(a) of Figure 55(b) using Volume Rendering based on 3D Texture Slicing(b).

order as the slices used for rendering, and use the same blending parameters. Simplified, the frame buffer images are 'thick' slices which are 'rendered' by writing their content to the destination frame buffer using the correct order.

For orthographic rendering, determining the compositing order of the input frames is trivial. The screen-space orientation of the volume bricks determines the order in which they have to be composited. The bricks in eVolve are created by slicing the volume along one dimension. Therefore the range of the resulting frame buffer images, together with the sorting order, is used to arrange the frames during compositing. Figure 55(a) shows this composition for one view.



(a) (b)

Figure 55: Back-to-Front Compositing for Orthogonal and Perspective Frusta

Finding the correct assembly order for perspective frusta is more complex. The perspective distortion invalidates a simple orientation criteria like the one used for orthographic frusta. For the view and frustum setup shown in Figure 55(b)[26] the correct compositing order is 4-3-1-2 or 1-4-3-2.

[26]Volume Data Set courtesy of: AVS, USA

To compute the assembly order, eVolve uses the angle between the *origin* → *slice* vector and the near plane, as shown in Figure 55(b). When the angle becomes greater than 90°, the compositing order of the remaining frames has to be changed. The result image of this composition naturally looks the same as the volume rendering would when rendered on a single channel. Figure 54(a) shows the result of the composition from Figure 55(b).

The assembly algorithm described in this section also works with parallel compositing algorithms such as direct-send.

7.2.10. Subpixel Processing

In eqPly, the image quality is gradually refined when the camera is not moving. Up to 256 samples per pixel are accumulated to implement idle antialiasing. This feature is compatible with subpixel compounds, which use a fixed non-idle anti-aliasing and then accelerate the generation of the remaining samples. The same basic algorithm might be applied to other multisampling effects, e.g., depth-of-field.

Transparent Software Anti-Aliasing Any Equalizer applications can benefit without modification from subpixel compounds. Applications performing their own, configurable idle or non-idle anti-aliasing can easily be integrated with subpixel compounds, as described in the next sections.

The default implementation of applyFrustum and applyOrtho in eq::Channel jitter the frustum when a subpixel parameter is set. Furthermore, the Compositor uses an eq::Accum buffer to accumulate and display the results of a subpixel decomposition in assembleFramesUnsorted and assembleFramesSorted.

Software Anti-Aliasing in eqPly The supersampling algorithm used by eqPly performs anti-aliasing, using a technique which computes randomized samples within a pixel by jittering the frustum by a subpixel amount. The pixel is split into an 16x16 subpixel grid, and a sample is taken randomly within each subpixel. The samples are accumulated and displayed after each step.

To accumulate the result, each eqPly::Channel maintains an accumulation buffer for each rendered eye pass. This accumulation buffer is lazily allocated and resized at the beginning of each frame:

```
// set up accumulation buffer
accum.buffer = new eq::util::Accum( glewGetContext( ));
const eq::PixelViewport& pvp = getPixelViewport();
LBASSERT( pvp.isValid( ));

if( !accum.buffer->init( pvp, getWindow()->getColorFormat( )) ||
    accum.buffer->getMaxSteps() < 256 )
{
    LBWARN <<"Accumulation buffer initialization failed, "
           << "idle AA not available." << std::endl;
    delete accum.buffer;
    accum.buffer = 0;
    accum.step = -1;
    return false;
}

// else
LBVERB << "Initialized "
       << (accum.buffer->usesFBO() ? "FBO accum" : "glAccum")
       << " buffer for " << getName() << " " << getEye()
       << std::endl;

view->setIdleSteps( accum.buffer ? 256 : 0 );
return true;
```

In idle mode, the results are accumulated at the end of the frame and displayed after each iteration by frameViewFinish. Since frameViewFinish is only called on destination channels this operation is done only on the final rendering result after assembly. When all the steps are done the config will stop rendering new frames.

If the current pixel viewport is different from the one saved in frameViewStart, the accumulation buffer needs also to be resized and the idle anti-aliasing is reset:

```
const eq::PixelViewport& pvp = getPixelViewport();
const bool isResized = accum.buffer->resize( pvp );

if( isResized )
{
    const View* view = static_cast< const View* >( getView( ));
    accum.buffer->clear();
    accum.step = view->getIdleSteps();
    accum.stepsDone = 0;
}
else if( frameData.isIdle( ))
{
    setupAssemblyState();

    if( !_isDone() && accum.transfer )
        accum.buffer->accum();
    accum.buffer->display();

    resetAssemblyState();
}
```

The subpixel area is a function of the current jitter step, the channel's subpixel description and the idle state. Each source channel is responsible for filling a subset of the sampling grid. To quickly converge to a good anti-aliasing, each channel selects its samples using a pseudo-random approach, using a precomputed prime number table to find the subpixel for the current step:

```
eq::Vector2i Channel::_getJitterStep() const
{
    const eq::SubPixel& subPixel = getSubPixel();
    const uint32_t channelID = subPixel.index;
    const View* view = static_cast< const View* >( getView( ));
    if( !view )
        return eq::Vector2i::ZERO;

    const uint32_t totalSteps = uint32_t( view->getIdleSteps( ));
    if( totalSteps != 256 )
        return eq::Vector2i::ZERO;

    const Accum& accum = _accum[ lunchbox::getIndexOfLastBit( getEye()) ];
    const uint32_t subset = totalSteps / getSubPixel().size;
    const uint32_t index = ( accum.step * _primes[ channelID % 100 ] )%subset +
                           ( channelID * subset );
    const uint32_t sampleSize = 16;
    const int dx = index % sampleSize;
    const int dy = index / sampleSize;

    return eq::Vector2i( dx, dy );
}
```

The FrameData class holds the applications idle mode. The Config updates the idle mode information depending on the application's state. Each Channel performs anti-aliasing when no user event requires a redraw.

When the rendering is not in idle mode, the jitter is queried from Equalizer which returns an optimal subpixel offset for the given subpixel decomposition. This is used during normal rendering of subpixel compounds:

```
eq::Vector2f Channel::getJitter() const
{
```

```
const FrameData& frameData = _getFrameData();
const Accum& accum = _accum[ lunchbox::getIndexOfLastBit( getEye()) ];

if( !frameData.isIdle() || accum.step <= 0 )
    return eq::Channel::getJitter();
```

During idle rendering of any decomposition, the jitter for the frustum is computed using the normalized subpixel center point and the size of a pixel on the near plane. A random position within the sub-pixel is set as a sample position, which will be used to move the frustum. The getJitter method will return the computed jitter vector for the current frustum. This method has a default implementation in eq::Channel for subpixel compounds, but is overwritten in eqPly to perform idle anti-aliasing:

```
const eq::Vector2i jitterStep = _getJitterStep();
if( jitterStep == eq::Vector2i::ZERO )
    return eq::Vector2f::ZERO;

const eq::PixelViewport& pvp = getPixelViewport();
const float pvp_w = float( pvp.w );
const float pvp_h = float( pvp.h );
const float frustum_w = float(( getFrustum().get_width( )));
const float frustum_h = float(( getFrustum().get_height( )));

const float pixel_w = frustum_w / pvp_w;
const float pixel_h = frustum_h / pvp_h;

const float sampleSize = 16.f; // sqrt( 256 )
const float subpixel_w = pixel_w / sampleSize;
const float subpixel_h = pixel_h / sampleSize;

// Sample value randomly computed within the subpixel
lunchbox::RNG rng;
const eq::Pixel& pixel = getPixel();

const float i = ( rng.get< float >() * subpixel_w +
                  float( jitterStep.x( )) * subpixel_w ) / float( pixel.w );
const float j = ( rng.get< float >() * subpixel_h +
                  float( jitterStep.y( )) * subpixel_h ) / float( pixel.h );

return eq::Vector2f( i, j );
```

Subpixel Compounds in eqPly Subpixel compounds accelerate the idle anti-aliasing computation in eqPly. The accumulation buffer used in the Compositor in frameAssemble is the same accumulation buffer used by eqPly in frameViewFinish for collecting the idle anti-aliasing results.

When an application passes an eq::Accum object to the compositor, the compositor adds subpixel decomposition result into this accumulation buffer. Otherwise it uses its own accumulation buffer, which it clears in the beginning of the compositing process.

Since eqPly accumulates the results over multiple rendering frames, each Channel manages its own accumulation buffer, which is passed to the compositor in frameAssemble and used in frameViewFinish to display the results accumulated so far.

The number of performed jitter steps is tracked in frameDraw and frameAssemble, and is used in frameFinish to decrement the outstanding anti-aliasing samples. Therefore, the idle anti-aliasing is finished much faster if the current configuration uses a subpixel compound.

7.2.11. Statistics

Statistics Gathering Statistics are measured in milliseconds since the configuration was initialized. The server synchronizes the per-configuration clock on each

node automatically. Each statistic event records the originator's (channel, window, pipe, node, view or config) unique identifier.

Statistics are enabled per entity using an attribute hint. The hint determines how precise the gathered statistics are. When set to fastest, the per-frame clock is sampled directly when the event occurs. When set to nicest, all OpenGL commands will be finished before sampling the event. This may incur a performance penalty, but gives more correct results. The default setting is fastest in release builds, and nicest in debug builds. The fastest setting often attributes times to the operation causing an OpenGL synchronization instead of the operation submitting the OpenGL commands, e.g., the readback time contains operations from the preceding draw operation.

