

Virtual Reality Application Programming with QVR

Computer Graphics and
Multimedia Systems Group

University of Siegen

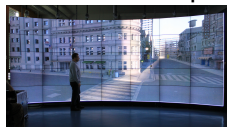
March 24, 2025



- **Challenges for VR frameworks**
- **Solutions for Multi-GPU / Multi-Host VR**
- **QVR Overview and Concepts**
- **QVR Application Interface**
- **QVR Configuration and Management**
- **QVR Example Application**
- **QVR Outlook**

Challenges

- VR applications run on a wide variety of graphics and display hardware setups:



- In general, a VR application must handle

- Multiple hosts (for render clusters)
- Multiple GPUs on a host
- Multiple displays devices attached to a GPU

whereas typical non-VR graphics applications only handle

- A single display device attached to a single GPU on a single host

VR frameworks

	Multi-GPU & Cluster	Vive, Oculus	Google VR	Allows own renderer	Li-cense	Remarks
Avocado	✓	✗	✗	✗	—	Dead
VRJuggler	✓	✗	✗	?	LGPL	Smelling funny
OpenSG	✓	✗	✗	✗	LGPL	Fraunhofer
ViSTA	✓	✗	✗	(✗)	LGPL	RWTH AC & DLR
Equalizer	✓	(✗)	✗	✓	LGPL	More than VR!
Unreal Eng.	(✗)	✓	✓	✗	Propr.	Epic Games
Unity Eng.	✗	✓	✓	✗	Propr.	Unity Tech.
QVR	✓	✓	(✓)	✓	MIT	

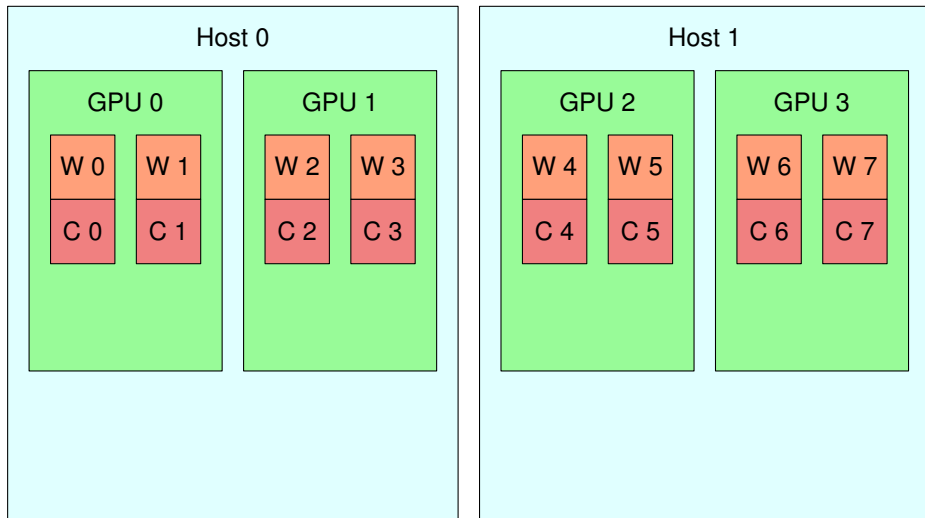
Typical non-VR graphics application



- The application uses a toolkit to create a window
- The toolkit creates an OpenGL context automatically and “makes it current”
- The application never needs to care about the context
 - There is only one context
 - The context is always current

