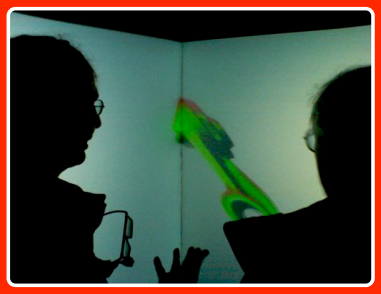
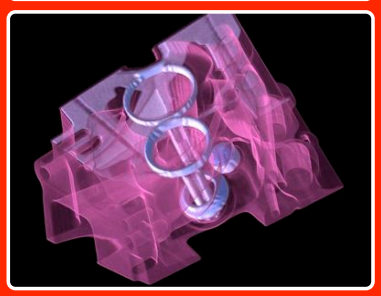
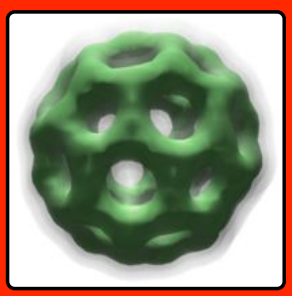
Equalizer Programming Guide

Eyescale Software GmbH







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Equalizer 0.5 Programming Guide

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Feedback

If you have comments about the content, accuracy or comprehensibility of this programming guide, please contact eile@equalizergraphics.com.

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The images on the front page show: a terrain rendering application on a six-node display wall [top left], the eqPly polygonal renderer in a three-sided CAVE [middle], two volume rendering results from eVolve[1] [bottom left and middle] and a six-node sort-last database decomposition with parallel direct-send recomposition[2] [bottom right].

[1] Data sets courtesy of General Electric, USA and AVS, USA
[2] Data set courtesy of Stanford University Computer Graphics Laboratory

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1.0	Oct 28, 2007	Initial Version for Equalizer 0.4
1.2	Apr 15, 2008	Version for Equalizer 0.5

1 Introduction

Equalizer provides a framework for the development of parallel OpenGL applications. Equalizer-based applications can run from a single shared-memory system with one or multiple graphics cards up to large-scale graphics clusters. This Programming Guide introduces the programming interface, often using the Equalizer example eqPly as a guideline.

Equalizer is the next step in the evolution of generic parallel programming interfaces for OpenGL-based visualization applications. Existing solutions, such as OpenGL Multipipe SDK, Cavelib and VRJuggler, implement a subset of concepts similar to Equalizer. In other areas, e.g., tracking device support, they provide more functionality.

In order to adapt 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 provides the domain-specific parallel rendering know-how and abstracts configuration, threading, synchronization, windowing and event handling. It is a 'GLUT on steroids', providing parallel and distributed execution, scalable rendering features and fully customizable event handling.

If you have any question regarding Equalizer programming, this programming guide, or other specific problems you encountered, please direct them to the eq-dev mailing list[3].

2 Getting Started

2.1 Installing Equalizer and running eqPly

Equalizer can be installed by downloading the distribution[4] and compiling the source code. After installing Equalizer, please take a look at the Quickstart Guide[5] to get familiar with the capabilities of the eqPly example.

Compiling Equalizer is as simple as running make on Linux and Mac OS X or building the Equalizer Visual Studio 2005 solution on Windows. Note that on Mac OS X 10.4 (Tiger), some prerequisites have to be installed before running make, as explained in README.Darwin.

2.2 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.

2.2.1 Server

Each Equalizer server is responsible for managing one visualization system, i.e., a shared memory system or graphics cluster. It controls and launches the application's rendering clients. Currently, Equalizer only supports one application per server, but it will provide concurrent and efficient multi-application support in future.

[3] http://www.equalizergraphics.com/lists.html
[4] http://www.equalizergraphics.com/downloads.html
[5] http://www.equalizergraphics.com/documents/EqualizerGuide.html

2.2.2 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 reacts on events, updates its database and controls the rendering.

2.2.3 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, based on the rendering tasks received from the server. The tasks are executed by calling the appropriate task methods (see Section 5.1) 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.

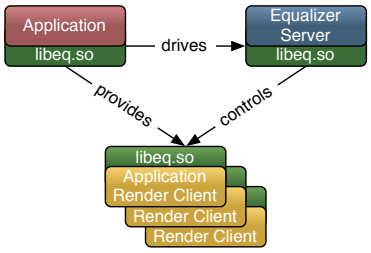


Figure 1: Equalizer Processes

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-related code, it is reduced to be the application's 'master' process without any OpenGL windows and rendering code.

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.

2.2.4 Parallel Rendering

Figure 2 illustrates the basic principle of any parallel rendering application. The typical OpenGL application, for example GLUT-based applications, has an event loop which redraws the scene, updates data based on received events, and eventually redraws a new frame.

A parallel rendering application uses the same basic execution model and extends it by separating the rendering code from the main event loop. The rendering code is then executed in parallel on different resources. This model is naturally followed by Equalizer, thus making application development as easy as possible.

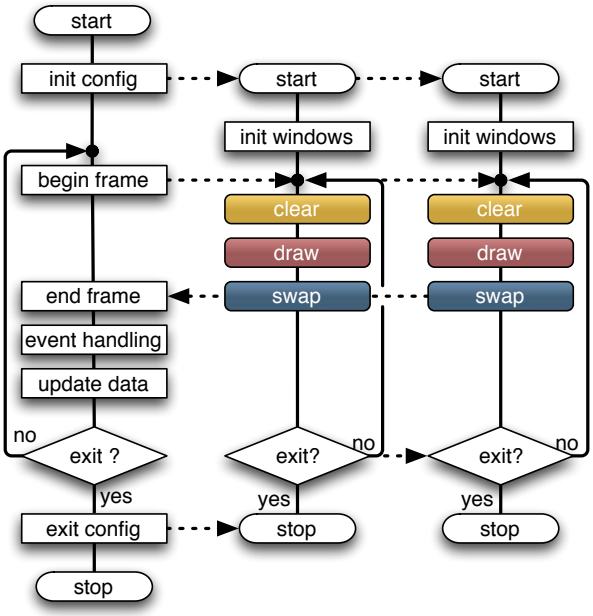


Figure 2: Parallel Rendering

3 Hello, World!

The eqHello example is a minimal application to illustrate the basic principle of an Equalizer application: The application developer has to implement the rendering method Channel::frameDraw, similar to the glutDisplayFunc in GLUT applications. It can be run as a stand-alone application from the command line.

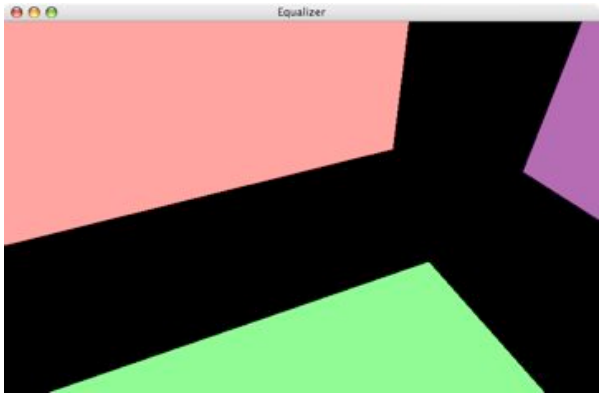


Figure 3: Hello, World!

The eqHello redraw function renders six colored quads, rotating around the origin. The frameDraw method provided by the eq::Channel can be used as a convience function to setup the frustum and other OpenGL state. After setting up some lighting parameters, eqHello rotates the scene and renders the quads using immediate mode:

```
void Channel::frameDraw( const uint32_t spin )
{
    // setup OpenGL State
    eq::Channel::frameDraw( spin );

    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 );

    // rotate scene around the origin
    glRotatef( static_cast< float >( spin ) * 0.5f, 1.0f, 0.5f, 0.25f );

    // render six axis-aligned colored quads around the origin
    [...]
}
```

The eqHello main function sets up the communication with the server, initializes and drives the rendering. The details of this setup are explained in Section 6.

4 Scalable Rendering

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

This section gives an introduction to scalable rendering, in order to provide some background for 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.

4.1 2D or Sort-First Compounds

2D or sort-first 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.

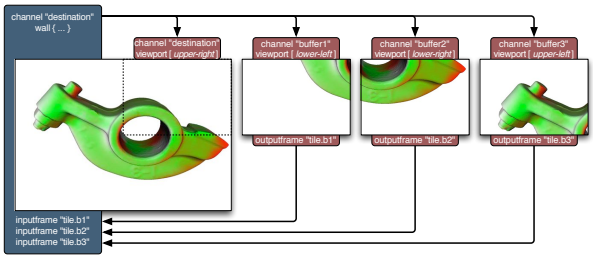


Figure 4: A 2D compound

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.

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.

4.2 DB or Sort-Last Compounds

DB or sort-last[6] decomposes the rendered database so that all rendering units process a part of the scene in parallel.

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.

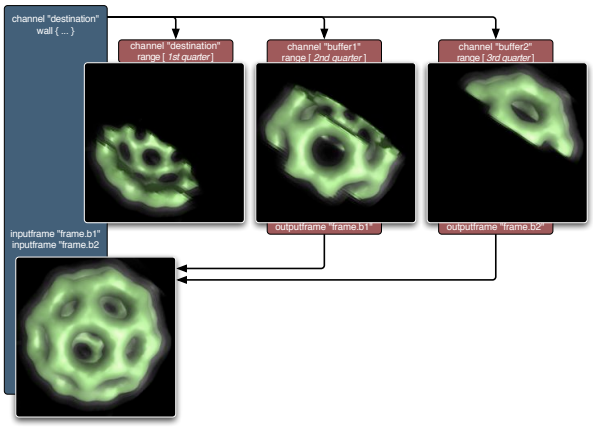


Figure 5: A database compound

This mode provides very good scalability, since each rendering unit processes only a part of the database. 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 recomposition algorithms, such as direct-send address this problem by keeping the per-node IO constant (see Figure 23).