The events are processed by the channel's and window's processEvent method. The default implementation sends these events to the config using Config::sendEvent, as explained in Section 7.2.1. When the default implementation of Config::handleEvent receives the statistics event, it sorts the event per frame and per originator. When a frame has been finished, the events are pushed to the local (app-)node for visualization. Furthermore, the server also receives these events, which are used by the equalizers to implement the various runtime adjustments.

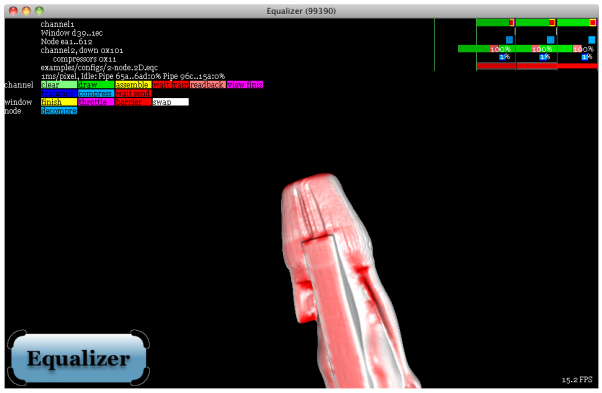


Figure 56: Statistics for a two node 2D compound

Figure 56 shows the visualization of statistics events in an overlay[27].

Statistics Overlay The eq::Channel provides the method drawStatistics which renders a statistics overlay using the gathered statistics events. Statistics rendering is toggled on and off using the 's' key in the shipped Equalizer examples.

Figure 57 shows a detailed view of Figure 56. The statistics shown are for a two-node 2D compound. The destination channel is on the appNode and contributes to the rendering.

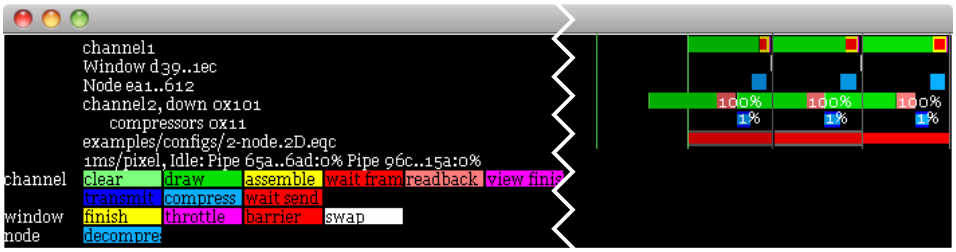


Figure 57: Detail of the Statistics from Figure 56.

This configuration executes two Channel::frameDraw tasks, one Channel::frameReadback task on the remote node, one Channel::frameAssemble task on the local node, as well as frame transmission and compression.

[27] 3D model courtesy Cyberware, Inc.

The X axis is the time, the right-most pixel is the most current time. One pixel on the screen corresponds to a given time unit, here one millisecond per pixel. The scale is zoomed dynamically to powers-of-ten milliseconds to fit the statistics into the available viewport. This allows easy and accurate evaluations of bottlenecks or misconfigurations in the rendering pipeline. The scale of the statistics is printed directly above the legend.

On the Y axis are the entities: channels, windows, nodes and the config. The top-most channel is the local channel since it executes frameAssemble, and the lower channel is the remote channel, executing frameReadback.

To facilitate the understanding, older frames are gradually grayed out. The right-most, current frame is brighter than the frame before it.

The configuration uses the default latency of one frame. Consequently, the execution of two frames overlaps. This can be observed in the early execution of the remote channel's frameDraw, which starts while the local channel is still drawing and assembling the previous frame.

The asynchronous execution allows operations to be pipelined, i.e., the compression, network transfer and assembly with the actual rendering and readback. This increases performance by minimizing idle and wait times. In this example, the remote channel2 has no idle times, and executes the compression and network transfer of its output frame in parallel with rendering and readback. Likewise, the application node receives and decompresses the frame in parallel to its rendering thread.

In the above example, the local channel finishes drawing the frame early, and therefore spends a couple of milliseconds waiting for the input frame from the remote channel. These wait events, rendered red, are a sub-event of the yellow frameAssemble task. Using a load_equalizer instead of a static 2D decomposition would balance the rendering in this example better and minimize or even eliminate this wait time.

The white Window::swapBuffers task might take a longer time, since the execution of the swap buffer is locked to the vertical retrace of the display. Note that the remote source window does not execute swapBuffers in this configuration, since it is a single-buffered FBO.

The beginning of a frame is marked by a vertical green line, and the end of a frame by a vertical gray line. These lines are also attenuated. The brightness and color matches the event for Config::startFrame and Config::finishFrame, respectively. The event for startFrame is typically not visible, since it takes less than one millisecond to execute. If no idle processing is done by the application, the event for finishFrame occupies a full frame, since the config is blocked here waiting for the frame current - latency to complete.

A legend directly below the statistics facilitates understanding. It lists the per-entity operations with its associated color. Furthermore, some other textual information is overlayed with the statistics. The total compression ratio is printed with each readback and compression statistic. In this case the image has been not been compressed during download. For network transfer it has been compressed to 1% of its original size since it contains many black background pixels. For readback the plugin with the name 0x101, EQ_COMPRESSOR_TRANSFER_RGBA_TO_BGRA has been used, and for compression the plugin 0x11, EQ_COMPRESSOR_RLE_DIFF_BGRA was used. The compressor names are listed in the associated plugin header compressorTypes.h.

7.2.12. GPU Computing with CUDA

The Equalizer parallel rendering framework can be used to scale GPU computing applications (also known as GPGPU) based on CUDA. The necessary steps to write a distributed GPGPU application using Equalizer are described in this section.

Please note that the support for CUDA is only enabled if the CUDA libraries are found in their default locations. Otherwise please adapt the build system accordingly.

CUDA Initialization Equalizer automatically initializes a CUDA context on each pipe (using the specified device number) whenever hint_cuda_GL_interop is set. The initialization is currently done using the CUDA runtime API to support device emulation. On the other side, if this hint is not set the OpenGL interop feature is not enabled, and furthermore, the GPU which executes CUDA code defaults to device 0.

Once CUDA is initialized correctly, C for CUDA can be used as any other GPU programming interface.

CUDA Memory Management Equalizer does not provide any facility to perform memory transfer from and to the CUDA devices. This is entirely left to the programmer.

8. The Collage Network Library

The Collage network library provides a peer-to-peer communication infrastructure. It is used by Equalizer to communicate between the application node, the server and the render clients. It can also be used by applications to implement distributed processing independently or complementary to the Equalizer functionality.

The network library is a separate project on github, implemented in the co namespace. It provides networking functionality of different abstraction layers, gradually providing higher level functionality for the programmer. The main primitives in Collage are:

Connection A stream-oriented point-to-point communication line. Different implementations of a connection exists. The connections transmit raw data 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, implements the protocol between Collage nodes.

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 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.

Figure 58 provides an overview of the major collage classes and their relationship, as discussed in the following sections.

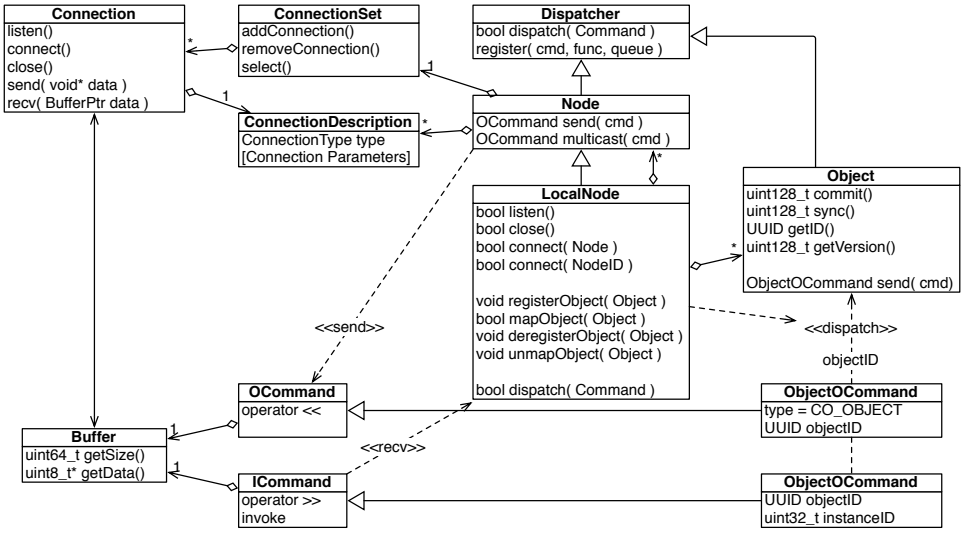


Figure 58: UML class diagram of the major Collage classes

8.1. Connections

The co::Connection is the basic primitive used for communication between processes in Equalizer. 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.

A co::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 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.

8.2. Command Handling

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

The dispatcher allows the registration of a 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 method dispatchCommand pushes the packet to the registered queue and sets the registered command function on the ICommand. When the commands are dequeued by the processing thread the registered method is executed using ICommand::invoke.

A command function groups the method and this pointer, allowing to call a C++ method on a concrete instance. If no queue is registered for a certain command, dispatchCommand directly calls the registered command function directly.

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 invoke the command when it is processed by these threads.

8.3. Nodes

The co::Node is the abstraction of one process in the cluster. 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 co::OCommands.

The co::LocalNode is the specialization 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 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, instantiating the node and connecting it. Both operations may fail.