Challenges for VR frameworks

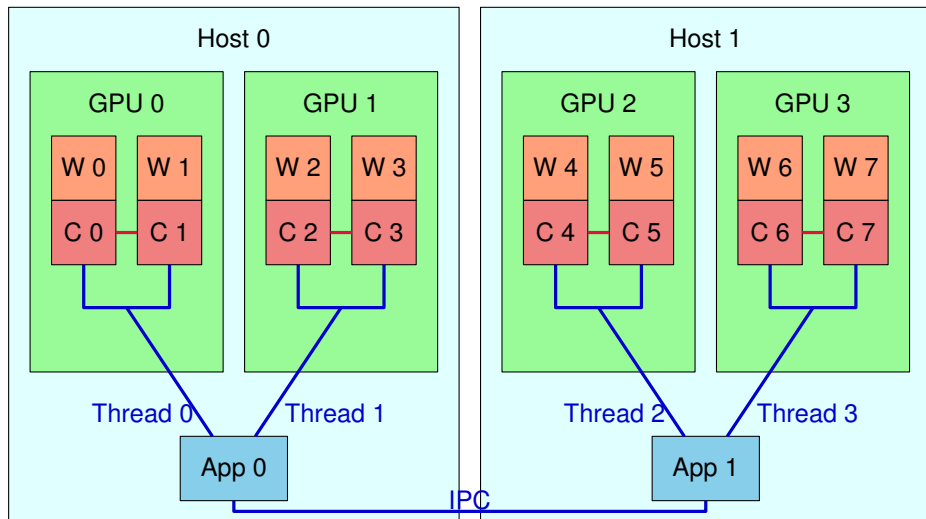
VR application using multiple hosts, GPUs, and displays



Challenges: OpenGL contexts and threading

- OpenGL contexts on the same GPU can *share* objects such as textures.
 - Only one context should manage OpenGL objects.
- A context can only be current in one thread at a time, and a switch of that thread is expensive.
 - All rendering to a context should happen from only one thread.
- Access to a single GPU is serialized by the driver.
 - Rendering into different contexts on the same GPU should be serialized to avoid context switches.
- The function that triggers swapping of back and front buffers blocks until the swap happened, and the swap is typically synchronized to the display frame rate.
 - The thread in which the context is current is often blocked.

Multi-Context Multi-Thread Approach



Multi-Context Multi-Thread Approach

- One process per host
- One context per window
- One thread per GPU
 - Contexts driven by thread share objects
 - Window views driven by thread are rendered sequentially
- An application process must be aware of
 - Multiple rendering threads
 - Multiple contexts that may or may not be sharing objects
- Interprocess communication:
 - Only between hosts

Single-Context Single-Thread Approach



Single-Context Single-Thread Approach

- One process per GPU
- One context per process (plus one hidden context per window)
- One thread per process (main thread)
 - Context sharing irrelevant to application
 - Window views are rendered sequentially
- An application process must be aware of
 - Only one thread (rendering threads are hidden)
 - Only one context (window contexts are hidden)
- Interprocess communication:
 - Between hosts
 - Between processes on same host if multiple GPUs are used

The QVR framework

- Implements the single-context single-thread approach for multi-GPU / multi-host support
- Based on Qt (requires nothing else)
- Manages four major types of objects:
 - *Devices* used for interaction, e.g. game controllers
 - *Observers* that view the virtual scene
 - *Windows* that provide views of the virtual scene
 - *Processes* that run on hosts and manage windows
- A VR application implements a simple interface:
 - *render()* to render a view of the scene into a texture
 - *update()* for interactions, animations, and other scene updates
 - Optional: one-time or per-frame actions per process or window
 - Optional: device/keyboard/mouse event handling
 - Optional: serialization, for multi-process support
- Applications run unmodified on different setups

Functionality

- Handles tracking
Glasses / HMDs,
Controllers, ...
- Handles input
Controller buttons /
joysticks, mouse /
keyboard
- Handles output
Puts left/right view
onto screen(s) as
appropriate