The application has to partion 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).

[6] 3D model courtesy of AVS, USA.

The best use of database compounds is to divide the data to a managable 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.

4.3 Stereo Compounds

Stereo compounds[7] assign each eye pass to individual rendering units. The resulting images are copied to the appropriate stereo buffer. This modes supports a variety of stereo modes, including active (quad-buffered) stereo, anaglyphic stereo and autostereo displays with multiple eye passes.

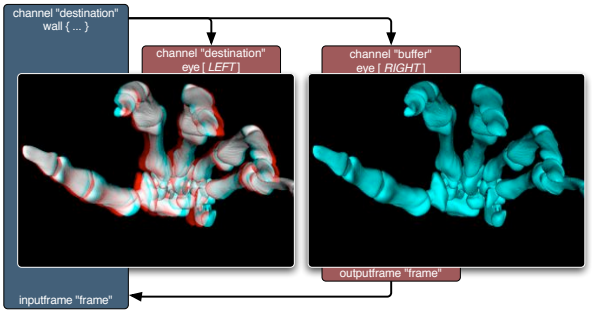


Figure 6: A stereo compound

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.

4.4 Pixel Compounds

Pixel compounds are similar to 2D compounds. The frustra of the source rendering units are modified so that each unit renders an evenly distributed subset of pixels.

As 2D compounds, pixels compounds have low, constant IO requirements for the pixel transfers during recomposition.

Pixel compounds work well for purely fill-limited applications, techniques like frustum culling do not reduce the rendered data for the source rendering resources.

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.

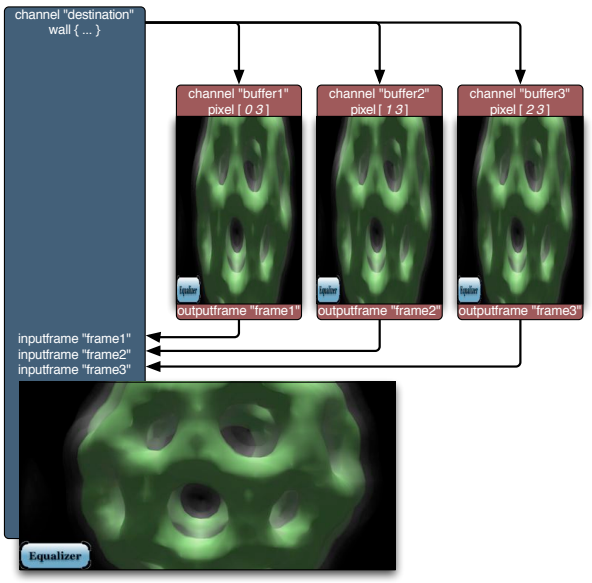


Figure 7: A pixel compound

[7] 3D model courtesy of Stereolithography Archive at Clemson University.

Pixel compounds are ideal for raytracing, which is highly fill-limited and needs the full database for rendering anyway. Volume rendering applications should choose this mode over 2D compounds.

5 The Programming Interface

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

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 other things– Node::frameStart to be called in all active render clients.

5.1 Task Methods

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. The eqPly section will discuss the most important task methods. A full list can be found on the website[8].

5.2 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 is the OpenGL 'threading model', which maintains a current context for each thread. If structured correctly, the application rarely has to take care of thread synchonization or protection of shared data.

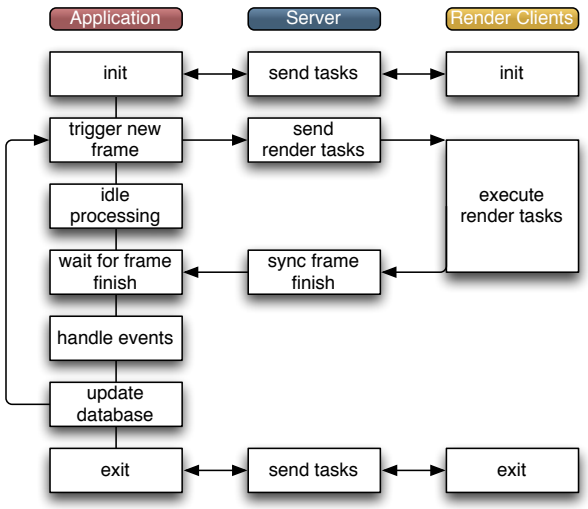


Figure 8: Simplified execution model

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 8.

The rendering threads concurrently render the application's database. The database should be accessed in a read-only fashion during rendering to avoid threading

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

problems. This is normally the case, for example all modern scene graphs use read-only render traversals.

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.

Rendering threads on a single node are by default synchronized. 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 application 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 7.2.2. Some scene graphs for example do implement multi-buffered data, and can profit from relaxing the frame synchronization.

5.3 Config

The eq::Config represents the current configuration of the application. The configuration is the session in which all render clients are registered. A configuration consists of the description of the rendering resources and the usage description for these 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.

The resource usage is configured using a compound tree, which is a hierarchical representation of the rendering decomposition and recomposition across the resources. It is explained in Section 5.4.

Figure 9 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. The compound description is only used by the server to compute the rendering tasks. The application is not aware of compounds, and does not need to concern itself with the parallel rendering logics of a configuration.

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.

5.3.1 Node

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.

5.3.2 Pipe

The eq::Pipe class is the abstraction of a graphics card (GPU). In the current implementation it is also one operating system thread. Non-threaded pipes are supported for integrating with thread-unsafe libraries, but have various performance caveats.

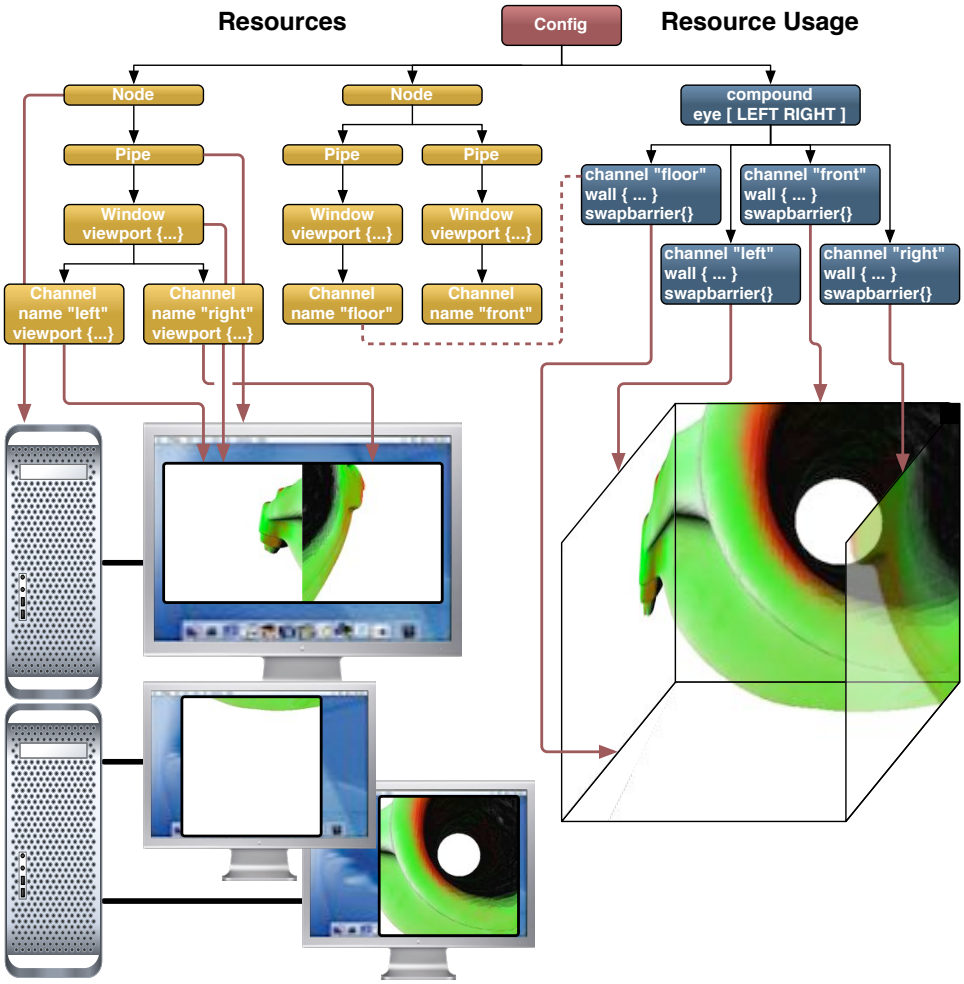


Figure 9: An example configuration

All pipe, window and channel task methods are executed from the pipe's thread, or in the case of non-threaded pipes from the main application thread[9].

Further versions of Equalizer might introduce threaded windows, where all window-related task methods are executed in a separate operating system thread.

5.3.3 Window

The eq::Window class holds a drawable and an OpenGL context. The drawable can be an on-screen window or an off-screen PBuffer. Framebuffer object (FBO) support will be implement by later version of Equalizer. The window holds window-system-specific handles to the drawable and context, e.g., an X11 window XID and GLXContext for the glX window system.

5.3.4 Channel

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.