8.3.1. Zeroconf Discovery

Each LocalNode provides a co::Zeroconf communicator, which allows node and resource discovery. This requires using a Lunchbox library supporting dns_sd. The service "_collage._tcp" is used to announce the presence of a listening LocalNode using the ZeroConf protocol to the network, unless the local node has no listening connections. The node identifier and all listening connection descriptions are announced using keys starting with "co_". Internally Collage uses this information to connect unknown nodes by using the node identifier alone.

Applications may use the ZeroConf communicator to add additional key-value pairs to announce application-specific data, and to retrieve a snapshot of all key-value pairs of all discovered nodes on the network.

8.3.2. Communication between Nodes

Figure 59 shows the communication between two nodes. When the remote node sends a command, the listening node receives the command and dispatches it from the receiver thread using the method dispatchCommand. The default implementation knows how to dispatch commands of type node or object. Applications can define custom data types for commands, and then have to extend dispatchCommand to handle these custom data types.

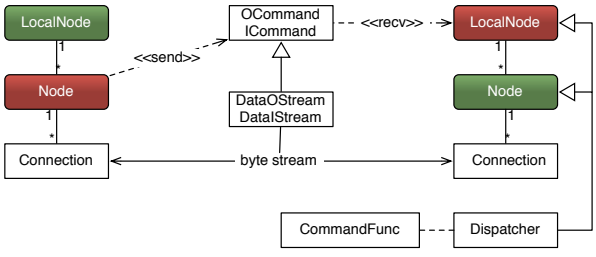


Figure 59: Communication between two Nodes

Node commands are directly dispatched using Dispatcher::dispatchCommand. For object commands, the appropriate object is found on the local node and Object::dispatchCommand is called on the instance to dispatch the command.

If dispatchCommand returns false, the command will be re-dispatched later. This is used if an object has not been mapped locally, and therefore the command could not be dispatched.

If an application wants to extend communication on the node level, it can define its own datatype for commands, define custom node commands or use custom commands.

Commands with a custom datatype use a command type greater or equal than COMMAND_CUSTOM. The receiving local node has to override LocalNode::dispatchCommand to handle them.

Custom node commands use the command type COMMAND_NODE and any command greater than CMD_NODE_CUSTOM. By registering a co::CommandFunc on the receiving local node for these commands, the co::Dispatcher dispatch and invoke mechanism is used automatically.

These two aforementioned mechanisms are very efficient but require a clear, linear inheritance from co::LocalNode. In more complex scenarios, e.g., when two libraries share the same local node for communication, custom commands can be used. Custom commands are indentified by a unique 128 bit integer, which is either generated randomly or based on a hash of a unique URI:

```
const co::uint128_t cmdID1( lunchbox::make_uint128( "ch.eyescale.collage.test.c1" ));
const co::uint128_t cmdID2( lunchbox::make_uint128( "ch.eyescale.collage.test.c2" ));
```

A specialized Node::send method transmits a CustomOCommand. The application has to register a custom command handler on the receiving side, which will be invoked during processing of the command on the given thread queue:

```
server->registerCommandHandler( cmdID1,
                                boost::bind( &MyLocalNode::cmdCustom1,
                                             server.get(), _1 ),
                                server->getCommandThreadQueue( ));
server->registerCommandHandler( cmdID2,
                                boost::bind( &MyLocalNode::cmdCustom2,
                                             server.get(), _1 ), 0 );
```

Like any other output command, CustomOCommands allow streaming additional data to the command:

```
serverProxy->send( cmdID1 );
serverProxy->send( cmdID2 ) << std::string( "hello" );
```

8.4. Objects

Distributed objects provide powerful, object-oriented data distribution for C++ objects. They facilitate the implementation of data distribution in a cluster environment. Their functionality and an example use case for parallel rendering has been described in Section 7.1.3.

Distributed objects subclass from co::Serializable or co::Object. The application programmer implements serialization and deserialization of the distributed data. Objects are dynamically attached to a listening local node, which manages the network communication and command dispatch between different instances of the same distributed object.

Objects are addresses using a universally unique identifier. The identifier is automatically created in the object constructor. The master version of a distributed object is registered with the co::LocalNode. The identifier of the master instance can be used by other nodes to map their instance of the object, thus synchronizing the object's data and identifier with the remotely registered master version.

One instance of an object is registered with its local node, which makes this object the master instance. Slave instance on the same or other nodes are mapped to this

master. During mapping they are initialized by transmitting a version of the master instance data. During commit, the change delta is pushed from the master to all mapped slave objects, using multicast connections when available. Slave objects can also commit data to their master instance, which in turn may recommit it to all slaves, as described in Section 8.4.4. Objects can push their instance data to a set of nodes, as described in Section 8.4.5.

Distributed objects can be static (immutable) or dynamic. Dynamic objects are versioned. New versions are committed from the master instance, which sends the delta between the previous and current version to all mapped slave objects. The slave objects sync the queued deltas when they need a version.

Objects may have a maximum number of unapplied versions, which will cause the commit on the master instance to block if any slave instance has reached the maximum number of queued versions. By default, slave instances can queue an unlimited amount of unapplied versions.

Objects use compression plugins to reduce the amount of data sent over the network. By default, the plugin with the highest compression ratio and lossless compression for EQ_COMPRESSOR_DATATYPE_BYTE tokens is chosen. The application may override Object::chooseCompressor to deactivate compression by returning EQ_COMPRESSOR_NONE or to select object-specific compressors.

8.4.1. Common Usage for Parallel Rendering

Distributed objects are addressed using universally unique identifiers, because pointers to other objects cannot be distributed directly; they have no meaning on remote nodes.

The entry point for shared data on a render client is the identifier passed by the application to eq::Config::init. This identifier typically contains the identifier of a static distributed object, and is passed by Equalizer to all configInit task methods. Normally this initial object is mapped by the render clients in Node::configInit. It normally contains identifiers of other shared data objects.

The distributed data objects referenced by the initial data object are often versioned objects, to keep them in sync with the rendered frames. Similar to the initial identifier passed to Config::init, an object identifier or object version can be passed to Config::startFrame. Equalizer will pass this identifier to all frameStart task methods. In eqPly, the frame-specific data, e.g., the global camera data, is versioned. The frame data identifier is passed in the initial data, and the frame data version is passed with each new frame request.

There are multiple ways of implementing data distribution for an existing C++ class hierarchy, such as a scene graph:

Subclassing The classes to be distributed inherit from co::Object and implement the serialization methods. This approach is recommended if the source code of existing classes can be modified. It is used for eqPly::InitData and eqPly::FrameData. (Figure 60(a))

Proxies For each object to be distributed, a proxy object is created which manages data distribution for its associated object. This requires the application to track changes on the object separately from the object itself. The model data distribution of eqPly is using this pattern. (Figure 60(b))

Multiple Inheritance A new class inheriting from the class to be distributed and from co::Object implements the data distribution. This requires the application to instantiate a different type of object instead of the existing object, and to create wrapper methods in the superclass calling the original method

and setting the appropriate dirty flags. This pattern is not used in eqPly. (Figure 60(c))

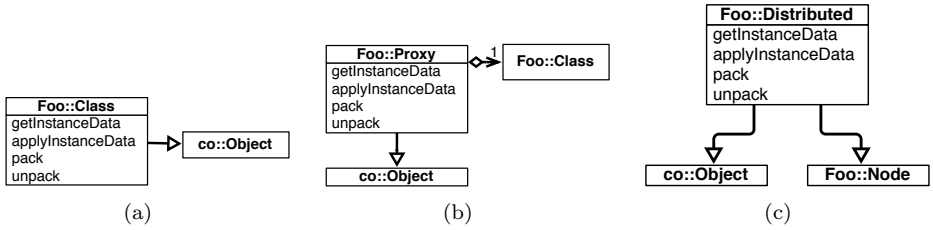


Figure 60: Object Distribution using Subclassing, Proxies or Multiple Inheritance

8.4.2. Change Handling and Serialization

Equalizer determines the way changes are to be handled by calling Object::getChangeType during the registration of the master version of a distributed object. The change type determines the memory footprint and the contract for the serialization methods. The deserialization always happens in the application thread causing the deserialization. The following change types are possible:

STATIC The object is not versioned nor buffered. The instance data is serialized whenever a new slave instance is mapped. The serialization happens in the command thread on the master node, i.e., in parallel to the application threads. Since the object's distributed data is supposed to be static, this should not create any race conditions. No additional data is stored.

INSTANCE The object is versioned and buffered. The instance and delta data are identical, that is, only instance data is serialized. The serialization always happens before LocalNode::registerObject or Object::commit returns. 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. Both the delta and instance data are serialized before Object::commit returns. The delta data is transmitted to slave instances for synchronization. Previous instance data is saved to be able to map old versions.

UNBUFFERED The object is versioned and unbuffered. No data is stored, and no previous versions can be mapped. The instance data is serialized from the command thread whenever a new slave instance is mapped, i.e., in parallel to application threads. The application has to ensure that this does not create any thread conflicts. The delta data is serialized before Object::commit returns. The application may choose to use a different, more optimal implementation to pack deltas by using a different implementation for getInstanceData and pack.

8.4.3. co::Serializable

co::Serializable implements one typical usage pattern for data distribution for co::Object. 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. It is easier to use, but imposes one typical way to implement data distribution.

For serialization, the default co::Object serialization functions are implemented by co::Serializable, which (de-)serializes and resets the dirty bits, and calls serialize or deserialize 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.