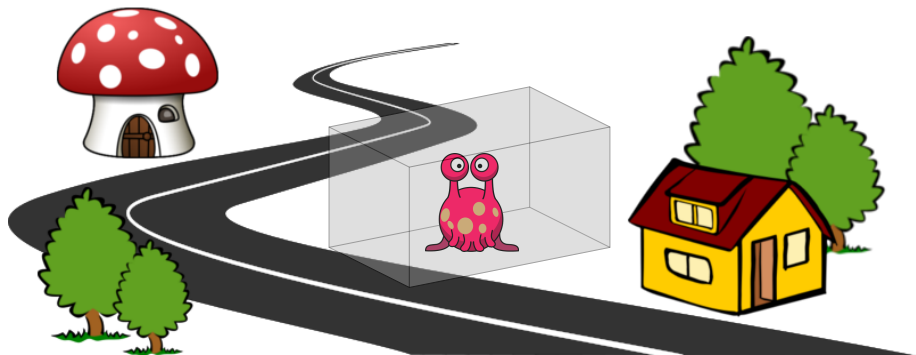
Application View

- Implements QVRApp
`render()`, `update()`,
...
- Can access
QVRDevice,
QVRObserver,
QVRWindow,
QVRProcess
- Does not need to
care about
VR hardware,
Multi-GPU, threads,
OpenGL contexts, ...

VR System View

- Configuration
describes
available VR
hardware
- Autodetected or
manually
configured
- Configuration
classes
`QVRDeviceConfig`,
`QVRObserverConfig`,
`QVRWindowConfig`,
`QVRProcessConfig`

Illustration



- You are an alien
- Your UFO is a transparent box
- You fly your UFO through a strange world
- You can move freely inside your UFO

Illustration

- The alien views the world through the sides of his UFO.
- The alien flies its UFO through the world.
- The alien moves inside its UFO.

QVR

- An *observer* views the virtual world in *windows*; each *window* provides a view for one *observer*.
- An observer *navigates* through the virtual world.
- An observer's movements are *tracked* inside a tracking space.

Devices (in illustration: for example the UFO remote control)

- Optional: can be tracked inside a tracking space
- Optional: provides buttons and other interaction controls
- Examples:
 - Tracked glasses
 - Traditional game controller
 - HTC Vive controllers
 - ART Flystick
- Configured through [QVRDeviceConfig](#)
 - Tracking
 - Type and parameters (e.g. based on VRPN, Oculus Rift)
 - Initial position and orientation
 - Digital buttons
 - Analog elements (triggers, joysticks, trackpads)
- Implemented as [QVRDevice](#)
 - Tracking: position and orientation
 - State of buttons and analogs
 - Accessible to the update() function for interaction

Observer (in illustration: the alien)

- Views the virtual world through one or more windows
- Can navigate through the virtual world
- Can be bound to tracked devices, e.g. glasses
- Configured through [QVRObserverConfig](#)
 - Navigation
 - Type and parameters (e.g. based on QVR device interaction)
 - Initial position and orientation
 - Tracking
 - Type and parameters (e.g. based on specific devices)
 - Initial position and orientation
 - Eye distance
- Implemented as [QVRObserver](#)
 - Navigation: position and orientation
 - Tracking: position and orientation *for each eye*

Window (in illustration: a side of the box-shaped UFO)

- Provides a view of the virtual world for exactly one observer
- Configured through [QVRWindowConfig](#)
 - Observer to provide a view for
 - Output mode (left/right/stereo view) and parameters
 - Geometry in pixels
 - 3D geometry in the virtual world (if the window corresponds to a physical screen wall)
- Implemented as [QVRWindow](#)
 - Accessible as QWindow for the application, if required
 - Hides its context and rendering thread

Process

- Provides one OpenGL context to the application
- Drives zero or more windows
- Runs one instance of the VR application
- First process is main process; child processes are started automatically when needed
- Configured through [QVRProcessConfig](#)
 - GPU to use (system specific)
 - Launcher command (e.g. for network processes)
 - List of window configurations
- Implemented as [QVRProcess](#)
 - Accessible as QProcess for the application, if required
 - Hides communication between main and child processes

Application

- Interface specified in the `QVRApp` class
- All functions except `render()` are optional to implement; the empty default implementation is sufficient
- `void render(QVRWindow* w, const QVRRenderContext& context, const unsigned int* textures)`
 - Called once per window per frame
 - Renders one (mono) or two (stereo 3D) views for window `w` into textures
 - The `context` contains all necessary information for the view(s)