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

5.4 Compounds

Usage of the rendering resources is configured using a compound tree. Although the API does not currently expose compounds, the basic design behind compounds is explained here for a better understanding of the Equalizer architecture. Further information on the configuration of compounds can be found on the Equalizer website[10].

5.4.1 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. Unused channels are not instantiated during initialization. The rendering tasks for the channels are computed by the server and send to the appropriate render clients.

5.4.2 Frustum

Compounds have a frustum description to define the physical layout of the display environment.

The frustum description is inherited by the children, therefore the frustum is typically defined on the top-most compound.

The frustrum can be specified as a wall or projection description.

A wall is completely defined by the bottom-left, bottom-right and top-left coordinates relative to the origin.

The 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.

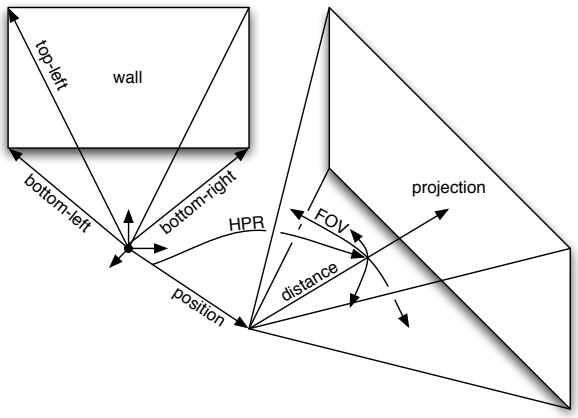


Figure 10: Wall and projection parameters

Figure 10 illustrates the wall and projection frustum parameters.

5.4.3 Compound Classification

The channels of the leaf compounds in the compound tree are designated as source channels. The top-most channel in the tree is the destination channel. Only source channels execute rendering tasks. 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 can not be overridden by child compounds.

5.4.4 Decomposition - Attributes

Compounds have attributes which configure the decomposition of the destination's channel 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

[10] see http://www.equalizergraphics.com/documents/design/compounds.html

its database, and an eye rendering pass can selectively render different stereo passes. A pixel parameter adapts the frustum so that the source channel renders every n*th* line out of m lines. 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.

5.4.5 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 7.6.

6 The eqPly polygonal renderer

In this section the source code of eqPly is explained in detail, and relevant design decisions, caveats and other remarks are raised.

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 rendering features or visual quality.

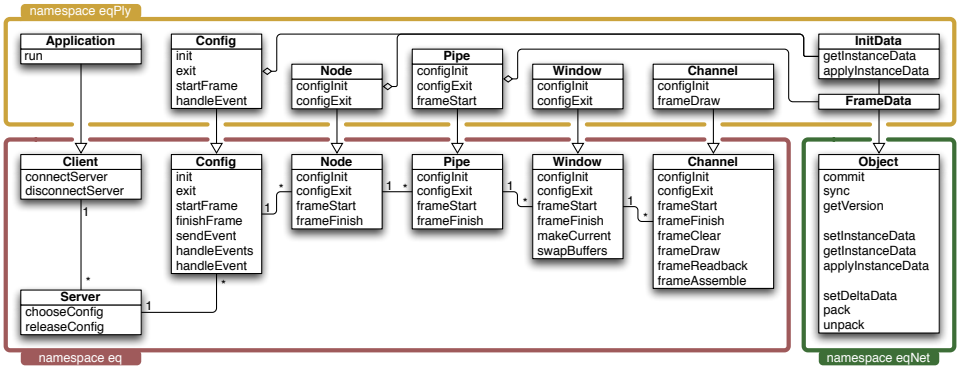


Figure 11: UML diagram of significant Equalizer and eqPly classes and task methods.

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. Figure 11 shows how the most important Equalizer classes are used through inheritance by the eqPly example.

The eqPly classes fall into two categories: Subclasses of the rendering entities introduced in Section 5.3, and two other classes for distributing data. The function and typical usage for each of the rendering entities is discussed in this section.

The distributed data classes are helper classes based on eqNet::Object. They illustrate the typical usage of distributed objects for static as well as dynamic, frame-specific data.

6.1 The main Function

The main function starts off with parsing 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 6.3.3:

```
int main( int argc, char** argv )
{
    // 1. parse arguments
    eqPly::LocalInitData initData;
    initData.parseArguments( argc, argv );
```

The second step is to initialize the Equalizer library. The initialization function of Equalizer also parses the command line, which is used to set certain default values based on Equalizer-specific options[11], 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:

```
    // 2. Equalizer initialization
    NodeFactory nodeFactory;
    if( !eq::init( argc, argv, &nodeFactory ))
    {
        EQERROR << "Equalizer init failed" << endl;
        return EXIT_FAILURE;
    }
```

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()
        { return new eqPly::Config; }
    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 ); }
};
```

The third step is to create an instance of the application and to initialize it locally. The application is an eq::Client, which in turn is an eqNet::Node. The underlying network layer in Equalizer is a peer-to-peer network of eqNet::Nodes. The application programmer does not usually have to be aware of the classes in the eqNet namespace, but both the eq::Client and the server are eqNet::Nodes.

The local initialization of a node creates a local listening socket, which allows the eq::Client to communicate over the network with other nodes, such as the server and the rendering clients.

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

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

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();
    client = 0;

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

6.2 Application

In the case of eqPly, the application is also the render client. The eqPly executable has three run-time behaviours:

1. **Application**: The executable started by the user, the controlling entity in 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.
3. **Resident render client**: Manually pre-started render client, listening on a specified port for server commands. This mode is selected using the command-line option –eq-client and potentially –eq-listen <address> and -r[12].

6.2.1 Main Loop

The application's main loop starts by connecting the application to an Equalizer server. The command line parameter –eq-server explicitly specifies a server address. If no server was 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 with a default one-channel configuration[13].

```
int Application::run()
{
    // 1. connect to server
    RefPtr<eq::Server> server = new eq::Server;
    if( !connectServer( server ))
    {
        EQERROR << "Can't open server" << 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 choosing the 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 cast necessary:

[12] see http://www.equalizergraphics.com/documents/design/residentNodes.html
[13] see http://www.equalizergraphics.com/documents/design/standalone.html

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

if( !config )
{
    EQERROR << "No matching config on server" << 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. It returns true only if all initialization task methods were successful.

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
eqBase::Clock clock;

config->setInitData( _initData );
if( !config->init( ))
{
    EQERROR << "Config initialization failed: "
            << config->getErrorMessage() << endl;
    server->releaseConfig( config );
    disconnectServer( server );
    return EXIT_FAILURE;
}

EQLOG( eq::LOG_CUSTOM ) << "Config init took " << clock.getTimef() << " ms"
                        << 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.

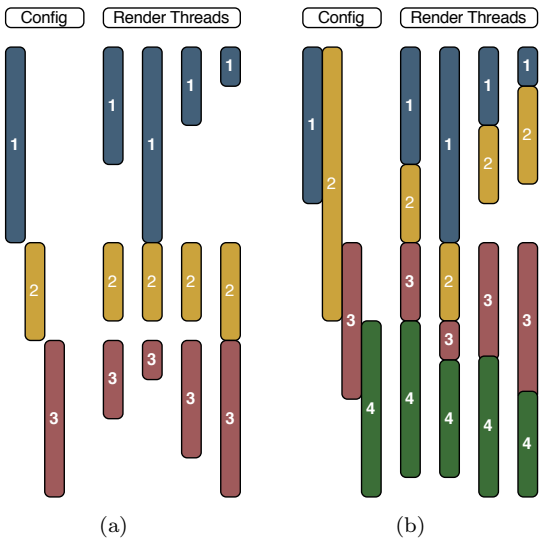


Figure 12: Synchronous and asynchronous execution

When the 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 synchronizes 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 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 exising 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 7.2.2.

Figure 12 shows the execution of (hypothetical) rendering tasks without latency (Figure 12(a)) and with a latency of one frame (Figure 12(b)). With eqPly, a speedup of 15% has been observed on a five-node rendering cluster when using a latency of one frame instead of no latency[14]. A latency of one or two frames is normally not perceived by the user.

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:

```
    // 4. run main loop
    uint32_t maxFrames = _initData.getMaxFrames();

    clock.reset();
    while( config->isRunning( ) && maxFrames-- )
    {
        config->startFrame();
        // config->renderData(...);
        config->finishFrame();
    }
    const uint32_t frame = config->finishAllFrames();
    const float    time  = clock.getTimef();
    EQLOG( eq::LOG_CUSTOM ) << "Rendering took " << time << " ms (" << frame
                            << " frames @ " << ( frame / time * 1000.f)
                            << " FPS)" << 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();
    EQLOG( eq::LOG_CUSTOM ) << "Exit took " << clock.getTimef() << " ms" <<endl;

    // 6. cleanup and exit
    server->releaseConfig( config );
    if( !disconnectServer( server ))
        EQERROR << "Client::disconnectServer failed" << endl;
    server = 0;
    return EXIT_SUCCESS;
}
```

6.2.2 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. In order to keep the client resident, the eqPly example overrides the client loop to keep it running beyond one configuration run:

```
bool Application::clientLoop()
{
    if( !_initData.isResident( )) // execute only one config run
```

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

```
        return eq::Client::clientLoop();

    // else execute client loops 'forever'
    while( true ) // TODO: implement SIGHUP handler to exit?
    {
        if( !eq::Client::clientLoop( ))
            return false;
        EQINFO << "One configuration run successfully executed" << endl;
    }
    return true;
}
```

6.3 Distributed Objects

Equalizer provides distributed objects which help implementing data distribution in a cluster environment. The master version of a distributed object is registered with a eqNet::Session, which assigns a session-unique identifier to the object. Other nodes can map their instance of the object to this identifier, thus synchronizing the object's data with the remotely registered master version.

