Equalizer Programming Guide

http://www.equalizergraphics.com/documents/Developer/ProgrammingGuide.pdf

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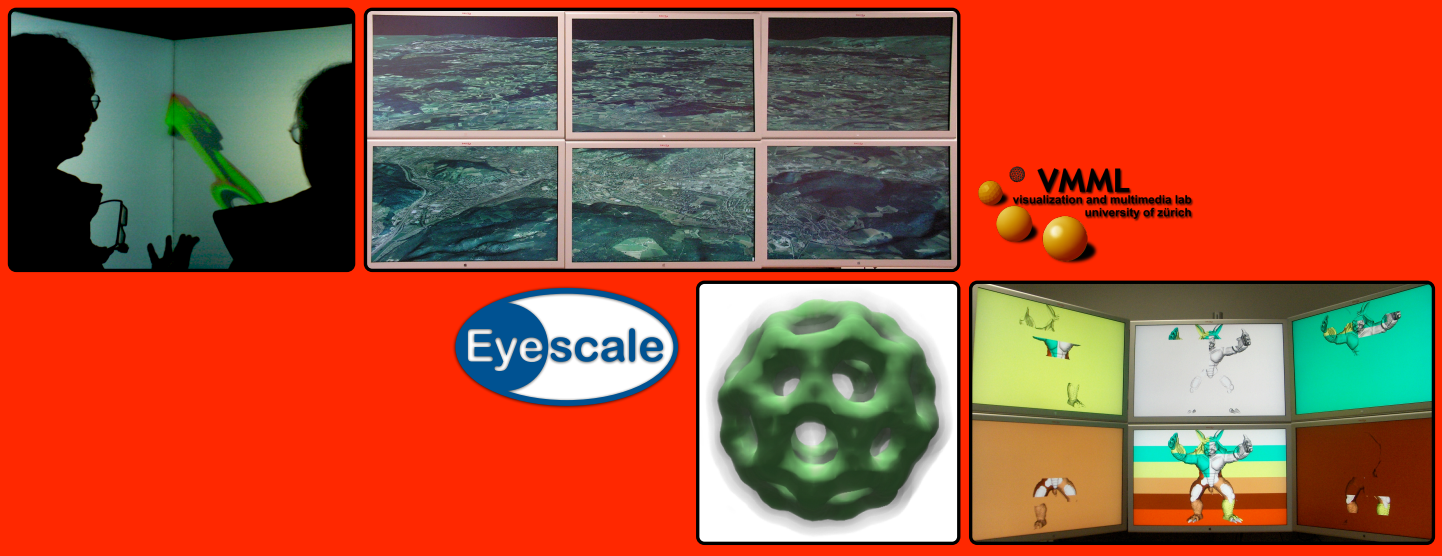

DRAFT

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Contents

Rev	**Date**	**Changes**
0.9	Oct 7, 2007	add eqHello, draft assembly in eVolve
0.8	Sep 28, 2007	add head tracking, finish channel, proof-reading pass
0.7	Sep 21, 2007	start channel and image compositing, add event handling, move to new eqPly code base
0.6	Sep 14, 2007	add pipe, window and object manager
0.5	Sep 3, 2007	add config and partly pipe
0.4	Aug 31, 2007	add distributed objects
0.3	Aug 26, 2007	add application and render client
0.2	Aug 20, 2007	add main function
0.1	Aug 19, 2007	outline the basic concepts

1 Introduction

Equalizer provides a framework for the development of parallel OpenGL™ applications. Equalizer-based applications can run a single shared-memory system with multiple graphics cards (GPU's) or on graphics clusters. This Programming Guide introduces the programming interface using the eqPly example shipped with Equalizer as a guideline.

Any questions related to Equalizer programming and this Programming Guide should be directed to the eq-dev mailing list[1].

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

Equalizer implements the minimum necessary layer to build parallel and scalable OpenGL applications. The programmer structures the application 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 for portability. It is a 'GLUT on steroids', providing parallel and distributed execution, scalable rendering features and fully customizable event handling.

2 Getting Started

2.1 Compiling and running eqPly

It is recommended to have a compiled version of Equalizer and the examples for this Programming Guide. The Quickstart Guide[2] should be executed once to get familar with the capabilities of the eqPly example.

Compiling Equalizer is as simple as running make on Linux or building the Equalizer solution on Windows. On Mac OS X, some prerequisites have to be installed before running make, as explained in README.Darwin.

2.2 Equalizer Processes

All functionality of Equalizer is accessed through the Equalizer client library, which implements all functionality discussed in this document. The client library provides communication between the Equalizer processes.

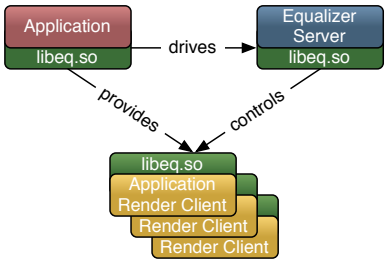


Figure 1: Equalizer Processes

2.2.1 Server

An Equalizer server is responsible for managing one visualization system, i.e., a shared memory system or graphics cluster. Currently it is only useful for running one application at a time, but it will be extended to support multiple applications concurrently and efficiently on one system. The server controls and potentially launches the application's rendering clients.