To use co::Serializable, the following steps have to be taken:

Inherit from co::Serializable: The base class will provide the dirty bit management and call serialize and deserialize appropriately. By optionally overriding getChangeType, the default versioning strategy might be changed:

```
namespace eqPly
{
    /**
     * Frame-specific data.
     *
     * The frame-specific data is used as a per-config distributed object and
     * contains mutable, rendering-relevant data. Each rendering thread (pipe)
     * keeps its own instance synchronized with the frame currently being
     * rendered. The data is managed by the Config, which modifies it directly.
     */
    class FrameData : public co::Serializable
    {
```

Define new dirty bits: Define dirty bits for each data item by starting at Serializable::DIRTY_CUSTOM, shifting this value consecutively for each new dirty bit:

```
        /** The changed parts of the data since the last pack(). */
        enum DirtyBits
        {
            DIRTY_CAMERA  = co::Serializable::DIRTY_CUSTOM << 0,
            DIRTY_FLAGS   = co::Serializable::DIRTY_CUSTOM << 1,
            DIRTY_VIEW    = co::Serializable::DIRTY_CUSTOM << 2,
            DIRTY_MESSAGE = co::Serializable::DIRTY_CUSTOM << 3,
        };
```

Implement serialize and deserialize: For each object-specific dirty bit which is set, stream the corresponding data item to or from the provided stream. Call the parent method first in both functions. For application-specific objects, write a (de-)serialization function:

```
void FrameData::serialize( co::DataOStream& os, const uint64_t dirtyBits )
{
    co::Serializable::serialize( os, dirtyBits );
    if( dirtyBits & DIRTY_CAMERA )
        os << _position << _rotation << _modelRotation;
    if( dirtyBits & DIRTY_FLAGS )
        os << _modelID << _renderMode << _colorMode << _quality << _ortho
           << _statistics << _help << _wireframe << _pilotMode << _idle
           << _compression;
    if( dirtyBits & DIRTY_VIEW )
        os << _currentViewID;
    if( dirtyBits & DIRTY_MESSAGE )
        os << _message;
}

void FrameData::deserialize( co::DataIStream& is, const uint64_t dirtyBits )
{
    co::Serializable::deserialize( is, dirtyBits );
    if( dirtyBits & DIRTY_CAMERA )
        is >> _position >> _rotation >> _modelRotation;
    if( dirtyBits & DIRTY_FLAGS )
        is >> _modelID >> _renderMode >> _colorMode >> _quality >> _ortho
```

```
            >> _statistics >> _help >> _wireframe >> _pilotMode >> _idle
            >> _compression;
    if( dirtyBits & DIRTY_VIEW )
        is >> _currentViewID;
    if( dirtyBits & DIRTY_MESSAGE )
        is >> _message;
}
```

Mark dirty data: In each 'setter' method, call setDirty with the corresponding dirty bit:

```
void FrameData::setCameraPosition( const eq::Vector3f& position )
{
    _position = position;
    setDirty( DIRTY_CAMERA );
}
```

The registration and mapping of co::Serializables is done in the same way as for co::Objects, which has been described in Section 8.4.

8.4.4. Slave Object Commit

Versioned slave objects may also commit data to the master instance. However, this requires the implementation to take special care to resolve conflicts during deserialization. The algorithm and constraints for slave object commits are explained in this section.

When using commit on slave object instances, multiple modifications on the same database may happen simultaneously. To avoid excessive synchronization in the network layer, Equalizer implements a lightweight approach which requires the application to avoid or handle conflicting changes on the same object.

When a slave object instance commits data, pack is called on the object. The data serialized by pack is send to the master instance of the object. On the master instance, notifyNewVersion is called from the command thread to signal the data availability. The slave instance generates a unique, random version. When no data was serialized, VERSION_NONE is returned.

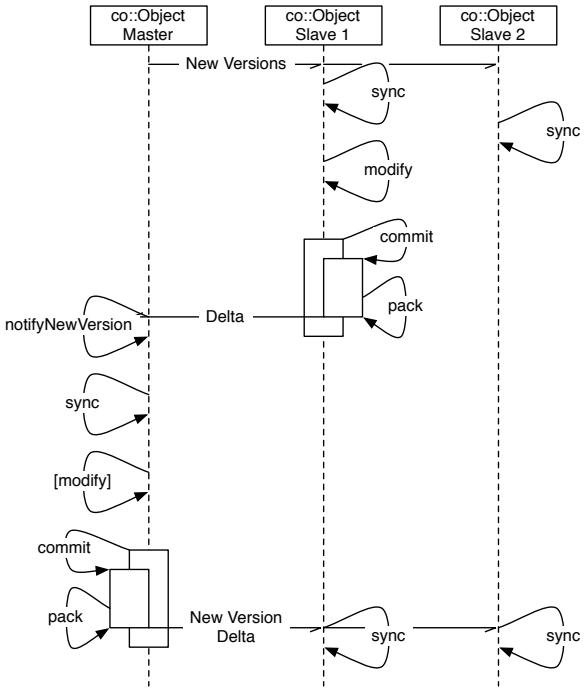


Figure 61: Slave Commit Communication Sequence

The master instance can sync delta data received from slaves. When using the version generated by the slave object commit, only the delta for this version is applied. When using VERSION_NEXT as the version parameter to sync, one slave commit is unpacked. This call may block if no data is pending. When using VERSION_HEAD all pending versions are unpacked. The data is synchronized in the order it has been received

from the slaves. If a specific order is needed, it is the application's responsibility to serialize the slave commits accordingly.

Synchronizing slave data on a master instance does not create a new version. The application has to explicitly mark the deserialized data dirty and call commit to pack and push the changed data to all slaves.

This approach requires the application to handle or avoid, if possible, the following situations:

- A slave instance will always receive its own changes when the master re-commits the slave change.
- A slave instance commits data which does not correspond to the last version of the master instance.
- Two different slave instances commit changes simultaneously which may result in conflicts.
- A master instance applies data to an already changed object.
- The master instance commits a new version while a slave instance is modifying its instance.

Figure 61 depicts one possible communication sequence. Where possible, it is best to adhere to the following rules:

- Handle the case that a slave instance will receive its own changes again.
- Set the appropriate dirty bits when unpacking slave delta data on the master object instance to redistribute the changes.
- Write your application code so that only one object instance is modified at any given time.
- When multiple slave instances have to modify the same object at the same time, try to modify and serialize disjunct data of the object.
- Before modifying a slave instance, sync it to the head version.
- Write serialization code defensively, e.g.:
  - When adding a new child to an object, check that it has not been added already.
  - When removing a child, transmit the child's identifier instead of its index for removal.
  - Modify a variable by serializing its value (instead of the operation modifying it), so that the last change will win.

8.4.5. Push Object Distribution

During normal object mapping, the slave object requests the mapping and thereby pulls its instance data from the master object. Push-based data distribution is initiated from an object and transmits the data to a set of given nodes. It allows more efficient initialization of a group of slave instances when multicast is used, since for all nodes only a single instance data is transmitted.

The transfer is initiated using Object::push. On all nodes given to the push command, LocalNode::objectPush is called once the data is received. The push operation prefers multicast connections, that is, objectPush is called on all nodes of the multicast groups used, even when they are not part of the node list given to the push command.

The push command transmits two application-specific variables: a group identifier and an object type.

The group identifier is intended to be used to identify the push operation. For example, a set of Equalizer render client nodes requests a scene to be pushed, transmitting the scene identifier to the master node. The master node collects all requests and then traverses the given scene graph pushing all scene objects using this scene identifier as the group identifier. The render client nodes will filter the received object pushes against their set of pending requests.

The object identifier is used by the receiving nodes to instantiate the correct object types when they need to be created. In the previous example, the object identifier would describe the scene graph node type and the render clients would use a factory to recreate the scene graph.

The LocalNode::objectPush callback is called from the command thread once the instance data is ready. It receives the aforementioned group identifier and object type as well as the object identifier and the DataIStream containing the instance data. The latter is typically used to call Object::applyInstanceData on the newly created object.

The default implementation of objectPush calls registered push handlers. For each group identifier, a separate handler function may be registered using LocalNode::registerPushHandler.

A push operation does not establish any master-slave object mapping, that is, the receiving side will typically use LocalNode::mapObject with VERSION_NONE to establish a slave mapping.

8.4.6. Communication between Object Instances

Objects can send commands to each other using ObjectOCommand, which is derived from OCommand. The object command extends the command by the object identifier and an object instance identifier. The object output command is created by Object::send and transmitted when it looses its scope.

Multiple instances of the same object (identifier) can be mapped on the same node and session simultaneously. Each object instance has a node-unique instance identifier. When the instance ID is set to EQ_INSTANCE_ALL (the default value), a command is dispatch to all object instances registered to the session with the correct object ID. Multiple object instances per node are used when different threads on the node need to process a different version of the same object.

When the command is intended for a specific instance, set the corresponding instance identifier during Object::send.

Distributed objects provide data synchronization functionality, as described above. Additionally, applications can send command commands by creating custom object commands with a command greater than CMD_OBJECT_CUSTOM.

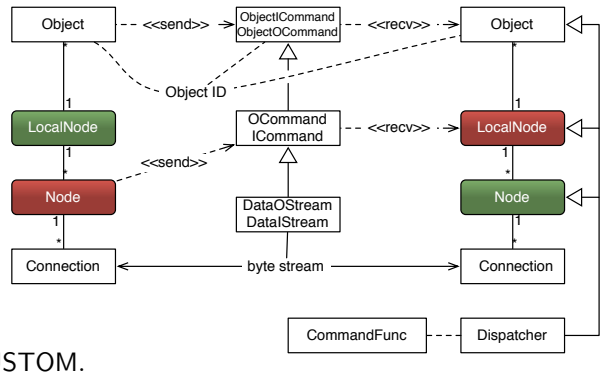


Figure 62: Communication between two Objects

Distributed object communication relies on the lower node communication layers, as shown in Figure 62.