Distributed objects are created by subclassing from eqNet::Object. Distributed objects can be static (immutable) or dynamic. Dynamic objects are versioned.

The eqPly example has a static distributed object to provide initial data to all rendering nodes, as well as a versioned object to provide frame-specific data such as the camera position to the rendering methods.

6.3.1 Object Usage for Rendering

Distributed objects are addressed using session-unique identifiers, because pointers to other objects can not be distributed directly, since they have no meaning on remote nodes. The session with which distributed objects are registered is normally the eq::Config.

The shared data entry point for the render clients is the identifier passed by the application to 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 eq::Node, and contains identifiers to 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 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 start frame request.

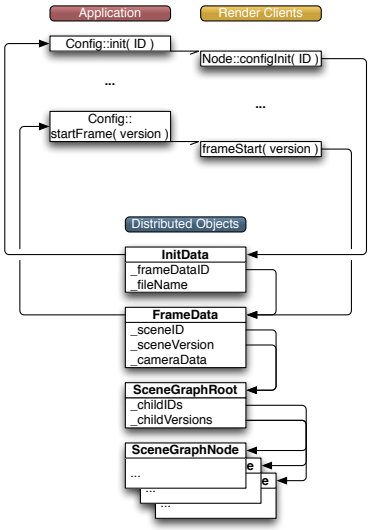


Figure 13: Distributed Data Handling

Applications distributing their scene graph, rather then relying on a shared filesystem like eqPly, use the frame data also as an entry point to their scene graph data structure. Figure 13 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 de-serializes his immediate children by transferring their identifier and current version.

The objects are still created by the application, and then registered or mapped with the session in order to distribute them. When mapping objects in a hierarchical data structure, their type often has to be known in order 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 task method.

6.3.2 Change Handling

The way changes are to be handled is determined 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 calling the serialization methods. The following change types are possible:

STATIC The object is not versioned. The instance data is serialized whenever a new slave instance is mapped. No additional data is stored.

INSTANCE The object is versioned, and the instance and delta data is identical, that is, only instance data is serialized. Previous instance data is saved to be able to map old versions.

DELTA The object is versioned, and the delta data is typically smaller than the instance data. Both the delta and instance data are serialized and saved to map old versions.

DELTA_UNBUFFERED The object is versioned, and delta data is used to update slave instances. No data is stored, and no previous versions can be mapped. The instance data is serialized whenever a new slave instance is mapped.

6.3.3 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 either has to provide a pointer and size to its data using setInstanceData, or it has to implement getInstanceData and applyInstanceData. The first approach can be used if all distributed member variables are stored in one contiguous block of memory. The second approach is used otherwise.

The InitData class contains a string of variable length. Therefore it uses the second approach of manually serializing and de-serializing its data. Serialization in getInstanceData and de-serialization in applyInstanceData is performed by streaming all member variable to or from the provided data streams. Efficient buffering and data transport between nodes is implemented in the data streams:

```
void InitData::getInstanceData( eqNet::DataOStream& os )
{
    os << _frameDataID << _windowSystem << _useVBOs << _useGLSL << _filename;
}

void InitData::applyInstanceData( eqNet::DataIStream& is )
{
    is >> _frameDataID >> _windowSystem >> _useVBOs >> _useGLSL >> _filename;
```

```
    EQASSERT( _frameDataID != EQ_ID_INVALID );
    EQINFO << "New InitData instance" << endl;
}
```

The data input and output streams perform no type checking on the data. It is the application's responsibility to exactly match the order and types of variables during serialization and de-serialization.

6.3.4 FrameData - a Versioned Distributed Object

Versioned objects have to override getChangeType to indicate how they want to have changes to be handled. The current implementation has the following characteristics:

- Only the master instance of the object is writable, that is, eqNet::Object::commit can be called only on the master instance to generate a new version.
- Slave instance versions can only be advanced, that is, eqNet::Object::sync(version) with a version smaller than the current version will fail.
- Newly mapped slave instance are mapped to the oldest available version.

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 been committed or is still in transmission.

In addition to 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 the delta data happens to be layed out contiguously in memory, setDeltaData might be used. The default implementation of pack and unpack (de)serialize the delta data or the instance data if no delta data has been specified.

The eqPly frame data is layed out in one anonymous structure in memory. It also does not track changes since it is relatively small in size and changes frequently. Therefore, the instance and delta data are the same and set in the constructor. Furthermore, the change type is INSTANCE. The default Object implementation will take care of the distribution of the data:

```
FrameData()
    {
        reset();
        setInstanceData( &data, sizeof( Data ));
        EQINFO << "New FrameData " << std::endl;
    }
```

6.4 Config

The configuration 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.

6.4.1 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 is necessary to allow a speedy startup of the configuration on large-scale graphics clusters. On the other hand, it means that initialization functions are called even if the parent's initialization has failed.

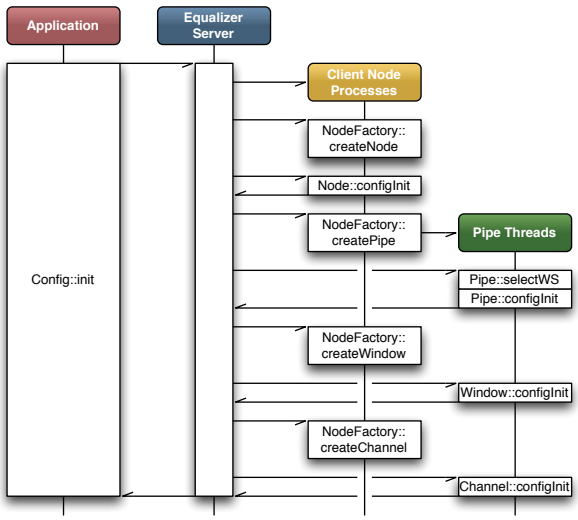


Figure 14: Config Initialization Sequence

The eqPly::Config class holds the master versions of the initialization and frame data. Both objects are registered with the eq::Config, which is the eqNet::Session used for rendering. Equalizer takes care of the session setup and exit in Client::chooseConfig and Client::releaseConfig, respectively.

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

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

```
bool Config::init()
{
    // init distributed objects
    _frameData.data.color = _initData.useColor();
    registerObject( &_frameData );
    _initData.setFrameDataID( _frameData.getID( ));

    registerObject( &_initData );

    // init config
    _running = eq::Config::init( _initData.getID( ));
    if( !_running )
        return false;
```

If the configuration was initialized correctly, the configuration tries to set up a tracking device for head tracking. Equalizer does not provide extensive support for tracking devices, as this is an orthogonal problem to parallel rendering. Tracking device support has already been solved by a number of implementations[15], which can easily be integrated with Equalizer. The example code in eqPly provides a reference implementation for the integration of such a tracking library. Section 7.5 provides more background on head tracking.

```
    // init tracker
    if( !_initData.getTrackerPort().empty( ))
    {
        if( !_tracker.init( _initData.getTrackerPort() ))
            EQWARN << "Failed to initialise tracker" << endl;
        else
        {
            // Set up position of tracking system in world space
            // Note: this depends on the physical installation.
            vmml::Matrix4f m( vmml::Matrix4f::IDENTITY );
```

[15] VRCO Trackd, VRPN, etc.

```
            m.scale( 1.f, 1.f, -1.f );
            //m.x = .5;
            _tracker.setWorldToEmitter( m );

            m = vmml::Matrix4f::IDENTITY;
            m.rotateZ( -M_PI_2 );
            _tracker.setSensorToObject( m );
            EQLOG( eq::LOG_CUSTOM ) << "Tracker initialised" << endl;
        }
    }

    return true;
}
```

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 with the session:

```
bool Config::exit()
{
    _running = false;
    const bool ret = eq::Config::exit();

    _initData.setFrameDataID( EQ_ID_INVALID );
    deregisterObject( &_initData );
    deregisterObject( &_frameData );

    return ret;
}
```

6.4.2 Frame Control

The rendering frames are issued by the application. The eqPly::Config only overrides startFrame in order to update its data before forwarding the start frame request to the eq::Config.

If a tracker is used, the current head position and orientation is retrieved and passed to Equalizer, which uses the head matrix together with the wall or projection description to compute the view frustra[16].

The camera position is updated and the frame data is commited, which generates a new version of this object. 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:

```
uint32_t Config::startFrame()
{
    // update head position
    if( _tracker.isRunning() )
    {
        _tracker.update();
        const vmml::Matrix4f& headMatrix = _tracker.getMatrix();
        setHeadMatrix( headMatrix );
    }

    // update database
    _frameData.data.rotation.preRotateX( -0.001f * _spinX );
    _frameData.data.rotation.preRotateY( -0.001f * _spinY );
    const uint32_t version = _frameData.commit();

    return eq::Config::startFrame( version );
}
```

[16] see http://www.equalizergraphics.com/documents/design/immersive.html

6.4.3 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 do the event handling. The default implementation processes all pending events by calling Config::handleEvent for each of them.

For event-driven execution, the application can override Config::handleEvents to blockingly receive events using Config::nextEvent until a new frame has to be rendered.