[1] see http://www.equalizergraphics.com/lists.html
[2] http://www.equalizergraphics.com/documents/EqualizerGuide.html

2.2.2 Application

The application connects to an Equalizer server, which chooses a configuration for the application. It also provides a render client, to be launched by the server. The application reacts on events and controls the rendering.

2.2.3 Render Clients

The render client implements –obviously– the rendering part of an application. Its execution is passive, completely driven by rendering tasks received from the server. The tasks are executed by calling the appropriate task methods (see Section 4.1) in the correct thread and context.

The application might 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.

The rendering client can be the same executable as the application, as is the case with eqPly. 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 real-world applications often implement a separate, light-weight rendering client.

3 Hello, World!

The eqHello example is a minimal example 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.

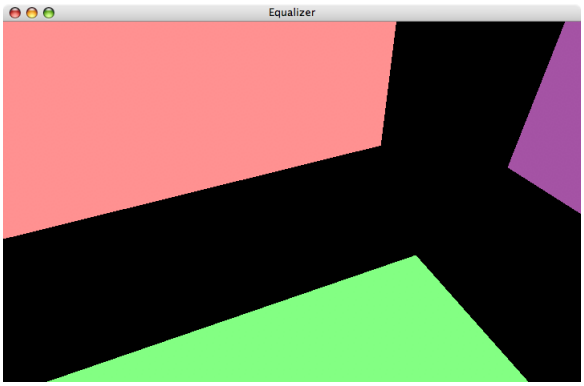


Figure 2: Hello, World!

The eqHello redraw function renders six rotating, colored quads around the origin, where the viewer is usually positioned. The Equalizer frameDraw method is used as a convience function to setup the frustum and other OpenGL state. After setting up some additional lighting parameter, eqHello rotates the scene and render 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 5.

4 The Programming Interface

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

4.1 Task Methods

The application subclasses Equalizer objects and overrides virtual functions to implement certain functionality, e.g., the application's OpenGL rendering in eq::Channel::frameDraw. These task methods are in concept similar to C function callbacks. The eqPly section will discuss the most important task methods. A full list can be found on the website[3].

4.2 The Resource Tree

The rendering resources are represented in a hierarchical tree structure which corresponds to the physical and logical resources found in a 3D rendering environment.

Figure 3 shows one example configuration for a four-side CAVE^{TM}, running on two machines (node) using three graphics cards (pipe) 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 deployment one node and pipe should be used for each computer and graphics card, respectively.

4.2.1 Configuration

The root of the resource tree is the eq::Config, which represents the current configuration of the application. The configuration is the session in which all render clients are registered. The config instance on a given node currently only holds the local node, not all nodes of the configuration.

4.2.2 Node

An eq::Node is the representation of a single computer in the system. One operating system process of the render client will be used for each node. Each configuration

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

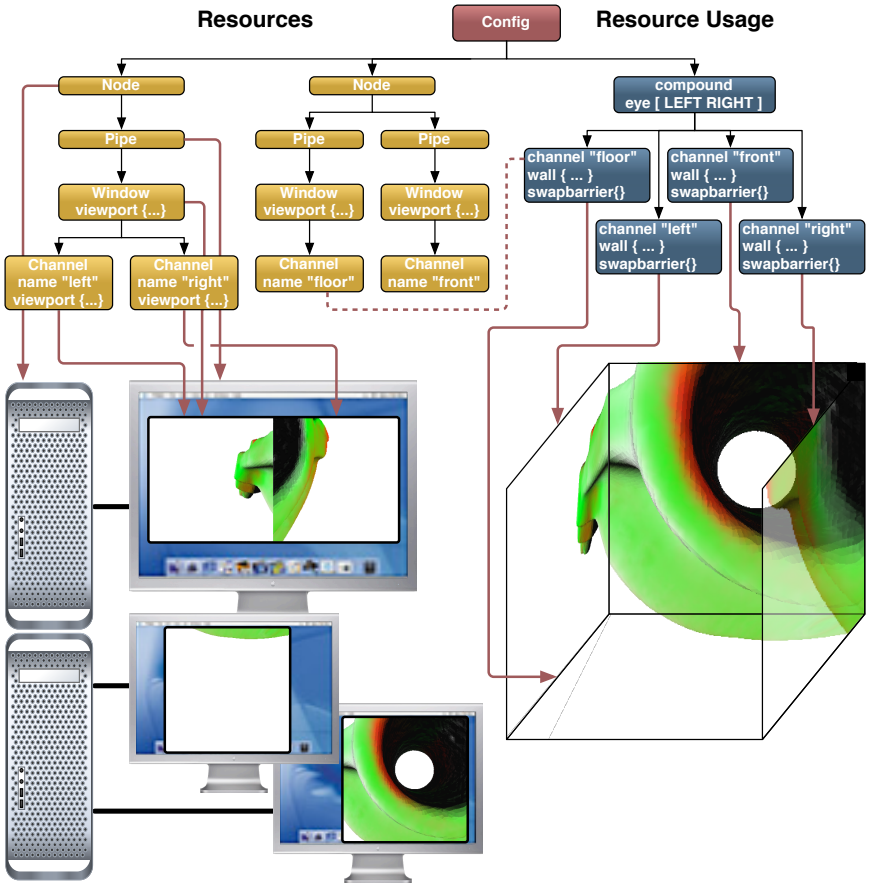


Figure 3: An example configuration

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.

4.2.3 Pipe

The eq::Pipe is the abstraction of a graphics card (GPU). In the current implementation it is also one operating system thread, unless the pipe's thread hint is set to false. All pipe, window and channel task methods are executed from the pipe thread for threaded pipes or from the main application thread for non-threaded pipes[4].