8.4.7. Usage in Equalizer

The Equalizer client library and server are built on top of the network layer. They influence the design of it, and serve as a sample implementation on how to use classes in the co namespace.

Equalizer uses the common base class eq::fabric::Object, which derives from co::Serializable for implementing data distribution between the server, application and render clients. This class manages common entity data, and is not intended to be subclassed directly. The inheritance chain eq::View → eq::fabric::View → eq::fabric::Object → co::Serializable → co::Object serves as sample implementation for this process.

Equalizer objects derived from co::Serializable, e.g., eq::View, are registered, mapped and synchronized by Equalizer. To execute the rendering tasks, the server send the task command command to the render clients, which dispatch and execute them in the received order.

8.5. Barrier

The co::Barrier provides a networked barrier primitive. It is an co::Object used by Equalizer to implement software swap barriers, but it can be used as a generic barrier in application code.

The barrier uses both the data distribution for synchronizing its data, as well as custom command commands to implement the barrier logics. A barrier is a versioned object. Each version can have a different height, and enter requests are automatically grouped together by version.

8.6. ObjectMap

The co::ObjectMap is a specialized co::Serializable which provides automatic distribution and synchronization of co::Objects. All changed objects are committed when co::ObjectMap is committed, and sync() on slave instances updates mapped objects to their respective versions.

The objects on slave ObjectMap instances are mapped explicitly, either by providing an already constructed instance or using implicit object creation through the co::ObjectFactory. The factory needs to be supplied upon construction of the co::ObjectMap and implement creation of the desired object types. Implicitly created objects are owned by the object map which limits their lifetime. They are released upon unmapping caused by deregister(), explicit unmapping or destruction of the slave instance ObjectMap.

In Sequel, the co::ObjectMap is used to distribute and synchronize all objects to the rendering frames. The InitData and FrameData objects are implicitely known and managed by Sequel, and other objects might be used in addition. The commit and synchronization of the object map, and consequently all its objects, is automatically performed in the correct places, most importantly the commit at the beginning of the frame, and the sync when accessing an object from the renderer.

A. Command Line Options

Equalizer recognizes a number of command line options. To not pollute the application namespace for argument, all Equalizer command line options start with –eq- and all Collage command line options with –co-. The following options are recognized:

–eq-help shows all available library command line options and their usage.

–eq-client is used to start render client processes. Starts a resident render client when used without additional arguments, as described in Section 4.3.1. The server appends an undocumented argument to this option which is used by the eq::Client to connect to the server and identify itself.

–eq-layout <**layoutName**> activates all layouts of the given name on all respective canvases during initialization. This option may be used multiple times.

–eq-gpufilter applies the given regular expression against nodeName:port.device during autoconfiguration and only uses the matching GPUs.

–eq-modelunit <**unitValue**> is used for scaling the rendered models in all views. The model unit defines the size of the model wrt the virtual room unit which is always in meter. The default unit is 1 (1 meter or EQ_M).

–eq-logfile <**filename**> redirects all Equalizer output to the given file.

–eq-server <**connection**> provides a connection description when using a separate server process.

–eq-config <**sessionName**|**filename.eqc**> is used to configure an application-local server, as described in Section 3.1.2.

–eq-config-flags <multiprocess | multiprocess_db | ethernet | infiniband | 2D_horizontal | 2D_vertical | 2D_tiles> is used as input for the autoconfiguration to tweak the configuration generation.

–eq-config-prefixes <**CIDR-prefixes**> is used as input for the autoconfiguration to filter network interfaces.

–eq-render-client <**filename**> provides an alternate executable name for starting render clients. This option is useful if the client machines use a different directory layout from the application machine.

–co-listen <**connection**> configures the local node to listen on the given connections. The formation of the connection argument is documented in co::ConnectionDescription::fromString(). This option may be used multiple times.

B. File Format

The current Equalizer file format is a one-to-one representation of the server's internal data structures. Its purpose is intermediate, that is, it will gradually be replaced by automatic resource detection and configuration. However the core scalability engine will always use a similar structure as currently exposed by the file format.

The file format represents an ASCII deserialization of the server. Streaming an eq::server::Server to an lunchbox::Log ostream produces a valid configuration file. Likewise, loading a configuration file produces an eq::server::Server.

The file format uses the same syntactical structure as VRML. If your text editor supports syntax highlighting and formatting for VRML, you can use this mode for editing .eqc files.

The configuration file consist of an optional global section and a server configuration. The global section defines default values for various attributes. The server section represents an eq::server::Server.

B.1. File Format Version

B.2. Global Section

The global section defines default values for attributes used by the individual entities in the server section. The naming convention for attributes is:

EQ_<ENTITY>_<DATATYPE>ATTR_<ATTR_NAME>

The entity is the capitalized name of the corresponding section later in the configuration file: connection, config, pipe, window, channel or compound. The connection is used by the server and nodes.

The datatype is one capital letter for the type of the attribute's value: S for strings, C for a character, I for an integer and F for floating-point values. Enumeration values are handled as integers. Strings have always to be surrounded by double quotes '"'. A character has to be surrounded by single quotes '''.

The attribute name is the capitalized name of the entities attribute, as discussed in the following sections.

Global attribute values have useful default parameters, which can be overridden with an environment variable of the same name. For enumeration values the corresponding integer value has to be used. The global values in the config file override environment variables, and are in turn overridden by the corresponding attributes sections of the specific entities.

The globals section starts with the token global and an open curly brace '{', and is terminated with a closing curly brace '}'. Within the braces, globals are set using the attribute's name followed by its value. The following attributes are available:

Name	EQ_CONNECTION_SATTR_HOSTNAME
Value	string
Default	"localhost"
Details	The hostname or IP address used to connect the server or node. When used for the server, the listening port of the server is bound to this address. When used for a node, the server first tries to connect to the render client node using this hostname, and then tries to launch the render client executable on this host.
See also	EQ_NODE_SATTR_LAUNCH_COMMAND EQ_CONNECTION_IATTR_PORT EQ_CONNECTION_IATTR_TYPE

Name	EQ_CONNECTION_IATTR_TYPE
Value	TCPIP | SDP | RSP | PIPE [Win32 only]
Default	TCPIP
Details	The protocol for connections. SDP programmatically selects the socket direct protocol (AF_INET_SDP) provided by most InfiniBand protocol stacks, TCPIP uses normal TCP sockets (AF_INET). RSP provides reliable UDP multicast. PIPE uses a named pipe to communicate between two processes on the same machine.

Name	EQ_CONNECTION_IATTR_PORT
Value	unsigned
Default	0
Details	The listening port used by the server or node. For nodes, the port can be used to contact prestarted, resident render client nodes or to use a specific port for the node. If 0 is specified, a random port is chosen. Note that a server with no connections automatically creates a default connection using the server's default port.

Name	EQ_CONNECTION_IATTR_FILENAME
Value	string
Default	none
Details	The filename of the named pipe used by the server or node. The filename has to be unique on the local host.

Name	EQ_CONFIG_IATTR_ROBUSTNESS
Value	ON | OFF
Default	ON
Details	Handle initialization failures robustly by deactivating the failed resources but keeping the configuration running.

Name	EQ_CONFIG_FATTR_EYE_BASE
Value	float
Default	0.05
Details	The default distance in meters between the left and the right eye, i.e., the eye separation. The eye base influences the frustum during stereo rendering. See Section 7.2.6 for details.
See also	EQ_WINDOW_IATTR_HINT_STEREO EQ_COMPOUND_IATTR_STEREO_MODE EQ_CONFIG_FATTR_FOCUS_DISTANCE EQ_CONFIG_IATTR_FOCUS_MODE

Name	EQ_CONFIG_FATTR_FOCUS_DISTANCE
Value	float
Default	1.0
Details	The default distance in meters to the focal plane. The focus distance and mode influence the calculation of stereo frusta. See Section 7.2.6 for details.
See also	EQ_CONFIG_IATTR_FOCUS_MODE EQ_CONFIG_FATTR_EYE_BASE

Name	EQ_CONFIG_IATTR_FOCUS_MODE
Value	fixed |relative_to_origin |relative_to_observer
Default	fixed
Details	The mode how to use the focus distance. The focus mode and distance influence the calculation of stereo frusta. See Section 7.2.6 for details.
See also	EQ_CONFIG_IATTR_FOCUS_DISTANCE EQ_CONFIG_FATTR_EYE_BASE

Name	EQ_NODE_SATTR_LAUNCH_COMMAND
Value	string
Default	ssh -n %h %c >& %h.%n.log [POSIX] ssh -n %h %c [WIN32]
Details	The command used by the server to auto-launch nodes which could not be connected. The launch command is executed from a process forked from the server process. The % tokens are replaced by the server at runtime with concrete data: %h is replaced by the hostname, %c by the render client command to launch, including command line arguments and %n by a node-unique identifier. Each command line argument is surrounded by launch command quotes.
See also	EQ_NODE_SATTR_LAUNCH_COMMAND_QUOTE EQ_NODE_IATTR_LAUNCH_TIMEOUT

Name	EQ_NODE_CATTR_LAUNCH_COMMAND_QUOTE
Value	character
Default	' [POSIX] " [WIN32]
Details	The server uses command line arguments to launch render client nodes correctly. Certain launch commands or shells use different conventions to separate command line arguments. These arguments might contain white spaces, and therefore have to be surrounded by quotes to identify their borders. This option is mostly used on Windows.