The eqPly example continuously renders new frames. It 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 with respect to latency, and is therefore saved in the frame data:

```
bool Config::handleEvent( const eq::ConfigEvent* event )
{
    switch( event->type )
    {
        [...]
        case eq::ConfigEvent::POINTER_MOTION:
            if( event->pointerMotion.buttons == eq::PTR_BUTTON_NONE )
                return true;

            if( event->pointerMotion.buttons == eq::PTR_BUTTON1 )
            {
                _spinX = 0;
                _spinY = 0;

                _frameData.data.rotation.preRotateX(
                    -0.005f * event->pointerMotion.dx );
                _frameData.data.rotation.preRotateY(
                    -0.005f * event->pointerMotion.dy );
            }
            else if( event->pointerMotion.buttons == eq::PTR_BUTTON2 ||
                     event->pointerMotion.buttons == ( eq::PTR_BUTTON1 |
                                                       eq::PTR_BUTTON3 ))
            {
                _frameData.data.translation.z +=
                    .005f * event->pointerMotion.dy;
            }
            else if( event->pointerMotion.buttons == eq::PTR_BUTTON3 )
            {
                _frameData.data.translation.x +=
                    .0005f * event->pointerMotion.dx;
                _frameData.data.translation.y -=
                    .0005f * event->pointerMotion.dy;
            }
            return true;

        default:
            break;
    }
    return eq::Config::handleEvent( event );
}
```

6.5 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 should 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.

During node initialization the init data is mapped to a local instance using the identifier passed from Config::init. The model is loaded based on the filename in the initialization data. No pipe, window or channel tasks methods are executed before Node::configInit has returned.

```
bool Node::configInit( const uint32_t initID )
{
    eq::Config* config = getConfig();
    const bool mapped = config->mapObject( &_initData, initID );
    EQASSERT( mapped );

    const string& filename = _initData.getFilename();
    EQINFO << "Loading model " << filename << endl;

    _model = new Model();
    if ( !_model->readFromFile( filename.c_str() ) )
    {
        EQWARN << "Can't load model: " << filename << endl;
        delete _model;
        _model = 0;
    }

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

The node config exit function deletes the loaded model and unmaps the initialization data:

```
bool Node::configExit()
{
    delete _model;
    _model = NULL;

    eq::Config* config = getConfig();
    config->unmapObject( &_initData );

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

The two remaining functions in the node relax the thread synchronization between the node and pipe threads, since all dynamic data is multi-buffered in eqPly. Section 7.2 provides a detailed explanation of thread synchronization in Equalizer:

```
void Node::frameDrawFinish( const uint32_t frameID,
                            const uint32_t frameNumber )
{ /* nop, see frameStart */ }

void Node::frameStart( const uint32_t frameID, const uint32_t frameNumber )
{
    startFrame( frameNumber ); // unlock pipe threads

    // Don't wait for pipes to release frame locally, sync not needed since all
    // dynamic data is multi-buffered
    releaseFrameLocal( frameNumber );
}
```

6.6 Pipe

All task methods for a pipe and its children are executed in a separate thread. This approach optimizes usage of the GPU, since all tasks are executed serially and therefore do not compete for resources or cause OpenGL context switches. Later versions of Equalizer might introduce threaded windows to allow the parallel and independent execution of rendering tasks on a single pipe.

6.6.1 Initialization and Exit

Pipe threads are not explicitely synchronized with each other, that is, pipes might be rendering different frames at any given time. Therefore frame-specific data has to be allocated for each pipe thread, which in the eqPly example is the frame data. The frame data is a member variable of the eqPly::Pipe, and is mapped to the identifier provided by the initialization data. The initialization in eq::Pipe does the GPU-specific initialization, which is window-system-dependent. On AGL the display ID is determined, and on glX the display connection is opened.

```
bool Pipe::configInit( const uint32_t initID )
{
    const Node*      node        = static_cast<Node*>( getNode( ));
    const InitData& initData     = node->getInitData();
    const uint32_t  frameDataID = initData.getFrameDataID();
    eq::Config*      config      = getConfig();

    const bool mapped = config->mapObject( &_frameData, frameDataID );
    EQASSERT( mapped );

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

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();
}
```

6.6.2 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[17].

Each pipe might use a different window system for rendering, which is determined before Pipe::configInit by Pipe::selectWindowSystem. The default implementation of selectWindowSystem loops over all window systems and returns the first supported window system, determined by using supportsWindowSystem.

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 Node*             node      = static_cast<Node*>( getNode( ));
    const InitData&         initData = node->getInitData();
    const eq::WindowSystem ws        = initData.getWindowSystem();

    if( ws == eq::WINDOW_SYSTEM_NONE )
        return eq::Pipe::selectWindowSystem();
    if( !supportsWindowSystem( ws ))
    {
        EQWARN << "Window system " << ws
               << " not supported, using default window system" << endl;
        return eq::Pipe::selectWindowSystem();
    }
```

[17] see http://www.equalizergraphics.com/compatibility.html

```
    return ws;
}
```

6.6.3 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 various 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.

6.6.4 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 then unlocks its child entities by calling startFrame:

```
void Pipe::frameStart( const uint32_t frameID, const uint32_t frameNumber )
{
    // don't wait for node to start frame, local sync not needed
    // node->waitFrameStarted( frameNumber );
    _frameData.sync( frameID );
    startFrame( frameNumber );
}
```

6.7 Window

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

6.7.1 Initialization and Exit

The initialization sequence uses multiple, overrideable task methods. The main task method configInit executes a 'child' task method to create the drawable and context. The child task method depends on the window system of the pipe. The default implementations of configInitGLX, configInitWGL or configInitAGL create an on-screen window using OS-specific methods. If the OpenGL drawable and context were created 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.

Figure 15 shows a flow chart of the window initialization. The colored functions are task methods and can be replaced by application-specific implementations.

The window-system specific 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 Equalizer will test for their availability and enable them if possible.

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

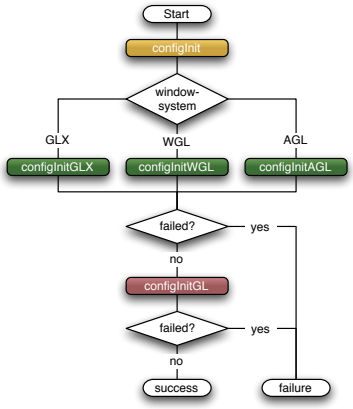


Figure 15: Window Initialization

```
bool Window::configInitGL( const uint32_t initID )
{
    if( !eq::Window::configInitGL( initID ))
        return false;

    eq::Pipe*  pipe        = getPipe();
    Window*    firstWindow = static_cast< Window* >( pipe->getWindows()[0] );

    EQASSERT( !_state );

    if( firstWindow == this )
    {
        _state = new VertexBufferState( glewGetContext( ));

        const Node*     node     = static_cast< const Node* >( getNode( ));
        const InitData& initData = node->getInitData();

        if( initData.useVBOs() )
        {
            // Check if VBO funcs available, else leave DISPLAY_LIST_MODE on
            if( GLEW_VERSION_1_5 )
            {
                _state->setRenderMode( mesh::BUFFER_OBJECT_MODE );
                EQINFO << "VBO rendering enabled" << endl;
            }
            else
                EQWARN << "VBO function pointers missing, using display lists"
                       << endl;
        }

        if( initData.useGLSL() )
        {
            // Check if all functions are available
            if( GLEW_VERSION_2_0 )
            {
                EQINFO << "Shaders supported, attempting to load" << endl;
                _loadShaders();
            }
            else
                EQWARN << "Shader function pointers missing, using fixed "
                       << "pipeline" << endl;
        }

        _loadLogo();
    }
```

```
    else
    {
        _state       = firstWindow->_state;
        _logoTexture = firstWindow->_logoTexture;
        _logoSize    = firstWindow->_logoSize;
    }

    if( !_state ) // happens if first window failed to initialize
    {
        setErrorMessage( "No state handler object" );
        return false;
    }

    // turn off OpenGL lighting if we are using our own shaders
    if( _state->getProgram( pipe ) != VertexBufferState::FAILED )
        glDisable( GL_LIGHTING );

    return true;
}
```

The state object is used to handle the creation of OpenGL objects in a multipipe, multi-threaded execution environment. It uses an object manager, which is described in detail in Section 6.7.2. It is used in conjunction with a reference-counting smart-pointer here, since it is potentially 'owned' by multiple windows at the same time.

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 ommitted, since the code consists of standard OpenGL calls and is not Equalizer-specific.

The window exit function de-allocates all OpenGL objects when the state object is about to be disposed. The object manager does not delete the object in its destructor, since it does not know if an OpenGL context is still current. Additionally, eq::Window::configExit is called to destroy the drawable and context:

```
bool Window::configExit()
{
    if( _state.isValid() && _state->getRefCount() == 1 )
        _state->deleteAll();

    _state = 0;
    return eq::Window::configExit();
}
```

6.7.2 Object Manager

The object manager is not strictly 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 and spawns all contexts of a single GPU[18].

The OM is a template class. The template type is the key used to identify objects. The same key is used by all contexts to get the OpenGL name of an object.

Each eq::Window has an object manager with the key type const void* for as long as it has an OpenGL context. The OM is shared between all windows of a pipe, if the windows are created using the default configInit functions. If the window is created by the application, the OM is not shared since no assumption can be made about OpenGL context sharing. Later version of Equalizer will introduce an API

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

to configure OpenGL context sharing, and therefore OM sharing, for application-created windows.

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. All objects managed by the OM are reference counted. If an application releases the objects properly, they are automatically de-allocated. It is also possible to manually manage de-allocation of objects, which might be more convenient in some cases.

Currently, support for display lists, VBO's, textures and shaders is implemented. 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. Increases the reference count of existing objects.

newObject(key) allocates a new object for the given key. Returns FAILED if the object already exists or if the allocation failed. Sets the reference count of a newly created object to one.

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

releaseObject(key | name) decreases the reference count and deletes the object if the reference count reaches zero.

deleteObject(key | name) manually deletes the object. To be used if reference counting is not used.

6.8 Channel

The channel is the heart of the application in that it contains the actual rendering code. The channel is used to perform the various rendering operations for the compounds.

6.8.1 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 uint32_t initID )
{
    setNearFar( 0.1f, 10.0f );
    return true;
}
```

6.8.2 Rendering

The central rendering routine is Channel::frameDraw. This routine contains the application's OpenGL rendering code, which is being rendered using 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 method(s) and then calls the appropriate OpenGL function(s). It is also possible to just query the values from Equalizer using the get methods, and use them to set up the OpenGL state appropriatly, 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 in order 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.