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

4.2.4 Window

An eq::Window holds a drawable and OpenGL context. The drawable can be an on-screen window or an off-screen PBuffer or FBO[5]. 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.

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

[5] off-screen drawables are not yet implemented, but can be created by the application and used with Equalizer

4.2.5 Channel

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

4.3 Compounds

How the rendering resources are to be used is configured using a compound tree. Although the API does not currently expose compounds, the basic design behind compounds is explained here to increase the understanding of the architecture behind Equalizer.

Each compound has a channel, which it uses to execute the rendering tasks. One channel might be used by multiple compounds. Unused channels are not instantiated. The rendering tasks for the channels are computed by the server and send to the appropriate render clients.

The channels of the leaf compounds (source channels) in the compound tree execute the rendering for the top-most compound's channel (destination channel). The top-most compound with a channel defines the 2D pixel viewport rendered by all leaf compounds. The destination channel and pixel viewport can not be overridden.

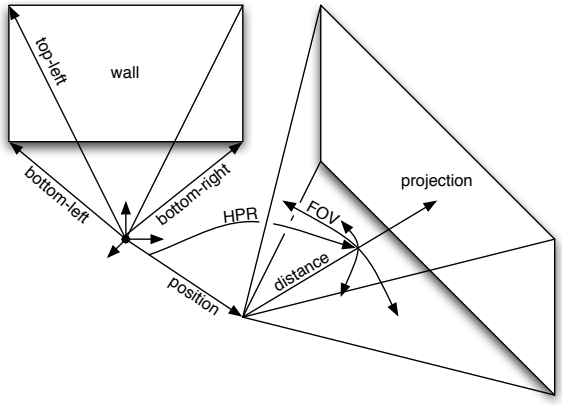


Figure 4: Frustrum descriptions

Compounds have a frustum description, which is inherited to the children. The frustum can be overridden by children, but this is rarely used since there is no use case for this behaviour. The frustrum can be specified as a wall, which is completely defined by the bottom-left, bottom-right and top-left coordinates relative to the origin, or as a projection, which 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 to the projection wall. Figure 4 illustrates the wall and projection frustum parameters.

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 its database, and an eye pass can selectively render different stereo passes.

Compounds have output and input frames which configure the recomposition of the resulting pixels from the source compound channels. An output frame connects to an input frame of the same name, and transports the selected frame buffer data from the output channel to the input channel. This composition process is extensively described in Section 6.2.

More information on the configuration of compounds can be found on the Equalizer website[6].

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

5 The eqPly polygonal renderer

The eqPly example is shipped with the Equalizer distribution and serves as a reference implementation of an Equalizer-based application of medium complexity. Its focus is not on rendering features or visual quality, but it is used as a show case for the integration of most of the Equalizer features.

In this section the source code of eqPly is discussed in detail, and relevant design decision and remarks are raised.

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 by windowing systems. Figure 5 shows the most important Equalizer classes and how they are subclassed in the eqPly example.

The derived classes fall into two categories: The subclassed rendering entities as discussed in Section 4.2, and two classes for distributing data. For each of the rendering entities, its function and typical usage will be discussed. The distributed data classes illustrate the typical usage of static and dynamic, frame-specific data.

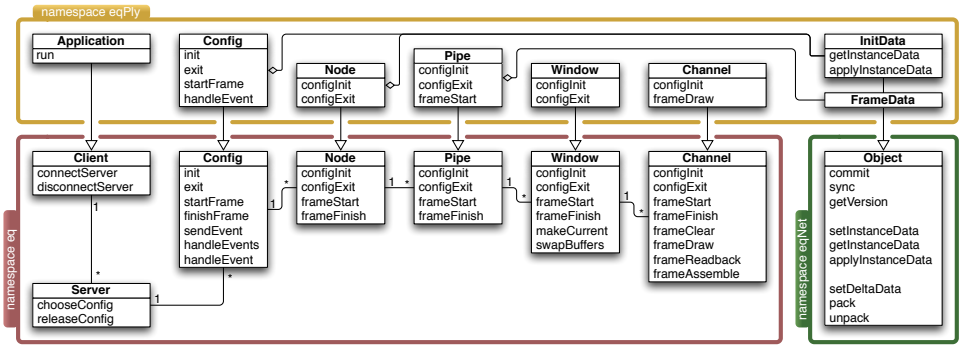


Figure 5: UML diagram of significant Equalizer and eqPly classes and task methods.

5.1 The main Function

The main function starts off with parsing the command line into the LocalInitData data structure, which in part will be distributed to all render client nodes. For actual command line parsing is done by the LocalInitData class and will be discussed there:

```
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[7], e.g., the default server location. Furthermore, a node factory 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;
    }
```

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

The node factory is used by Equalizer to create the object instances for the 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 a 'plain' Equalizer object, thus making it possible to selectively subclass individual entity types. For each rendering resource used in the configuration, one C++ object will be created:

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

The third step is to create an instance of the application and to initialize it locally. The application is an eq::Client, which is an eqNet::Node. The underlying network distribution in Equalizer is a peer-to-peer network structure of eqNet::Nodes. The application programmer rarely is aware of the classes in the eqNet namespace, but both the eq::Client and the server are eqNet::Nodes. The local initialization of nodes creates a local listening socket, so that the node, and therefore the eq::Client can 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;
    }
```

Finally everything is set up to run the eqPly application:

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

After it has finished, the application and Eqply is deinitialized and the main function returns:

```
    // 5. cleanup and exit
    client->exitLocal();
    client = 0;

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

5.2 Application

In the **eqPly** case, the application is also the render client. It has three run-time behaviours:

1. **Application**: The executable started by the user, which is 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.