Application: render()

```
void render(QVRWindow* w, const QVRRenderContext& context,
           const unsigned int* textures) {
    for (int view = 0; view < context.viewCount(); view++) {
        // Get view dimensions
        int width = context.textureSize(view).width();
        int height = context.textureSize(view).height();
        // Set up framebuffer object to render into texture
        setupFBO(textures[view]);
        // Set up view
        glViewport(0, 0, width, height);
        glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
        QMatrix4x4 P = context.frustum(view).toMatrix4x4();
        QMatrix4x4 V = context.viewMatrix(view);
        // Render
        ...;
    }
}
```

Application (continued)

- `void update(const QList<QVRObserver*>& observers)`
 - Called once before each frame *on the main process*
 - Updates scene state, e.g. for animations
 - May update observers, e.g. for navigation
 - May use QVR devices for interaction
- `bool wantExit()`
 - Called once before each frame *on the main process*
 - Signals if the application wants to exit
- Optional: `void getNearFar(float& near, float& far)`
 - Called once before each frame *on the main process*
 - Sets the preferred near and far clipping plane

Application (continued)

- Optional: process and window initialization
 - `bool initProcess(QVRProcess* p)`
 - `void exitProcess(QVRProcess* p)`
 - `bool initWindow(QVRWindow* w)`
 - `void exitWindow(QVRWindow* w)`
- Optional: per-frame process and window actions
 - `void preRenderProcess(QVRProcess* p)`
 - `void postRenderProcess(QVRProcess* p)`
 - `void preRenderWindow(QVRWindow* w)`
 - `void postRenderWindow(QVRWindow* w)`

Application (continued)

- Optional: serialization for multi-process / multi-GPU support
 - Data that changes between frames
 - `void serializeDynamicData(QDataStream& ds) const`
 - `void deserializeDynamicData(QDataStream& ds)`
 - Data that is initialized once and remains constant
 - `void serializeStaticData(QDataStream& ds) const`
 - `void deserializeStaticData(QDataStream& ds)`
- Optional: Qt-style event handling for QVR devices, mouse, and keyboard
 - `deviceButtonPressEvent()`, `deviceButtonReleaseEvent()`, `deviceAnalogChangeEvent()`, `keyPressEvent()`, `keyReleaseEvent()`, `mouseMoveEvent()`, `mousePressEvent()`, `mouseReleaseEvent()`, `mouseDoubleClickEvent()`, `wheelEvent()`
 - All keyboard / mouse functions get the Qt event *and the QVRRenderContext from which it came*

Render context

- Implemented as [QVRRenderContext](#)
- Relevant for rendering and event interpretation
- Provides:
 - Process index, window index
 - Qt window and screen geometry
 - Navigation pose
 - Window screen wall coordinates (virtual world)
 - Window output mode and required views
 - Per view:
 - Eye corresponding to this view pass (left/right/center)
 - Tracking pose
 - View frustum / projection matrix
 - View matrix

Configuration

- Accessible by application:
 - A list of QVRDeviceConfig instances
 - A list of QVRObserverConfig instances
 - A list of QVRProcessConfig instances
 - A list of QVRWindowConfig instances
- Configuration file:
Corresponds 1:1 to QVR*Config classes
 - List of device definitions
 - List of observer definitions
 - List of process definitions
 - List of window definitions
- Completely defines VR setup
- Application runs unmodified on different setups using different configuration files

Example configuration: one window on a desktop computer

```
observer my-observer
  navigation wasdqe
  tracking custom

process main
  window my-window
    observer my-observer
    output red_cyan
    position 800 100
    size 400 400
    screen_is_fixed_to_observer true
    screen_is_given_by_center true
    screen_center 0 0 -1
```

Example configuration: Oculus Rift

```
device oculus-head
    tracking oculus head
device oculus-eye-left
    tracking oculus eye-left
device oculus-eye-right
    tracking oculus eye-right

observer oculus-observer
    navigation wasdqe
    tracking device oculus-eye-left oculus-eye-right

process oculus-process
    window oculus-window
        observer oculus-observer
        output oculus
```

Example configuration: four-sided CAVE, one GPU per side

```
device glasses
    tracking vrpn DTrack@localhost 0

device flystick
    tracking vrpn DTrack@localhost 1
    buttons  vrpn DTrack@localhost 4 1 3 2 0
    analogs  vrpn DTrack@localhost 1 0

observer cave-observer
    navigation device flystick
    tracking device glasses
```