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

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, with the exception of the range which will be used later during rendering:

```
void eq::Channel::frameDraw( const uint32_t frameID )
{
    applyBuffer();
    applyViewport();

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

    glMatrixMode( GL_MODELVIEW );
```

```
    glLoadIdentity();
    applyHeadTransform();
}

void Channel::frameDraw( const uint32_t frameID )
{
    // Setup OpenGL state
    eq::Channel::frameDraw( frameID );
```

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 the frame data to ensure that all channels render a given frame using the same position.

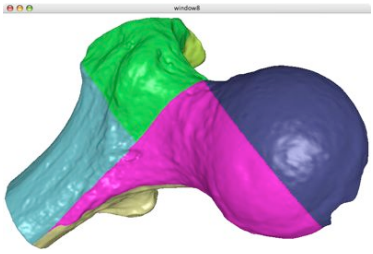


Figure 16: Destination view of an DB compound

Furthermore, a white color is set in case the model does not contain color information, or the color information is not used. In sort-last rendering, eqPly uses a different color for each channel to illustrate the database decomposition, as shown in Figure 16. The Equalizer channel provides a method to obtain a random, but unique color for all channels in the configuration. This color is determined by the server to ensure uniqueness across all channels of the configuration:

```
    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 Pipe*       pipe      = static_cast<Pipe*>( getPipe( ));
    const FrameData& frameData = pipe->getFrameData();

    glTranslatef( frameData.data.translation.x,
                  frameData.data.translation.y,
                  frameData.data.translation.z );
    glMultMatrixf( frameData.data.rotation.ml );

    Node*             node  = (Node*)getNode();
    const Model*      model = node->getModel();
    const eq::Range& range = getRange();

    if( !range.isFull( )) // Color DB-patches
    {
        const vmml::Vector3ub color = getUniqueColor();
        glColor3ub( color.r, color.g, color.b );
    }
    else if( !frameData.data.color || (model && !model->hasColors( )) )
    {
        glColor3f( 1.0f, 1.0f, 1.0f );
    }
```

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

```
    if( model )
    {
        _drawModel( model );
    }
    else
```

```
    {
        glColor3f( 1.f, 1.f, 0.f );
        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();
    }
}
```

In order to draw the model, a helper class for view frustum culling is set up using the view frustum from Equalizer and the camera position 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.

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* model )
{
    Window*                    window    = static_cast<Window*>( getWindow() );
    mesh::VertexBufferState&   state     = window->getState();

    const Pipe*                pipe      = static_cast<Pipe*>( getPipe( ));
    const FrameData&           frameData = pipe->getFrameData();

    const eq::Range&           range     = getRange();
    vmml::FrustumCullerf       culler;

    state.setColors( frameData.data.color &&
                     range.isFull() &&
                     model->hasColors() );
    _initFrustum( culler, model->getBoundingSphere( ));

    model->beginRendering( state );
```

The model data is spatially organized in an 3-dimensional kD-tree[19] for efficient view frustum culling. When the model is loaded by Node::configInit, it is preprocessed into the kD-tree and 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 use.

The rendering loop maintains a list of candidates to render, which initially contains the root node. Each candidate of this list is tested

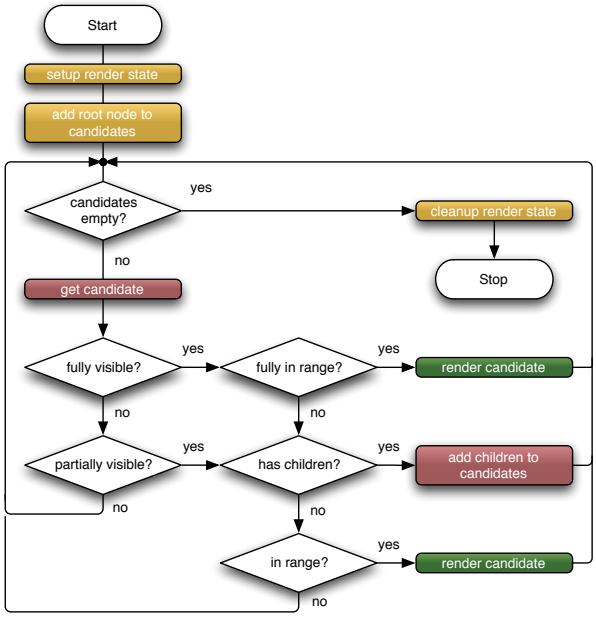


Figure 17: Main Rendering Loop

[19] See also http://en.wikipedia.org/wiki/Kd-tree

for full visiblity 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 17 shows a flow chart of the rendering algorithm, which performs efficient view frustum and range culling.

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 VBO's. 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 VBO's across all windows of a pipe.

The main rendering loop in eqPly looks like this:

```
model->beginRendering( state );

// start with root node
vector< const VertexBufferBase* > candidates;
candidates.push_back( model );

while( !candidates.empty() )
{
    const VertexBufferBase* treeNode = candidates.back();
    candidates.pop_back();

    // completely out of range check
    if( treeNode->getRange()[0] >= range.end ||
        treeNode->getRange()[1] < range.start )
        continue;

    // bounding sphere view frustum culling
    switch( culler.testSphere( treeNode->getBoundingSphere() ) )
    {
        case vmml::VISIBILITY_FULL:
            // if fully visible and fully in range, render it
            if( treeNode->getRange()[0] >= range.start &&
                treeNode->getRange()[1] < range.end )
            {
                treeNode->render( state );
                break;
            }
            // partial range, fall through to partial visibility
        case vmml::VISIBILITY_PARTIAL:
        {
            const VertexBufferBase* left = treeNode->getLeft();
            const VertexBufferBase* right = treeNode->getRight();

            if( !left && !right )
            {
                if( treeNode->getRange()[0] >= range.start )
                    treeNode->render( state );
                // else drop, to be drawn by 'previous' channel
            }
            else
            {
                if( left )
                    candidates.push_back( left );
                if( right )
                    candidates.push_back( right );
            }
            break;
        }
        case vmml::VISIBILITY_NONE:
            // do nothing
            break;
```

```
        }
    }

    model->endRendering( state );
}
```

7 Advanced Features

This section discusses some additional important features not covered by the previous eqPly section. Where possible, code examples from the Equalizer distribution are used to illustrate one use case of the feature.

7.1 Event Handling

Event handling requires a lot of 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-related 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. More information on event handling can be found on the Equalizer website[20].

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

7.1.1 Threading

In general, events are received and processed by the pipe thread a window belongs to. An exception to this rule is AGL, where all events are dispatched from the main node thread. WGL and GLX receive and process the events from the pipe threads that created the windows. Whenever the term **event thread** is used, it refers to the thread receiving the event, i.e., the pipe thread for WGL and GLX, and the main thread for AGL.

7.1.2 Initialization and Exit

During window and pipe initialization the event handling is set up. For both entities, initEventHandler is called to register the pipe or window with an event handler. This method may be overwritten to use a custom event handler, or to not install an event handler at all in order to disable event handling. Likewise, exitEventHandler is called to de-initialize event handling.

An event handler consists of two parts: the generic base class providing the interface and generic functions, and the window-system-specific part providing the actual implementation.

Event handling is initialized whenever a new window-system-specific pipe or window handle is set. First, exitEventHandler is called to de-initialize event handling for the old handle (if set), and then initEventHandler is called for the new handle.

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

AGL uses an event handler singleton, GLX uses one event handler per pipe and WGL uses one event handler per window.

7.1.3 Message Pump

In order to dispatch the events, Equalizer 'pumps' the native events. On WGL and GLX, this has happens on each thread with windows, whereas on AGL it has to happen only on the main thread. By default, Equalizer pumps these events automatically for the application in-between executing task methods.

The methods Client::useMessagePump and Pipe::useMessagePump can be overridden to return false to disable this behaviour for their respective threads. On non-threaded pipes, Pipe::useMessagePump is not called.

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

7.1.4 Event Data Flow

Events are received by an event handler. The event handler finds the eq::Window associated to the event. It then creates a generic WindowEvent, which holds important event data in an independent format. The original event is attached to the generic window event.

The event handler then passes the window event to Window::processEvent, which is responsible for either handling the event locally, or for translating it into a generic ConfigEvent. The config events are send to the application thread using Config::sendEvent.

If the event was processed by processEvent, the function has to return true. If false is returned, the event will be passed to a previously installed, window-system-specific event handling function. The default implementation of Window::processEvent passes most events on to the application.

Events send using Config::sendEvent 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 be implemented.

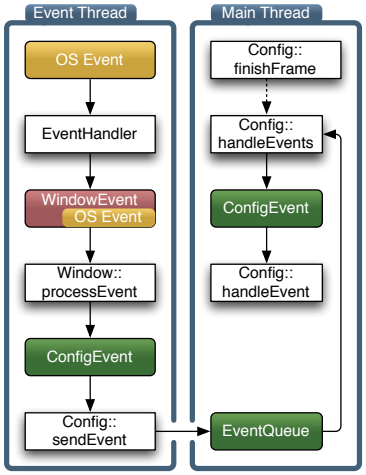


Figure 18: Event Processing

Later Equalizer versions will introduce Pipe::processEvent and PipeEvent to communicate pipe-specific events, e.g., monitor resolution changes.

7.1.5 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 ConfigEvent derives from the eq::ConfigEvent structure and has the following definition:

```
struct ConfigEvent : public eq::ConfigEvent
{
public:
    enum Type
    {
        READBACK = eq::ConfigEvent::USER,
        ASSEMBLE
    };

    ConfigEvent()
        {
            size = sizeof( ConfigEvent );
        }

    // channel name is in user event data
    char            formatType[64];
    vmml::Vector2i  area;
    float           msec;
};
```

The Config::sendEvent method transmits an eq::ConfigEvent or derived class to the application. The ConfigEvent has to be a C-type structure, and its size member has to be set to the full size of the event to be transmitted. Each event has a type which is used to identify it by the config processing function.

User-defined types start at eq::ConfigEvent::USER, and the member variable ConfigEvent::user can be used to store up to EQ_USER_EVENT_SIZE[21] bytes. In this space, the channel's name is stored. Additional variables are used to transport the pixel format and type, the size and the time it took for rendering.

On the application end, Config::handleEvent uses the ostream operator for the derived config event to output these events in a nicely formatted way:

```
std::ostream& operator << ( std::ostream& os, const ConfigEvent* event );
...
bool Config::handleEvent( const eq::ConfigEvent* event )
{
    switch( event->type )
    {
        case ConfigEvent::READBACK:
        case ConfigEvent::ASSEMBLE:
            cout << static_cast< const ConfigEvent* >( event ) << endl;
            return true;

        default:
            return eq::Config::handleEvent( event );
    }
}
```

7.2 Multi-Threading and Synchronization

Equalizer applications use multiple, asynchronous execution threads. The default execution model is focused on making the porting of existing applications as easy as possible, as described in Section 5.2. The default, per-node thread synchronization provided by Equalizer can gradually be relaxed by advanced applications to gain better performance through higher asynchronicity.

This section explains the multi-threading in Equalizer in detail and gives advice on how to optimize applications for performance.

[21] currently 32 bytes

7.2.1 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.

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

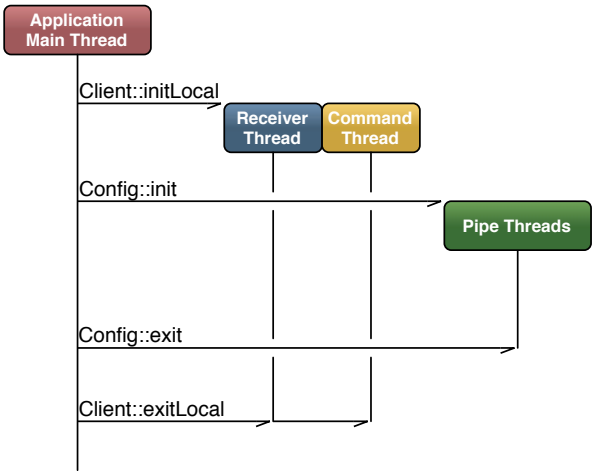


Figure 19: Threads within one node process

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 Equalizer-related request from other nodes, for example during eqNet::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. The pipe threads are terminated during Config::exit.

The rest of this section discusses the thread synchronization between the main thread and the pipe threads.

7.2.2 Thread Synchronization Model

The node main thread and the pipe threads are synchronized with each other, so that all draw task methods of one rendered frame are executed at the same time. 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.

Please note that the default thread synchronization synchronizes all Channel::frameDraw operations on a **single** node with the node's main thread. The per-node frame synchronization does not break the asynchronous execution across nodes. Advanced applications can remove the per-node frame synchronization.

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 in order 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.

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 20 illustrates this synchronization model.

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.

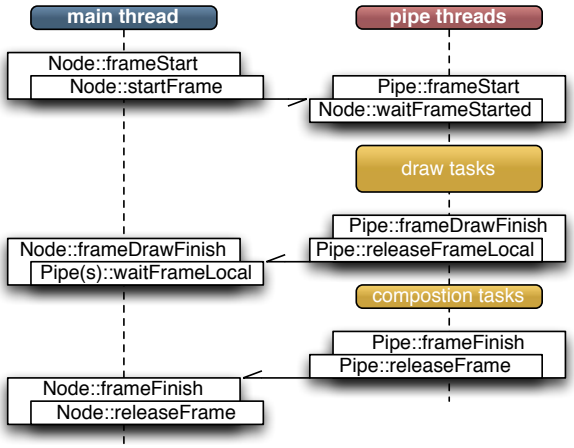


Figure 20: Per-Node Frame Synchronization

The local synchronization consists of releaseFrameLocal to unlock the local frame, and of waitFrameLocal to wait for the unlock. For the default synchronization model, 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.

Figure 20 illustrates the local frame synchronization. By removing the calls to waitFrameLocal, the node thread can disable the synchronization with the pipe threads, which causes the node operations to overlap with the rendering.

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 entitity 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.

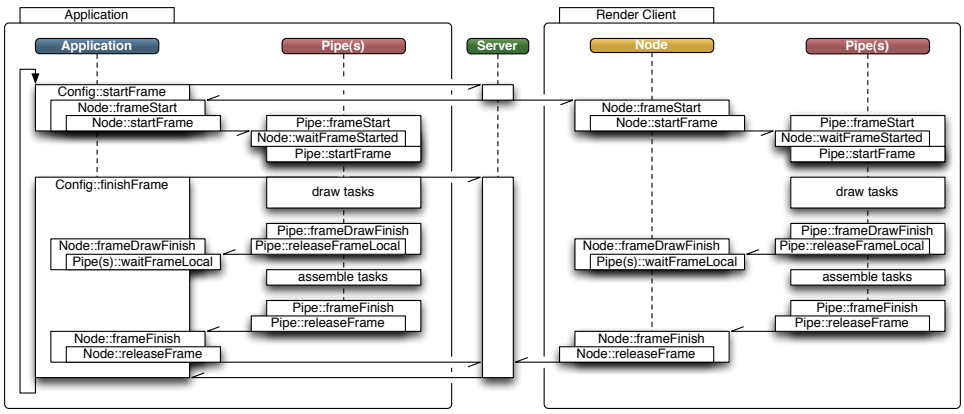


Figure 21: Synchronization of frame tasks

Figure 21 outlines the synchronization for the application, node and pipe classes for an application node and one render client. 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 implementation of the node task methods does take care of that.

Since eqPly multi-buffers all dynamic data, it completely removes frame synchronization by:

- releasing the local synchronization early in Node::frameStart
- not waiting for the node to start the frame by not calling Node::waitFrameStarted in Pipe::frameStart
- not waiting for the pipe synchronization in Node::frameDrawFinish by not calling Pipe::waitFrameLocal

7.3 OpenGL Extension Handling

Equalizer uses GLEW[22] for OpenGL extension handling, particularly the GLEW MX implementation providing multi-context support.

Each eq::Window has a GLEWContext. This context can be obtained by using glewGetContext on the window or channel. GLEW MX uses this function to dispatch the functions to the correct context. Equalizer (re-)initializes the GLEW context whenever a new OpenGL context is set on the window.

Extended OpenGL functions called from a 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 );
    ...
}
```

Functions called from another place need to define a macro or function glewGetContext that returns the pointer to the GLEWContext of the appropriate window:

```
// 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 );
    ...
}
```

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

7.4 Advanced Window Initialization

This section explains window initialization in detail. It discusses in detail the handling on the different window systems. The entry point for the window initialization is the task method Window::configInit. This task method first calls a window-system-specific task method, and then Window::configInitGL to do generic OpenGL state setup, as shown in Figure 15.

Since window initialization is notoriously error-prone and hard to debug, the default Equalizer functions propagate the reason for errors from the render clients back to the application. The Pipe and Window classes have a setErrorMessage method, which is used to set an error string. This string is passed to the Config instance on the application node, where it can be queried using getErrorMessage.

The window-system-specific initialization methods use overrideable 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.

7.4.1 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 6.6.3 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 returned pixel format has to be destroyed using Window::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 configInitAGLFullscreen, configInitAGLWindow or configInitAGLPBuffer

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

```
bool Window::configInitAGL()
{
    AGLPixelFormat pixelFormat = chooseAGLPixelFormat();
    if( !pixelFormat )
        return false;

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

    if( !context )
        return false;

    return configInitAGLDrawable();
}
```

7.4.2 GLX Window Initialization

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

```
bool Window::configInitGLX()
{
    XVisualInfo* visualInfo = chooseXVisualInfo();
    if( !visualInfo )
        return false;

    GLXContext context = createGLXContext( visualInfo );
    setGLXContext( context );

    if( !context )
        return false;

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

    if( success && !_xDrawable )
    {
        setErrorMessage( "configInitGLXDrawable did set no X11 drawable" );
        return false;
    }

    return success;
}
```

7.4.3 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. getWGLPipeDC is used to get an affinity device context, which might be needed for window creation. If a context is returned, a function pointer to delete the returned device context is set as well. This function might return 0, which is not an error.

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.