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 and -r[8].

5.2.1 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 try first to connect to a server on the local machine using the default port 4242. If that fails, it will create a server running within the applications process with a default 1-channel configuration[9].

```
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 implementations to provide additional hints and information to the server for choosing a configuration. The configuration is created using NodeFactory::createConfig. Therefore it is of type eqPly::Config, but the return value is eq::Config, making q cast necessary:

```
    // 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 measures 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 does return after all nodes, pipes, windows and channels are initialized. It returns true only if all init task methods were successful. The EQLOG macro allows topic-specific logging. The numeric topic values are specified in the respective log.h header files:

```
    // 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;
```

[8] see http://www.equalizergraphics.com/documents/design/residentNodes.html
[9] see http://www.equalizergraphics.com/documents/design/standalone.html

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

When 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, were they are executed in the order they arrive.

Config::finishFrame synchronizes on the completion of the frame current - latency. The latency is specified in the configuration file, and allows several outstanding frames for which the tasks are already queued in the node and pipe threads for execution. This enables overlapped execution and minimizes idle times. The first latency Config::finishFrame return immediately, since they have no frame to synchronize upon. Figure 6 shows the execution of (hypothetical) rendering tasks without latency (Figure 6(a)) and with a latency of one (Figure 6(b)).

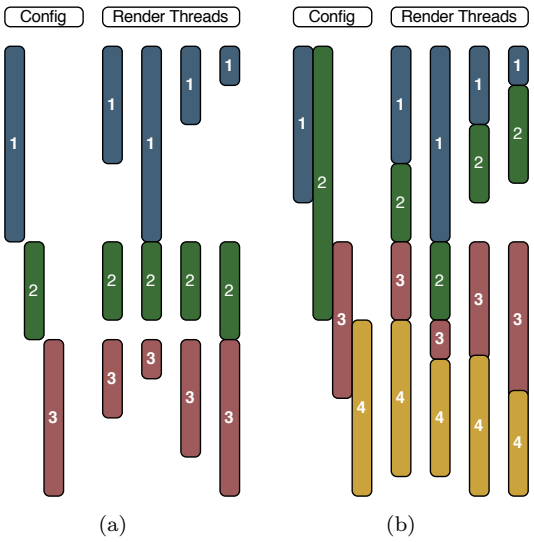


Figure 6: Synchronous and asynchronous execution

When the main loop is finished, Config::finishAllFrames catches up with the latency. It returns after all outstanding frames have been rendered, and is needed here 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 the 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;
}
```

5.2.2 Render Clients

In the second and third case, 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
        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;
}
```

5.3 Distributed Objects

Equalizer provides distributed objects which help implementing data distribution in a graphics cluster. 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 object.

Distributed object 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.

5.3.1 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.

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 can be outlayed 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 deserializing its data. The serialization is done in getInstanceData and deserialization in applyInstanceData by streaming all member variable to or from the provided data streams. The data transport between nodes is implemented in the data streams and various other Equalizer classes:

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

```
}

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

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

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

5.3.2 FrameData - a Versioned Distributed Object

Versioned objects have to override isStatic to return false, to indicate that they are versioned. The current implementation has the following characteristics:

- Only the master instance of the object is writable, that is, eqNet::Object::commit can be called 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.

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 needed to map an object, versioned objects may implement pack and unpack to serialize or deserialize 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 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, for the instance and delta date are the same and set in the constructor:

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

5.4 Config

The configuration is driving the applications 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.

5.4.1 Initialization and Exit

The config initialization happens in parallel, that is, all config initialization tasks are transmitted by the server at once and their execution is synchronized later.

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 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.

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.

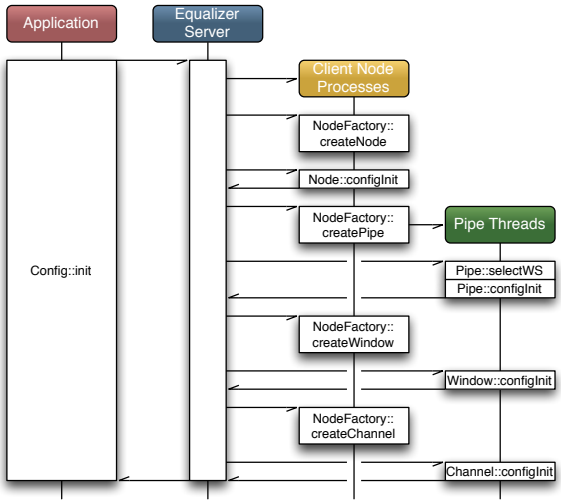


Figure 7: Config Initialization Sequence

The frame data is registered first, since its identifier is transmitted using the initialization data, which is registered afterwards. 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 device, as this is an orthogonal problem to parallel rendering, and has been solved already by a number of implementations[10]. The example code in eqPly is one reference implementation for the integration of such a tracking library:

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

            m = vmml::Matrix4f::IDENTITY;
            m.rotateZ( -M_PI_2 );
```

[10] VRCO Trackd, VRPN, etc.

```
            _tracker.setSensorToObject( m );
            EQLOG( eq::LOG_CUSTOM ) << "Tracker initialised" << endl;
        }
    }

    return true;
}
```

The exit of the configuration stops the render clients by calling eq::Config::exit, and then deregisters 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;
}
```

5.4.2 Frame Control

The rendering frames are issued by the application. The Config only overrides startFrame in order to update the 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 given to Equalizer, which uses the head matrix together with the wall or projection description to compute the view frustra[11].

The camera position is updated and the frame data is commited, which generates a new version. This version is passed to the rendering callbacks and will be used 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 );
}
```

5.4.3 Event Handling

Events are send 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.