Name	EQ_NODE_IATTR_LAUNCH_TIMEOUT
Value	unsigned
Default	60'000 (1 minute)
Details	Defines the timeout in milliseconds to wait for an auto-launched node. If the render client process did not contact the server within that time, the node is considered to be unreachable and the initialization of the configuration fails.

Name	EQ_NODE_IATTR_THREAD_MODEL
Value	ASYNC | DRAW_SYNC | LOCAL_SYNC
Default	DRAW_SYNC
Details	The threading model for node synchronization. See Section 7.2.3 for details.

Name	EQ_PIPE_IATTR_HINT_THREAD
Value	OFF | ON
Default	ON
Details	Determines if all task methods for a pipe and its children are executed from a separate operating system thread (default) or from the node main thread. Non-threaded pipes have certain performance limitations and should only be used where necessary.

Name	EQ_PIPE_IATTR_HINT_AFFINITY
Value	OFF | AUTO | CORE unsigned | SOCKET unsigned
Default	AUTO
Details	Determines how all pipe threads are bound to processing cores. When set to OFF, threads are unbound and will be scheduled by the operation system on any core. If set to AUTO, threads are bound to all cores of the processor which is closest to the GPU used by the pipe, that is, which have the lowest latency to access the GPU device. This feature requires that Lunchbox and Equalizer have been compiled with the hwloc library version 1.5 or later. When set to CORE, the pipe threads will be bound to the given core. When set to SOCKET, the pipe threads will be bound to all cores of the given processor (socket). The CORE and SOCKET settings require that Lunchbox and Equalizer have been compiled with the hwloc library version 1.2 or later.

Name	EQ_PIPE_IATTR_HINT_CUDA_GL_INTEROP
Value	OFF | ON
Default	OFF
Details	Determines if the pipe thread enables interoperability between CUDA and OpenGL or not. When set to ON, the CUDA device is configured on which the thread executes the CUDA device code. If no graphics adapter is specified in the config file, the one providing the highest compute performances on the particular node is chosen. When set to OFF, no CUDA device is configured at all.

Name	EQ_WINDOW_IATTR_HINT_STEREO
Value	OFF | ON | AUTO
Default	AUTO
Details	Determines if the window selects a quad-buffered stereo visual. When set to AUTO, the default window initialization methods try to allocate a stereo visual for windows, but fall back to a mono visual if allocation fails. For pbuffers, AUTO selects a mono visual.
See also	EQ_COMPOUND_IATTR_STEREO_MODE

Name	EQ_WINDOW_IATTR_HINT_DOUBLEBUFFER
Value	OFF | ON | AUTO
Default	AUTO
Details	Determines if the window selects a double-buffered stereo visual. When set to AUTO, the default window initialization methods try to allocate a double-buffered visual for windows, but fall back to a single-buffered visual if allocation fails. For pbuffers, AUTO selects a single-buffered visual.

Name	EQ_WINDOW_IATTR_HINT_DECORATION
Value	OFF | ON
Default	ON
Details	When set to OFF, window borders and other decorations are disabled, and typically the window cannot be moved or resized. This option is useful for source windows during decomposition. The implementation is window-system specific.

Name	EQ_WINDOW_IATTR_HINT_FULLSCREEN
Value	OFF | ON
Default	OFF
Details	When set to ON, the window displays in fullscreen. This option forces window decorations to be OFF. The implementation is window-system specific.

Name	EQ_WINDOW_IATTR_HINT_SWAPSYNC
Value	OFF | ON
Default	ON
Details	Determines if the buffer swap is synchronized with the vertical retrace of the display. This option is currently not implemented for GLX. For WGL, the WGL_EXT_swap_control extension is required. For optimal performance, set swap synchronization to OFF for source-only windows. This option has no effect on single-buffered windows.

Name	EQ_WINDOW_IATTR_HINT_DRAWABLE
Value	window | pbuffer | FBO | OFF
Default	window
Details	Selects the window's drawable type. A window is an on-screen, window system-dependent window with a full-window OpenGL drawable. Pbuffers are off-screen drawables created using window system-dependent pbuffer APIs. FBO are off-screen frame buffer objects. A disabled drawable creates a system window without a frame buffer for context sharing, e.g., for asynchronous operations in a separate thread. To calculate the pbuffer or FBO size on unconnected devices, a pipe viewport size of 4096x4096 is assumed, unless specified otherwise using the pipe's viewport parameter.

Name	EQ_WINDOW_IATTR_HINT_STATISTICS
Value	OFF | FASTEST [ON] | NICEST
Default	FASTEST [Release Build] NICEST [Debug Build]
Details	Determines how statistics are gathered. OpenGL buffers commands, which causes the rendering to be executed at an arbitrary point in time. Nicest statistics gathering executes a Window::finish, which calls by default glFinish, in order to accurately account the rendering operations to the sampled task method. However, calling glFinish has a performance impact. Therefore, the fastest statistics gathering samples the task statistics directly, without finishing the OpenGL commands first. Some operations, e.g., frame buffer readback, inherently finish all previous OpenGL commands.
See also	EQ_NODE_IATTR_HINT_STATISTICS EQ_CHANNEL_IATTR_HINT_STATISTICS

Name	EQ_WINDOW_IATTR_HINT_GRAB_POINTER
Value	OFF | ON
Default	ON
Details	Enables grabbing the mouse pointer outside of the window during a drag operation.

Name	EQ_WINDOW_IATTR_PLANES_COLOR
Value	unsigned | RGBA16F | RGBA32F
Default	AUTO
Details	Determines the number of color planes for the window. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of color planes specified. RGBA16F and RGBA32F select floating point framebuffers with 16 or 32 bit precision per component, respectively. AUTO selects a visual with a reasonable quality, typically eight bits per color.

Name	EQ_WINDOW_IATTR_PLANES_ALPHA
Value	unsigned
Default	UNDEFINED
Details	Determines the number of alpha planes for the window. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of alpha planes specified. By default no alpha planes are requested.

Name	EQ_WINDOW_IATTR_PLANES_DEPTH
Value	unsigned
Default	AUTO
Details	Determines the precision of the depth buffer. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of depth bits specified. AUTO select a visual with a reasonable depth precision, typically 24 bits.

Name	EQ_WINDOW_IATTR_PLANES_STENCIL
Value	unsigned
Default	AUTO
Details	Determines the number of stencil planes for the window. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of stencil planes specified. AUTO tries to select a visual with at least one stencil plane, but falls back to no stencil planes if allocation fails. Note that for depth-compositing and pixel-compositing at least one stencil plane is needed.

Name	EQ_WINDOW_IATTR_PLANES_ACCUM
Value	unsigned
Default	UNDEFINED
Details	Determines the number of color accumulation buffer planes for the window. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of accumulation buffer planes specified.

Name	EQ_WINDOW_IATTR_PLANES_ACCUM_ALPHA
Value	unsigned
Default	UNDEFINED
Details	Determines the number of alpha accumulation buffer planes for the window. The interpretation of this value is window system-specific, as some window systems select a visual with the closest match to this value, and some select a visual with at least the number of accumulation buffer planes specified. If this attribute is undefined, the value of EQ_WINDOW_IATTR_PLANES_ACCUM is used to determine the number of alpha accumulation buffer planes.

Name	EQ_WINDOW_IATTR_PLANES_SAMPLES
Value	unsigned
Default	UNDEFINED
Details	Determines the number of samples used for multisampling.

Name	EQ_CHANNEL_IATTR_HINT_STATISTICS
Value	OFF | FASTEST [ON] | NICEST
Default	FASTEST [Release Build] NICEST [Debug Build]
Details	See EQ_WINDOW_IATTR_HINT_STATISTICS.
See also	EQ_NODE_IATTR_HINT_STATISTICS EQ_WINDOW_IATTR_HINT_STATISTICS

Name	EQ_COMPOUND_IATTR_STEREO_MODE
Value	AUTO | QUAD | ANAGLYPH | PASSIVE
Default	AUTO
Details	Selects the algorithm used for stereo rendering. QUAD-buffered stereo uses the left and right buffers of a stereo window (active stereo). Anaglyphic stereo uses glColorMask to mask colors for individual eye passes, used in conjunction with colored glasses. PASSIVE stereo never selects a stereo buffer of a quad-buffered drawable. AUTO selects PASSIVE if the left or right eye pass is not used, QUAD if the drawable is capable of active stereo rendering, and ANAGLYPH in all other cases.

Name	EQ_COMPOUND_IATTR_STEREO_ANAGLYPH_LEFT_MASK
Value	[RED GREEN BLUE]
Default	[RED]
Details	Select the color mask for the left eye pass during anaglyphic stereo rendering.

Name	EQ_COMPOUND_IATTR_STEREO_ANAGLYPH_RIGHT_MASK
Value	[RED GREEN BLUE]
Default	[GREEN BLUE]
Details	Select the color mask for the right eye pass during anaglyphic stereo rendering.

B.3. Server Section

The server section consists of connection description parameters for the server listening sockets and a number of configurations for this server. Currently only the first configuration is used.

B.3.1. Connection Description

A connection description defines the network parameters of an Equalizer process. Currently TCP/IP, SDP, RDMA, RSP and PIPE connection types are supported. TCP/IP creates a TCP socket. SDP is very similar, except that the address family AF_INET_SDP instead of AF_INET is used to enforce a SDP connection. RDMA implements native connections over the InfiniBand verbs protocol on Linux and Windows. RSP provides reliable multicast over UDP. PIPE uses a named pipe for fast interprocess communication on Windows.