Example configuration: four-sided CAVE, one GPU per side
(continued)

```
process main-gpu0
    window back-side
        observer cave-observer
        output stereo
        fullscreen true
        screen_is_fixed_to_observer false
        screen_is_given_by_center false
        screen_wall -1 0 -2 +1 0 -2 -1 2 -2
process child-gpu1
    window left-side
        observer cave-observer
        output stereo
        fullscreen true
        screen_is_fixed_to_observer false
        screen_is_given_by_center false
        screen_wall -1 0 0 -1 0 -2 -1 2 0
```

Example configuration: four-sided CAVE, one GPU per side
(continued)

```
process child-gpu2
    window right-side
        observer cave-observer
        output stereo
        fullscreen true
        screen_is_fixed_to_observer false
        screen_is_given_by_center false
        screen_wall 1 0 -2 1 0 0 1 2 -2
process child-gpu3
    window bottom-side
        observer cave-observer
        output stereo
        fullscreen true
        screen_is_fixed_to_observer false
        screen_is_given_by_center false
        screen_wall -1 0 0 +1 0 0 -1 0 -2
```

Manager

- Singleton, implemented as [QVRManager](#)
- Initialized in `main()`, similar to `QApplication`
- Reads (or creates) configuration
- Creates devices, observers, processes, windows

```
int main(int argc, char* argv[])
{
    QApplication app(argc, argv);
    QVRManager manager(argc, argv);

    MyQVRApp qvrapp;
    if (!manager.init(&qvrapp)) {
        qCritical("Cannot initialize QVR manager");
        return 1;
    }
    return app.exec();
}
```


Command line options (only the most important)

- `--qvr-config=<config.qvr>`
Specify a QVR configuration file.
- `--qvr-log-level=<level>`
Set a log level (fatal, warning, info, debug, firehose).

Putting it all together: [a minimal example program](#)

- The virtual scene is a rotating cube with 2m edge length, centered at (0,0,-15)
- The scene is rendered using modern OpenGL
- We let QVR handle navigation and tracking
- We want to exit when the user hits ESC
- We want multi-process support

Putting it all together: [a minimal example program](#)

- Which functions do we need to implement?
 - To initialize OpenGL objects and state: `initProcess()`
 - Always required: `render()`
 - For animated rotation: `update()`
 - To signal that we want to exit: `wantExit()`
 - To receive the ESC key: `keyPressEvent()`
 - For multi-process support: `serializeDynamicData()` and `deserializeDynamicData()`

Putting it all together: [a minimal example program](#)

- To initialize OpenGL objects and state: `initProcess()`

```
bool QVRMinimalExample::initProcess(QVRProcess* /* p */) {
    initializeOpenGLFunctions();
    glGenFramebuffers(1, &_fbo);
    glGenTextures(1, &_fboDepthTex);
    // setup _fbo and _fboDepthTex
    glGenVertexArrays(1, &_vao);
    glBindVertexArray(_vao);
    // upload vertex data to buffers and setup VAO
    _vaoIndices = 36;
    _prg.addShaderFromSourceFile(QOpenGLShader::Vertex,
        ":vertex-shader.glsl");
    _prg.addShaderFromSourceFile(QOpenGLShader::Fragment,
        ":fragment-shader.glsl");
    _prg.link();
    return true;
}
```

Putting it all together: [a minimal example program](#)

- Always required: `render()`

```
void QVRExampleOpenGLMinimal::render(QVRWindow* /* w */,
    const QVRRenderContext& context,
    const unsigned int* textures) {
    for (int view = 0; view < context.viewCount(); view++) {
        // Get view dimensions
        int width = context.textureSize(view).width();
        int height = context.textureSize(view).height();
        // Set up framebuffer object to render into
        glBindTexture(GL_TEXTURE_2D, _fboDepthTex);
        glTexImage2D(GL_TEXTURE_2D, 0, GL_DEPTH_COMPONENT, width,
            height, 0, GL_DEPTH_COMPONENT, GL_FLOAT, NULL);
        glBindFramebuffer(GL_FRAMEBUFFER, _fbo);
        glFramebufferTexture2D(GL_FRAMEBUFFER, GL_COLOR_
            ATTACHMENT0, GL_TEXTURE_2D, textures[view], 0);
        glViewport(0, 0, width, height);
        glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
```