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

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::WINDOW_CLOSE:
            _running = false;
            return true;

        [...]

        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 );
}
```

5.5 Node

Foreach 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 have only 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 initialization data is mapped to a local instance using the passed identifier 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 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();
}
```

5.5.1 Frame Control

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 entity unlock all its 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 execution within the thread.

Likewise, Config::finishFrame causes the invokation of the frameFinish task methods. These task methods unlock their parents by calling finishFrame.

The explicit synchronization of child or parent resources allows the application to optimize the processing, by doing certain, independent operations when the child or parent resources are already unlocked.

Figure 8 outlines the synchronization for the application, node and pipe classes. The window and channel synchronization is similar and omitted for simplicity. The eqPly example does not override Node::frameStart or frameFinish, but it is absolutely vital for the execution that Node::startFrame or Node::finishFrame are called, respectively. The default implementation of the node task methods does take care of that.

5.6 Pipe

All task methods for a pipe and its children are executed in a separate thread. This approach optimizes usage of the GPU resource, since all tasks are executed serially and do not compete for the usage, i.e., context switches are minimized.

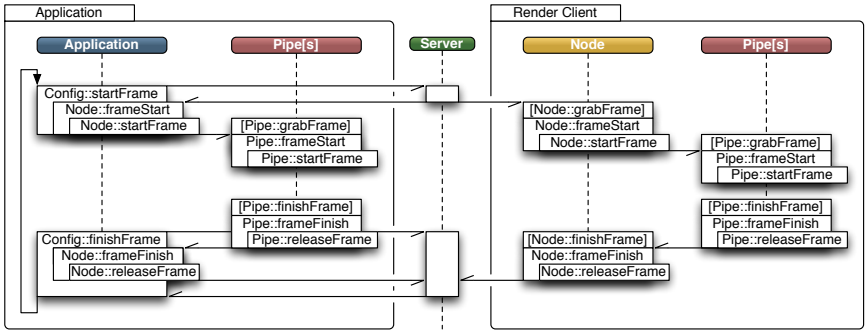


Figure 8: Synchronization of frame tasks

Later versions of Equalizer might introduce threaded windows to allow the parallel and independent execution of rendering tasks on a single pipe.

5.6.1 Initialization and Exit

Pipe threads are not explicitely synchronized with each other, that is, pipes might be rendering different frames at one 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 GPU-specific initialization, e.g., the display connection is opened when glX/X11 is used:

```
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 is again symmetric 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();
}
```

5.6.2 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[12].

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

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

selectWindowSystem loops over all window systems and returns the first supported window system, determined using supportsWindowSystem.

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

```
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();
    }

    return ws;
}
```

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[13]. Carbon call in the window event handling routine Window::processEvent are thread-safe. Please contact the Equalizer developer mailing list if you need to use Carbon calls on a per-frame basis.

5.6.3 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 )
{
    _frameData.sync( frameID );
    startFrame( frameNumber );
}
```

5.7 Window

The Equalizer window holds an OpenGL drawable and rendering context. Subclassed windows should maintain all data specific to the OpenGL context. The Equalizer window creation routines share the OpenGL context with the first window of the pipe, this allowing the reuse of OpenGL objects, e.g., display lists and textures.

[13] for various reasons enterCarbon might block up to 50 milliseconds

5.7.1 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 pipe's window system. The default implementations configInitGLX, configInitWGL or configInitAGL create an on-screen window using OS-specific methods. If the OpenGL drawable and context was 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 9 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 various frame buffer attachments (color, alpha, depth, stencil) as well as other framebuffer properties, such as quad-buffered stereo, doublebuffering, fullscreen mode and window decorations. Some of the attributes, such as stereo, doublebuffer and stencil can be set to eq::AUTO, in which case the default implementation tries to use them and gradually backs off upon failure.

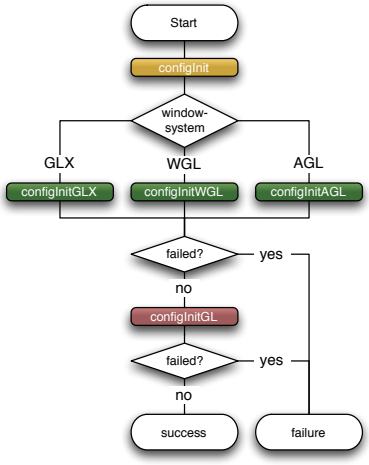


Figure 9: Window Initialization

The eqPly window initialization function first calls eq::Window::configInit to use the generic window setup. If that was successful, it initializes a state object and an overlay logo:

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

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

    EQASSERT( !_state );

    if( firstWindow == this )
    {
        _state = new VertexBufferState( getGLFunctions( ));
        _loadLogo();

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

        if( initData.useVBOs() )
        {
            const eq::GLFunctions* glFunctions = getGLFunctions();
            // Check if all VBO funcs available, else leave DISPLAY_LIST_MODE on
            if( glFunctions->hasGenBuffers() && glFunctions->hasBindBuffer() &&
                glFunctions->hasBufferData() && glFunctions->hasDeleteBuffers())
            {
                _state->setRenderMode( mesh::BUFFER_OBJECT_MODE );
                EQINFO << "VBO rendering enabled" << endl;
            }
            else
                EQWARN << "VBO function pointers missing, using display lists"
```