RDMA connections provide the fastest implementation for InfiniBand fabrics. SDP is slower than RDMA and faster than IP over InfiniBand. Note that you can also use the transparent mode provided by most InfiniBand implementations to use SDP with TCP connections by preloading the SDP shared library.

Furthermore, a port for the socket can be specified. When no port is specified for the server, the default port 4242 (+UID on Posix systems) is used. When no port is specified for a node, a random port will be chosen by the operating system. For prelaunched render clients, a port has to be specified for the server to find the client node.

The hostname is the IP address or resolvable host name. A server or node may have multiple connection descriptions, for example to use a named pipe for local communications and TCP/IP for remote nodes.

The interface is the IP address or resolvable host name of the adapter to which multicast traffic is send.

A server listens on all provided connection descriptions. If no hostname is specified for a server connection description, it listens to INADDR_ANY, and is therefore reachable on all network interfaces. If the server's hostname is specified, the listening socket is bound only to this address. If any of the given hostnames is not resolvable, or any port cannot be used, server initialization will fail.

For a node, all connection descriptions are used while trying to establish a connection to the node. When auto-launched by the server, all connection descriptions of the node are passed to the launched node process, which will cause it to bind to all provided descriptions.

```
server
{
    connection # 0-n times, listening connections of the server
    {
        type        TCPIP | SDP | RDMA | PIPE | RSP
        port        unsigned # TCPIP, SDP
        filename    string   # PIPE
        hostname    string
        interface   string   # RSP
    }
```

B.3.2. Config Section

A configuration has a number of parameters, nodes, observers, layouts, canvases and compounds.

The nodes and their children describe the rendering resources in a natural, hierarchical way. Observers, layouts and canvases describe the properties of the physical projection system. Compounds use rendering resources (channels) to execute rendering tasks.

For an introduction to writing configurations and the concepts of the configuration entities please refer to Section 3.

The latency of a config defines the maximum number of frames the slowest operation may fall behind the application thread. A latency of 0 synchronizes all rendering tasks started by Config::startFrame in Config::finishFrame. A latency of one synchronizes all rendering tasks started one frame ago in finishFrame.

For a description of config attributes please refer to Section B.2.

```
    config # 1-n times, currently only the first one is used by the server
    {
        latency int    # Number of frames nodes may fall behind app, default 1
        attributes
        {
            eye_base      float     # distance between left and right eye
            focus_distance float
            focus_mode     fixed | relative_to_origin | relative_to_observer
            robustness    OFF | ON  # tolerate resource failures (init only)
        }
```

B.3.3. Node Section

A node represents a machine in the cluster, and is one process. It has a name, a hostname, a number of connection descriptions and at least one pipe. The name of the node can be used for debugging, it has no influence on the execution of

Equalizer. The host is used to automatically launch remote render clients. For a description of node and connection attributes please refer to Section B.2.

```
(node|appNode) # 1-n times, a system in the cluster
               # 0|1 appNode: launches render thread within app process
{
    name       string
    host       string  # Used to auto-launch render nodes
    connection # 0-n times, possible connections to this node
    {
        type           TCPIP | SDP | PIPE
        port           unsigned
        hostname       string
        filename       string
    }
    attributes
    {
        thread_model ASYNC | DRAW_SYNC | LOCAL_SYNC
        launch_command        string      # render client launch command
        launch_command_quote 'character' # command argument quote char
        launch_timeout        unsigned    # timeout in milliseconds
    }
```

B.3.4. Pipe Section

A pipe represents a graphics card (GPU), and is one execution thread. It has a name, GPU settings and attributes. The name of a pipe can be used for debugging, it has no influence on the execution of Equalizer.

The GPU is identified by two parameters, a port and a device. The port is only used for the GLX window system, and identifies the port number of the X server, i.e., the number after the colon in the DISPLAY description (':**0**.1').

The device identifies the graphics adapter. For the GLX window system this is the screen number, i.e., the number after the dot in the DISPLAY description (:0.**1**). The OpenGL output is restricted by glX to the GPU attached to selected screen.

For the AGL window system, the device selects the nth display in the list of online displays. The OpenGL output is optimized for the selected display, but not restricted to the attached GPU.

For the WGL window system, the device selects the nth GPU in the system. The GPU can be offline, in this case only pbuffer windows can be used. To restrict the OpenGL output to the GPU, the WGL_NV_gpu_affinity extension is used when available. If the extension is not present, the window is opened on the nth monitor, but OpenGL commands may be sent to a different or all GPUs, depending on the driver implementation.

The viewport of the pipe can be used to override the pipe resolution. The viewport is defined in pixels. The x and y parameter of the viewport are currently ignored. The default viewport is automatically detected. For offline GPUs, a default of 4096x4096 is used.

For a description of pipe attributes please refer to Section B.2.

```
pipe # 1-n times
{
    name       string
    port       unsigned      # X server number or ignored
    device     unsigned      # graphics adapter number
    viewport [ viewport ] # default: autodetect
    attributes
    {
        hint_thread   OFF | ON   # default ON
        hint_affinity AUTO | OFF | CORE unsigned | SOCKET unsigned
    }
```

B.3.5. Window Section

A window represents an OpenGL drawable and holds an OpenGL context. It has a name, a viewport and attributes. The name of a window can be used for debugging, it has no influence on the execution of Equalizer, other then it being used as the window title by the default window creation methods.

The viewport of the window is relative to the pipe. It can be specified in relative or absolute coordinates. Relative coordinates are normalized coordinates relative to the pipe, e.g., a viewport of [0.25 0.25 0.5 0.5] creates a window in the middle of the screen, using 50% of the pipe's size. Absolute coordinates are integer pixel values, e.g., a viewport of [50 50 800 600] creates a window 50 pixels from the upper-left corner, sized 800x600 pixels, regardless of the pipe's size. The default viewport is [0 0 1 1], i.e., a full-screen window.

For a description of window attributes please refer to Section B.2.

```
window # 1-n times
{
    name      string
    viewport [ viewport ] # wrt pipe, default full screen

    attributes
    {
        hint_stereo          OFF | ON | AUTO
        hint_doublebuffer    OFF | ON | AUTO
        hint_decoration      OFF | ON
        hint_fullscreen      OFF | ON
        hint_swapsync        OFF | ON          # AGL, WGL only
        hint_drawable        window | pbuffer | FBO | OFF
        hint_statistics      OFF | FASTEST [ON] | NICEST
        hint_grab_pointer    OFF | [ON]
        planes_color         unsigned | RGBA16F | RGBA32F
        planes_alpha         unsigned
        planes_depth         unsigned
        planes_stencil       unsigned
        planes_accum         unsigned
        planes_accum_alpha   unsigned
        planes_samples       unsigned
    }
```

B.3.6. Channel Section

A channel is a two-dimensional area within a window. It has a name, viewport and attributes. The name of the channel is used to identify the channel in the respective segments or compounds. It should be unique within the config.

Output channels are referenced in their respective segments. Source channels are directly referenced by their respective source compounds.

The viewport of the channel is relative to the window. As for windows, it can be specified in relative or absolute coordinates. The default viewport is [0 0 1 1], i.e., fully covering its window.

The channel can have an alternate drawable description. Currently, the window's framebuffer can be replaced by framebuffer objects bound to the window's OpenGL context. The window's default framebuffer can be partially overwritten with framebuffer objects.

For a description of channel attributes please refer to Section B.2.

```
channel # 1-n times
{
    name      string
    viewport [ viewport ] #wrt window, default full window
    drawable [ FBO_COLOR FBO_DEPTH FBO_STENCIL ]
    attributes
```

```
        {
            hint_statistics      OFF | FASTEST [ON] | NICEST
        }
    }
```

B.3.7. Observer Section

An observer represents a tracked entity, i.e, one user. It has a name, eye separation, focal plane parameters and tracking device settings. The name of an observer can be used for debugging, it has no influence on the execution of Equalizer. It can be used to reference the observer in views, in which case the name should be unique. Not all views have to be tracked by an observer. The focal plane parameters are described in Section 7.2.6. The OpenCV camera identifies the camere device index to be used for tracking on the application node. The VRPN tracker identifies the VRPN device tracker device name for the given observer.

```
observer # 0...n times
{
    name      string
    eye_base float   # convenience
    eye_left    [ float float float ]
    eye_cyclop [ float float float ]
    eye_right   [ float float float ]
    focus_distance float
    focus_mode      fixed | relative_to_origin | relative_to_observer
    opencv_camera [OFF] | AUTO | ON | integer  # head tracker
    vrpn_tracker string                        # head tracker device name
}
```

B.3.8. Layout Section

A layout represents a set of logical views on one or more canvases. It has a name and child views. The name of a layout can be used for debugging, it has no influence on the execution of Equalizer. It can be used to reference the layout, in which case the name should be unique.

A layout is applied to a canvas. If no layout is applied to a canvas, nothing is rendered on this canvas, i.e, the canvas is inactive.

The layout assignment can be changed at runtime by the application. The intersection between views and segments defines which output (sub-)channels are available. These output channels are typically used as destination channels in a compound. They are automatically created during configuration loading or creation.

```
layout  # 0...n times
{
    name string
    view  # 1...n times
```

B.3.9. View Section

A view represents a 2D area on a canvas. It has a name, viewport, observer and frustum. The name of a view can be used for debugging, it has no influence on the execution of Equalizer. It can be used to reference the view, in which case the name should be unique. The viewport specifies which 2D area of the parent layout is covered by this view in normalized coordinates.

A 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. If the view does not

specify a frustum, the corresponding destination channels will use the sub-frustum resulting from the view/segment intersection.