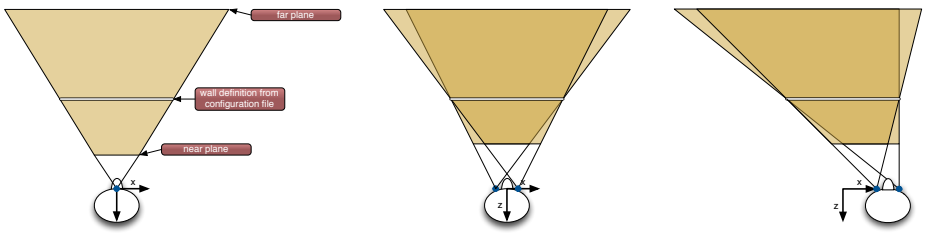
The full configInitWGL task method, including error handling and cleanup, looks as follows:

```
bool Window::configInitWGL()
{
    PFNEQDELETEDCPROC deleteDCProc = 0;
    HDC dc = getWGLPipeDC( deleteDCProc );
    EQASSERT( !dc || deleteDCProc );

    int pixelFormat = chooseWGLPixelFormat( dc );
    if( pixelFormat == 0 )
    {
        if( dc )
            deleteDCProc( dc );
        return false;
```

```
    }

    if( !configInitWGLDrawable( dc, pixelFormat ))
    {
        if( dc )
            deleteDCProc( dc );
        return false;
    }

    if( !_wglDC )
    {
        if( dc )
            deleteDCProc( dc );
        setErrorMessage( "configInitWGLDrawable did not set a WGL drawable" );
        return false;
    }

    HGLRC context = createWGLContext( dc );
    setWGLContext( context );

    if( !context )
    {
        if( dc )
            deleteDCProc( dc );
        return false;
    }

    if( dc )
        deleteDCProc( dc );
    return true;
}
```

7.5 Head Tracking

The eqPly example contains rudimentary support for head tracking, in order to show how head tracking can be integrated with Equalizer. Support for a wide range of tracking devices is not within the scope of Equalizer. Other open source and commercial implementations cover this functionality sufficiently and can easily be integrated with Equalizer.



(a) (b) (c)

Figure 22: Monoscopic, Stereoscopic and Tracked frustra

Figure 22(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.

In stereo rendering, the scene is rendered twice, with the two frustra 'moved' by the distance between the eyes, as shown in Figure 22(b).

In immersive visualization, the observer is tracked in and the view frustra are adapted to the viewer's position and orientation, as shown in Figure 22(c). The transformation *origin* → *viewer* is set by the application using Config::setHeadMatrix,

which is used by the server to compute the frustra. The resulting off-axis frustra are positioned using the channel's head transformation, which can be retrieved using Channel::getHeadTransform.

7.6 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, when multiple channels are contributing to a single view.

The source 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 framebuffer. 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 provide a detailed description of the image compositing API in Equalizer.

7.6.1 Parallel Direct Send Compositing

In order 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.

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.

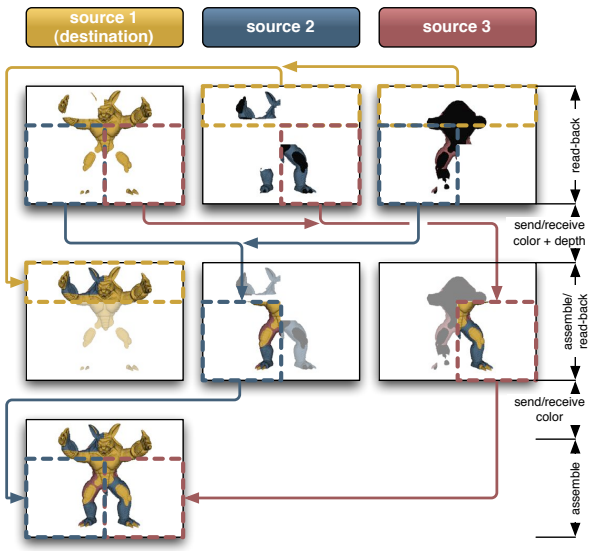


Figure 23: Parallel Direct Send Compositing

In direct send compositing, each rendering channel is also responsible for the sort-last composition of one screen-space tile. He receives the framebuffer pixels for his 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 23 illustrates this algorithm for three channels. The Equalizer website contains a presentation[23] explaining and comparing this algorithm with the binary-swap algorithm.

The following operations have to be possible in order 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

Furthermore it should be possible for the application to implement a read back of only the relevant region of interest, that is, the 2D area of the framebuffer actually updated during rendering. This optimization will be fully supported by later versions of Equalizer.

7.6.2 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 signalled 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.

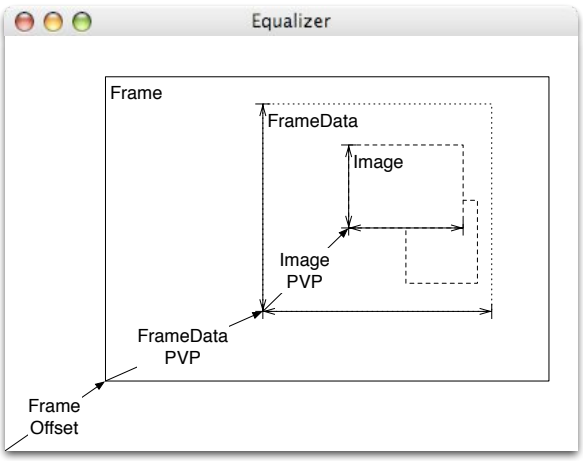


Figure 24: Hierarchy of assembly classes

Readback and assemble operations on frames and images are designed to be asynchronous. They have a start and finish method for both readback and assemble to allow the initiation and synchronization of the operation. Currently, only synchronous readback and assembly using glReadPixels and glDrawPixels is implemented in the respective start method of the image. Later versions of Equalizer will implement asynchronous pixel transfers.

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

[23] 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.

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 24 illustrates the relationship between frames, frame data and images.

7.6.3 Custom Assembly in eVolve

The eVolve example is a scalable volume renderer. It uses 3D texture-based volume rendering, where the 3D texture is intersected by view-aligned slices. The slices are rendered back-to-front and blended together to produce the final image, as shown in Figure 25[24].

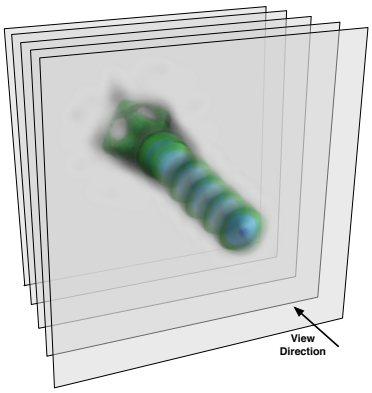


Figure 25: Blending Slices in 3D-Texture-based Volume Rendering

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

DB compounds have 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 per time step and channel). Since the amount of texture memory needed for each node decreases linearly, they make it possible to render data sets which are not feasible to visualize with any other approach.

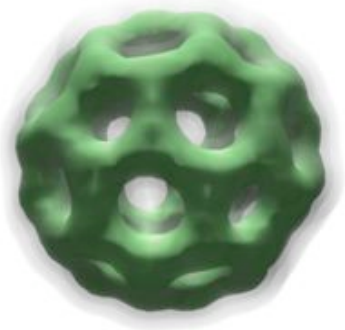
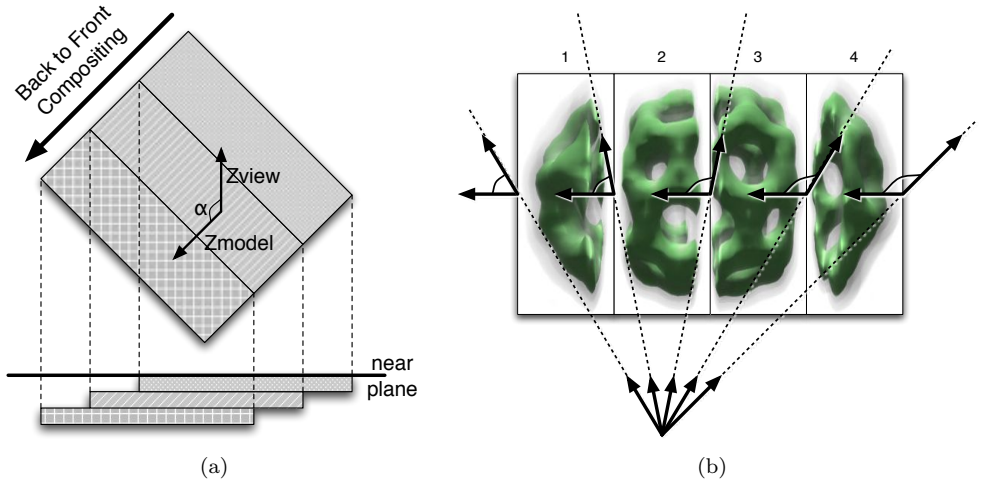


Figure 26: Result of Figure 27(b)

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

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



(a) (b)

Figure 27: Back-to-Front Compositing for Orthogonal and Perspective View Frustra

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 27(a) shows this composition for one view.

Finding the correct assembly order for perspective frustra is more complex. The perspective distortion invalidates a simple orientation criteria like the one used for orthographic frustra. For the view and frustum setup shown in Figure 27(b)[25] the correct compositing order is 4-3-1-2 or 1-4-3-2.

In order to compute the assembly order, eVolve uses the angle between the *origin* → *slice* vector and the near plane, as shown in Figure 27(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 26 shows the result of the composition from Figure 27(b).

The assembly algorithm described in this section also works with parallel compositing algorithms such as direct-send.

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