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

    if( !_state ) // happens if first window failed to initialize
        return false;

    return true;
}
```

The state object is used to handle the creation of OpenGL objects in a multi-pipe, multi-threaded execution environment. It uses an object manager, which is described in detail below. It is used in conjunction with a reference 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. The details of this code are omitted here, since they are pretty straight-forward and not Equalizer-specific.

The window exit deallocates all OpenGL objects if 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. In any case, 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();
}
```

5.7.2 Object Manager

The object manager is –strictly speaking– not part of the window. It is discussed here since the eqPly window uses an object manager.

The state object in eqPly gathers all rendering state, which includes an object manager for object state handling. This state object can easily be replaced to use the rendering code in a stand-alone application, e.g., for an GLUT-based renderer.

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, which normally spawns all contexts of a single GPU[14].

The OM is a template class. The template type is the key type, by which objects can be identified. The same key is used by all contexts to get the OpenGL name of an object. In eqPly, a key of type const void * is used. The rendering code uses the address of the data item to be rendered to obtain the associated OpenGL object.

The usage of objects is 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 is often the more convenient use case.

Currently handling for display lists, textures and buffers is implemented. For each object, the following functions are available:

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

supportsObjects() : returns true if the usage for this particular type of objects is supported. For basic objects, which are supported on all OpenGL implementations, 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.

5.8 Channel

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

5.8.1 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 to the current model position:

```
bool Channel::configInit( const uint32_t initID )
{
    setNearFar( 0.1f, 10.0f );
    return true;
}
```

5.8.2 Rendering

The central rendering routine is Channel::frameDraw. This routine contains the application's OpenGL rendering code, which is being rendered using the rendering context 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 should not write to the database, 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 seperation 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 : 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.

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.

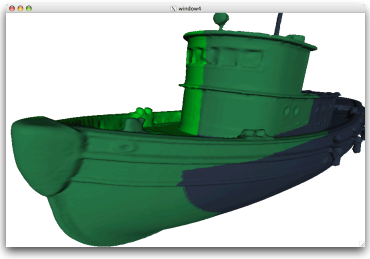


Figure 10: Destination view of an DB compound

Furthermore, a white color is set in case the model does not contain color information, or the color information is not to be used. In sort-last rendering, eqPly uses a different color for each channell to illustrate the database decomposition, as shown in Figure 10. 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 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. 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[15] 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, that is, 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.

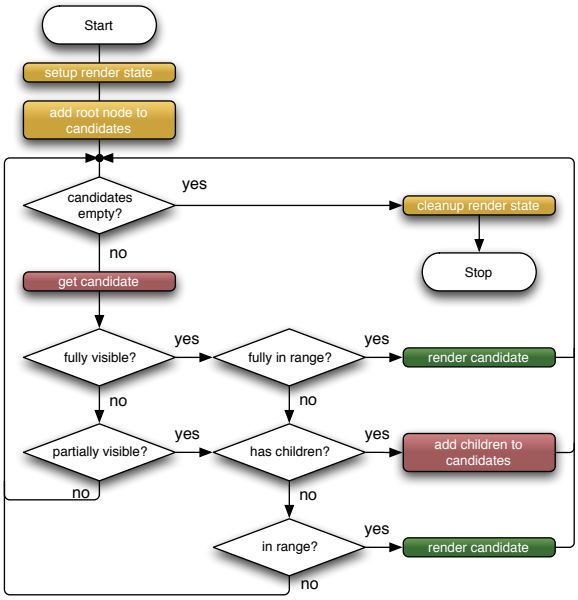


Figure 11: Main Rendering Loop

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

```
    model->beginRendering( state );

    // start with root node
    vector< const VertexBufferBase* > candidates;
```

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

```
    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 );
}
```

6 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.

6.1 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

OS-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 in any stage of the processing, to the extreme of making it possible to disable all event-related code in Equalizer. More information on event handling can be found on the Equalizer website[16].

The default implementation provides a convenient, easily accessible event framework, while allowing all necessary customizations. It gathers all events in the application main thread, 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.

6.1.1 Threading

Where possible, events are received and processed by a separate per-node event thread to allow asynchronous[17] event handling. Currently an event thread is only used by the X11/glX window system. WGL receives and processes the events from the pipe threads which created the windows. AGL receives the events from application or node main thread. Whenever the term **event thread** is used, it refers to the thread receiving the event, i.e., a per-node thread for glX, the pipe thread for WGL and the main thread for AGL.

6.1.2 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 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.

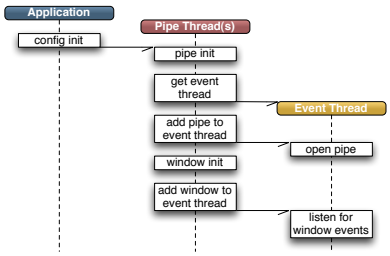


Figure 12: Event Handling Initialization

Pipe event handling is only used for glX, where one Display connection is created to subscribe to window events. 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. AGL and glX use an event handler singleton, whereas WGL uses one event handler per window.