A view has a stereo mode, which defines if the corresponding destination channel update the cyclop or left and right eye. The stereo mode can be changed at runtime by the application.

A view is a view on the application's model, 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.

```
view  # 1...n times
{
    name      string
    observer  observer-ref
    viewport [ viewport ]
    mode MONO | STEREO

    wall       # frustum description
    {
        bottom_left  [ float float float ]
        bottom_right [ float float float ]
        top_left     [ float float float ]
        type         fixed | HMD
    }
    projection # alternate frustum description, last one wins
    {
        origin       [ float float float ]
        distance     float
        fov          [ float float ]
        hpr          [ float float float ]
    }
}
```

B.3.10. Canvas Section

A canvas represents a logical projection surface of multiple segments. It has a name, frustum, layouts, and segments. The name of a canvas can be used for debugging, it has no influence on the execution of Equalizer. It can be used to reference the canvas, in which case the name should be unique.

Each canvas consists of one or more segments. Segments can be planar or non-planar to each other, and can overlap or have gaps between each other. A canvas can define a frustum, which will create default planar sub-frusta for its segments.

The layouts referenced by the canvas can be activated by the application at runtime. One layout can be referenced by multiple canvases. The first layout is the layout active by default, unless the command line option –eq-layout was used to select another default layout.

A canvas may have a swap barrier, which becomes the default swap barrier for all its subsequent segments. A swap barrier is used to synchronize the output of multiple windows. For software swap synchronization, all windows using a swap barrier of the same name are synchronized. Hardware swap synchronization is used when a NV_group is specified. All windows using the same NV_group on a single system are synchronized with each other using hardware synchronization. All groups using the same NV_barrier across systems are synchronized with each other using hardware synchronization. When using hardware synchronization, the barrier name is ignored.

```
canvas  # 0...n times
{
    name    string
    layout  layout-ref | OFF   # 1...n times
```

```
wall
{
        bottom_left   [ float float float ]
        bottom_right  [ float float float ]
        top_left      [ float float float ]
        type          fixed | HMD
}
projection
{
        origin        [ float float float ]
        distance      float
        fov           [ float float ]
        hpr           [ float float float ]
}
swapbarrier  # default swap barrier for all segments of canvas
{
    name string
    NV_group OFF | ON | unsigned
    NV_barrier OFF | ON | unsigned
}
```

B.3.11. Segment Section

A segment represents a single display, i.e., a projector or monitor. It references a channel, has a name, viewport, frustum and potentially a swap barrier. The name of a segment can be used for debugging, it has no influence on the execution of Equalizer. It can be used to reference the segment, in which case the name should be unique.

The channel referenced by the segment defines the output channel. The viewport of the segment defines the 2D area covered by the channel on the canvas. Segments can overlap each other, e.g., when edge-blended projectors or passive stereo is used. The intersections of a segment with all views of all layouts create destination channels for rendering. The destination channels are copies of the segment's output channel with a viewport smaller or equal to the output channel viewport.

The segment eyes define which eyes are displayed by this segment. For active stereo outputs the default setting 'all' is normally used, while passive stereo segments define the left or right eye, and potentially the cyclop eye.

A segment can define a frustum, in which case it overrides the default frustum calculated from the canvas frustum and segment viewport. A segment can have a swap barrier, which is used as the swap barrier on the destination compounds of all its destination channels.

```
segment # 1...n times
{
    channel  string
    name     string
    viewport [ viewport ]
    eye [ CYCLOP LEFT RIGHT ] # eye passes, default all

    wall       # frustum description
    {
        bottom_left   [ float float float ]
        bottom_right  [ float float float ]
        top_left      [ float float float ]
        type          fixed | HMD
    }
    projection # alternate frustum description, last one wins
    {
        origin        [ float float float ]
        distance      float
        fov           [ float float ]
        hpr           [ float float float ]
```

```
        }
        swapbarrier {...}  # set as barrier on all dest compounds
}
```

B.3.12. Compound Section

Compounds are the basic data structure describing the rendering setup. They use channels for rendering. Please refer to Section 3.11 for a description of compound operation logics.

The name of the compound is used for the default names of swap barriers and output frames.

A channel reference is either the name of the channel in the resource section if no canvases are used, or the destination channel reference of a view/segment intersection. Channel segment references are delimited by braces, in which the canvas, segment, layout and view describing the channel are named, i.e, 'channel (canvas "PowerWall" segment 0 layout "Simple" view 0)'.

Compound tasks describe the operations the compound executes. The default is all tasks for compounds with no children (leaf compounds) and CLEAR READBACK ASSEMBLE for all others. A leaf compound using the same channel as its parent compound does not have a default clear task, since this has been executed by the parent already. The readback and assemble tasks are only executed if the compound has output frames or input frames, respectively. Tasks are not inherited by the children of a compound.

The buffer defines the default frame buffer attachments read back by output frames. Output frames may change the buffer attachments used.

The eye attribute defines which eyes are handled by this compound. This attribute can be used to write one compound for monoscopic rendering and another for stereoscopic rendering, as illustrated in Figure 47.

The viewport restricts the rendering to the area relative to the parent compound. The range restricts the database range, relative to the parent. The pixel setting selects the pixel decomposition kernel, relative to the parent. The subpixel defines the jittering applied to the frustum, relative to the parent. The zoom scales the parent pixel viewport resolution. The DPlex period defines that $\frac{1}{period}$ frames are rendered, and the phase defines when in the period the rendering starts. All these attributes are inherited by the children of a compound. Viewport, range, pixel and period parameters are cumulative.

Equalizers are used to automatically optimize the decomposition. A 2D, horizontal or vertical load equalizer adjusts the viewport of all direct children of the compound each frame. A DB load equalizer adjusts the range of all direct children. A dynamic framerate (DFR) equalizer adjusts the zoom for a constant framerate. A framerate equalizer smoothens the framerate of the compound's window to produce a steady output framerate, typically for DPlex compounds. A monitor equalizer adjusts the output image zoom to monitor another canvas. A tile equalizer automatically sets up tile queues between the destination and all source channels.

For a description of compound attributes please refer to Section B.2.

A wall or projection description is used to define the view frustum of the compound. The frustum is normally inherited from the view or segment. The frustum is inherited and typically only defined on the topmost compound. The last specified frustum description is used. Sizes are specified in meters. Figure 14 illustrates the frustum parameters. Setting a frustum on a compound is discouraged, a proper view and segment description should be used instead. View frusta override segment frusta which override compound frusta.

Output frames transport frame buffer contents to input frames of the same name. If the compound has a name, the default frame name is frame.compoundName,

otherwise the default name is frame.channelName. The frame buffer attachments to read back are inherited from the compound, but can be overridden by output frames. Frames of type texture copy the framebuffer contents to a texture, and can only be used to composite frames between windows of the same pipe.

```
compound # 1-n times
{
    name      string
    channel   channel-ref            # see below

    task      [ CLEAR DRAW READBACK ASSEMBLE ] # CULL later
    buffer    [ COLOR DEPTH ]        # default COLOR

    eye       [ CYCLOP LEFT RIGHT ] # eyes handled, default all

    viewport  [ viewport ]           # wrt parent compound, sort-first
    range     [ float float ]        # DB-range for sort-last
    pixel     [ int int int int ]    # pixel decomposition (x y w h)
    subpixel  [ int int ]            # subpixel decomposition (index size)
    zoom      [ float float ]        # up/downscale of parent pvp
    period    int                    # DPlex period
    phase     int                    # DPlex phase

    view_equalizer {} # assign resources to child load_equalizers
    load_equalizer # adapt 2D tiling or DB range of children
    {
        mode 2D | DB | VERTICAL | HORIZONTAL
        damping float # 0: no damping, 1: no changes
        boundary [ x y ]             # 2D tile boundary
        boundary float               # DB range granularity
        resistance [ x y ]           # 2D tile pixel delta
        resistance float             # DB range delta
        assemble_only_limit float # limit for using dest as src
    }
    DFR_equalizer # adapt ZOOM to achieve constant framerate
    {
        framerate float # target framerate
        damping float   # 0: no damping, 1: no changes
    }
    framerate_equalizer {} # smoothen window swapbuffer rate (DPlex)
    monitor_equalizer {}   # set frame zoom when monitoring other views
    tile_equalizer
    {
        name string
        size [ int int ]     # tile size
    }

    attributes
    {
        stereo_mode     AUTO | QUAD | ANAGLYPH | PASSIVE # default AUTO
        stereo_anaglyph_left_mask     [ RED GREEN BLUE ] # default red
        stereo_anaglyph_right_mask    [ RED GREEN BLUE ] # df green blue
    }

    wall  # frustum description, deprecated by view and segment frustum
    {
        bottom_left   [ float float float ]
        bottom_right  [ float float float ]
        top_left      [ float float float ]
        type          fixed | HMD
    }
    projection # alternate frustum description, last one wins
    {
        origin        [ float float float ]
        distance      float
        fov           [ float float ]
        hpr           [ float float float ]
```

```
            }

            swapbarrier {...}  # compounds with the same name sync swap

            child-compounds

            outputframe
            {
                name   string
                buffer [ COLOR DEPTH ]
                type texture | memory
            }
            inputframe
            {
                name string # corresponding output frame
            }
            outputtiles
            {
                name   string
                size [ int int ]     # tile size
            }
            inputtiles
            {
                name string # corresponding output tiles
            }
        }

channel-ref:  'string' | '(' channel-segment-ref ')'
channel-segment-ref: ( canvas-ref ) segment-ref ( layout-ref ) view-ref
```