Putting it all together: [a minimal example program](#)

- Always required: `render()` (continued)

```
QMatrix4x4 P = context.frustum(view).toMatrix4x4();
QMatrix4x4 V = context.viewMatrix(view);
// Set up shader program
glUseProgram(_prg.programId());
_prg.setUniformValue("projection_matrix", P);
// Render
QMatrix4x4 M;
M.translate(0.0f, 0.0f, -15.0f);
M.rotate(_rotationAngle, 1.0f, 0.5f, 0.0f);
QMatrix4x4 MV = V * M;
_prg.setUniformValue("modelview_matrix", MV);
_prg.setUniformValue("normal_matrix", MV.normalMatrix());
glBindVertexArray(_vao);
glDrawElements(GL_TRIANGLES, _vaoInd, GL_UNSIGNED_INT, 0);
}
}
```

Putting it all together: [a minimal example program](#)

- For animated rotation: `update()`

```
void QVRMinimalExample::update(const QList<const QVRDevice*>& devices,
    const QList<QVRObserver*>& customObservers) {
    float seconds = _timer.elapsed() / 1000.0f;
    _rotationAngle = seconds * 20.0f;
}
```

- To signal that we want to exit: `wantExit()`
- To receive the ESC key: `keyPressEvent()`

```
bool QVRMinimalExample::wantExit() { return _wantExit; }
void QVRMinimalExample::keyPressEvent(
    const QVRRenderContext& /* context */,
    QKeyEvent* event) {
    if (event->key() == Qt::Key_Escape)
        _wantExit = true;
}
```

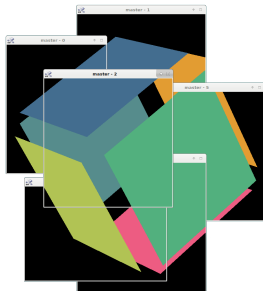
Putting it all together: [a minimal example program](#)

- For multi-process support: `serializeDynamicData()` and `deserializeDynamicData()`

```
void QVRMinimalExample::serializeDynamicData(  
    QDataStream& ds) const {  
    ds << _rotationAngle;  
}  
  
void QVRMinimalExample::deserializeDynamicData(  
    QDataStream& ds) {  
    ds >> _rotationAngle;  
}
```


QVR Example Application

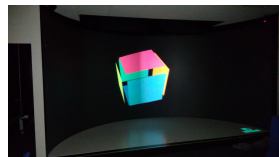
Putting it all together: [a minimal example program](#)



Desktop Test



Oculus Rift



VR Lab

What else is there?

- Support for VR hardware:
 - HTC Vive via OpenVR
 - Oculus Rift via Oculus SDK
 - Google Cardboard and Daydream via Google VR NDK
 - Tracking / interaction devices via VRPN
- Output plugins for arbitrary postprocessing of views
 - Edge blending, warping, color correction for multi-projector setups
 - Special stereo output modes not covered by QVR
- Example programs
 - [qvr-example-opengl-minimal](#): rotating cube
 - [qvr-example-opengl](#): simple demo scene with ground floor
 - [qvr-example-openscenegraph](#): full-featured [OSG](#) viewer
 - [qvr-example-vtk](#): [VTK](#) visualization pipeline
 - [qvr-sceneviewer](#): viewer for many 3D model and scene files
 - [qvr-videoplayer](#): a video screen for 2D and 3D videos
 - [qvr-vncviewer](#): [VNC](#) viewer (display remote desktops)

How do I get it?

- Go to <https://marlam.de/qvr>
- Download the latest version
- Unpack
- Make sure you have Qt
- Build *and install* `libqvr` first
- Build the examples and link against the *installed* `libqvr`