6.1.3 Message Pump

For the WGL and AGL window system it is required to manually receive and dispatch ('pump') events. On WGL, this has to happen 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.

[16] see http://www.equalizergraphics.com/documents/design/eventHandling.html
[17] with respect to the rendering

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, e.g., Trolltech's Qt.

6.1.4 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 a format independent of the window system. 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, 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.

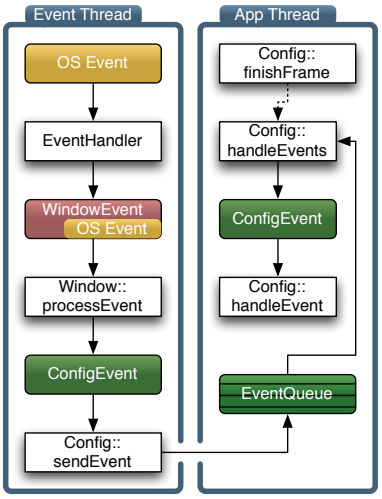


Figure 13: Event Processing

Events sent 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 this function, event-driven execution can be implemented.

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

6.1.5 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 a 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, by which the config processing function can identify it.

User-defined types start at eq::ConfigEvent::USER, and the member variable ConfigEvent::user can be used to store EQ_USER_EVENT_SIZE[18] 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 );
    }
}
```

6.2 Image Compositing for Scalable Rendering

Two task methods are responsible for collecting and compositing the result image during scalable rendering, when multiple channels are rendering for 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, if needed.

Normally the programmer does not need to interfere with the image compositing, or only 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.

6.2.1 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.

[18] currently 32 bytes

The motivation for 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 naive approach of compositing all frames on the destination channel, this channel quickly becomes the bottleneck in the system. Direct send distributes this workload evenly across all source channels, and thereby keeps the compositing work per channel constant.

In direct send compositing, each rendering channel is also responsible for the sort-last composition of one screen-space tile. 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 an 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.

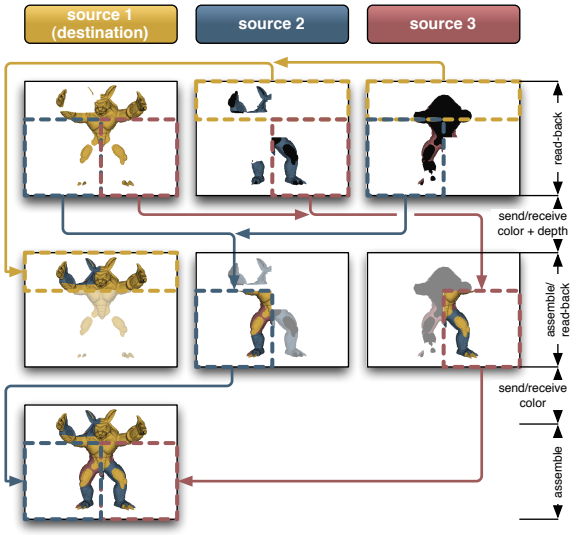


Figure 14: Parallel Direct Send Compositing

Figure 14 illustrates this algorithm for three channels. The Equalizer website contains a presentation for this algorithm[19].

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

- Selection of frame buffer attachments: color and/or depth
- 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.

6.2.2 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 and from the same compound tree will reference the same frame data.

The frame data is a holder for images and is used to signal the availability of the pixel data. An eq::Image holds a two-dimensional snapshot of the framebuffer and can contain color and/or depth information.

The frame data transports the inherited range of its compound. The range is needed to compute the assembly order of multiple input frames, e.g., for sorted-blend compositing in volume rendering applications.

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

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.

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.

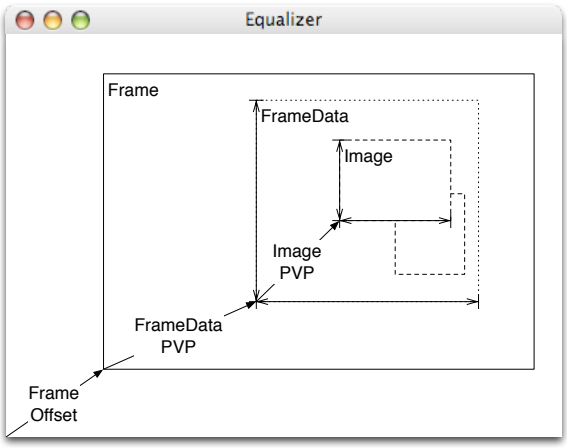


Figure 15: Hierarchy of assembly classes

For output frames, the frame data's pixel viewport (pvp) 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 pvp 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 read back. Currently this pvp has no offset and is as big as the frame data pvp. Only one image will be read back.

Figure 15 illustrates the relationship between frames, frame data and images.

6.2.3 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 16[20].

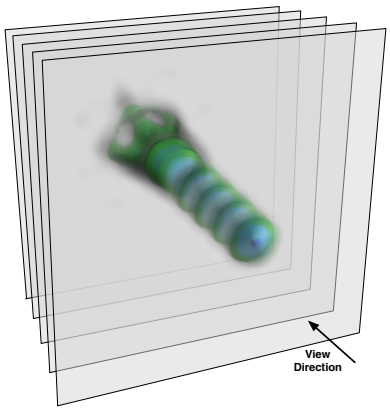


Figure 16: Blending Slices in 3D-Texture-based Volume Rendering

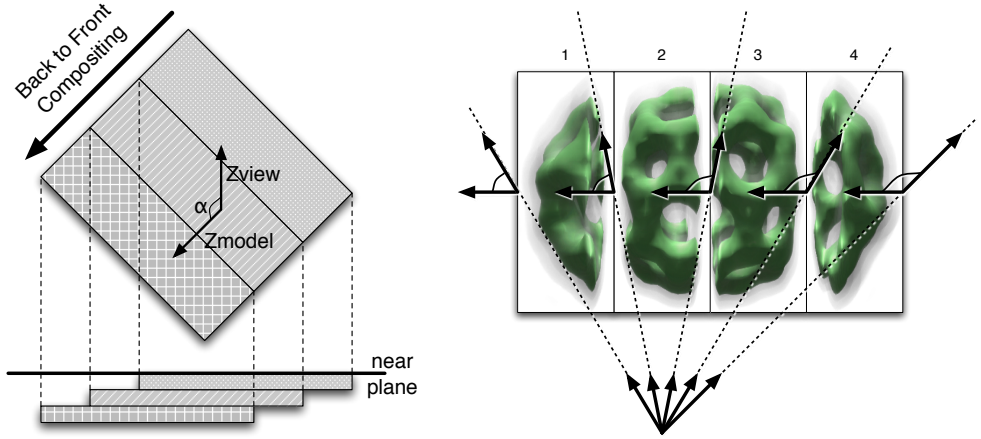
When using 2D (sort-first) or stereo decompositions, no special programming is needed to achieve good scalability, as eVolve is mostly fill-limited and therefore scales nicely in this mode.

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 the same as in the other modes. For recomposition, the RGBA frame buffer data resulting from these render passes then has to be assembled correctly.

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

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

channel) and IO bandwidth for time-dependend data (less data per time step and channel).



(a) (b)

Figure 17: Back-to-Front Compositing for Orthogonal and Perspective View Frustra

For recomposition, the 2D frame buffer contents are blended together to form a seamless picture. For currect blending, the frames are ordered in the same back-to-front order as the slices used for rendering using the same blending parameters. Simplified, the frame buffer images are 'thick' slices which are 'rendered' by writing their content to the destination frame buffer using the correct order.

For orthographic rendering, determining the compositing order of the input frames is trivial. The screen-space orientation of the volume bricks determines the order in which they have to be composited. The bricks in eVolve are created by slicing the volume along one dimension. Therefore the range of the resulting frame buffer images, together with the sorting order, is used to arrange the frames during compositing. Figure 17(a) shows this composition for one view.

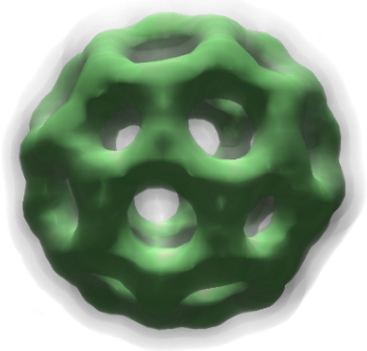


Figure 18: Result of Figure 17(b)

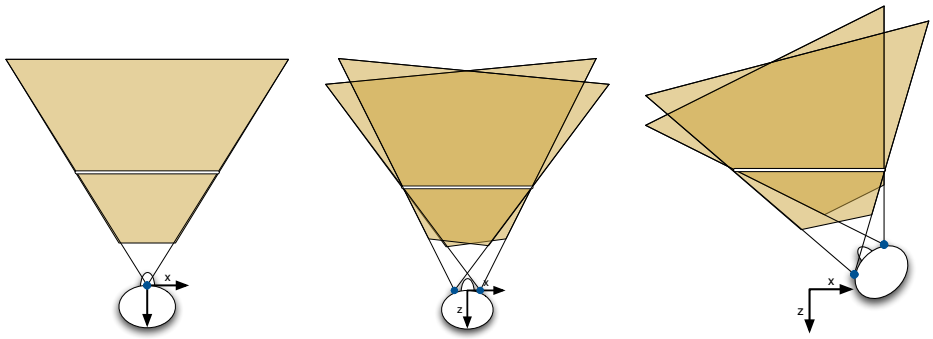
Finding the correct assembly order for a perspective frustra is more complex. The perspective distortion invalidates a simple orientation criteria like the one used for orthographic frustra. For the view and frustum setup shown in Figure 17(b)[21] the correct compositing order is 4-3-1-2 or 1-4-3-2. In order to compute the assembly order, eVolve uses the angle between the origin→slice vector and the near plane, as shown in Figure 17(b). The result image naturally looks the same as the volume rendering would when rendered n a singly channel, as shown in Figure 18.

6.3 Head Tracking

The eqPly example contains rudimentary support for head tracking, in order to show how head tracking can be integrated with Equalizer. Supporting a wide range of tracking devices is not within the scope of Equalizer. Other open source and

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

commercial implementations cover this functionality sufficiently and can easily be integrated with Equalizer.



(a) (b) (c)

Figure 19: Monoscopic, Stereoscopic and Tracked frustra

Figure 19(a) illustrates a monoscopic view frustum. The viewer is positioned at the origin, 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 19(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 19(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.