OCULUS VR, LLC

Oculus Developer Guide

SDK Version 0.4

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Irvine CA

Contents

1 Introduction

Thanks for downloading the Oculus Software Development Kit (SDK)!

This document describes how to install, configure, and use the Oculus SDK. The core of the SDK is made up of source code and binary libraries. The Oculus SDK also includes documentation, samples, and tools to help developers get started.

As of Oculus SDK version 0.4, we also now have the Oculus Runtime package which is discussed in more detail in the following section. This must be installed for applications built against the SDK to function. The package is available from developer.oculusvr.com.

This document focuses on the C/C++ API of the Oculus SDK. Integration with the Unreal Engine (UE3/UE4) and Unity game engine is available as follows:

- Unity integration is available as a separate package from developer.oculusvr.com.
- Unreal Engine 3 & 4 integrations are also available as a separate package from the Oculus Developer Center. You will need a full UE3 or UE4 license to access the version of Unreal with Oculus integration. If you have a full UE3 or UE4 license, you can email support@oculusvr.com to be granted download access.

2 Introducing DK2 and SDK 0.4

We're proud to begin shipping the second Oculus Rift Development Kit DK2. The Oculus SDK 0.4 adds support for DK2 whilst enhancing the support for DK1. The DK2 headset incorporates a number of significant improvements over DK1:

- **Higher Resolution and Refresh Rate** Resolution has been increased to 1920x1080 (960x1080 per eye) and the maximum refresh rate to 75Hz.
- **Low Persistence OLED Display** Eliminates motion blur and judder, significantly improving image quality and reducing simulator sickness.
- **Positional Tracking** Precise low latency positional tracking means that all head motion is now fully tracked.
- **Built-in Latency Tester** Constantly measures system latency to optimize motion prediction and reduce perceived latency.

In addition to the substantial hardware improvements, the SDK and runtime software stack have also undergone significant improvements. The prior Oculus SDK preview release 0.3.2 introduced developers to some of the changes being made, however 0.4 includes additional modifications to the API as well as some new software components. The changes compared to the last main release (0.2.5) are outlined below:

- All of the HMD and sensor interfaces have been organized into a C API. This makes it easy to bind from other languages.

- The new Oculus API introduces two distinct approaches to rendering distortion: *SDK Rendered* and *Client Rendered*. As before, the application is expected to render stereo scenes onto one or more render targets. With the SDK rendered approach, the Oculus SDK then takes care of distortion rendering, frame present, and timing within the SDK. This means that developers don't need to setup pixel and vertex shaders or worry about the details of distortion rendering, they simply provide the device and texture pointers to the SDK. In client rendered mode, distortion rendering is handled by the application as with previous versions of the SDK. SDK Rendering is the preferred approach for future versions of the SDK.
- The method of rendering distortion in client rendered mode is now mesh based. The SDK returns a mesh which includes vertices and UV coordinates which are then used to warp the source render target image to the final buffer. Mesh based distortion is more efficient and flexible than pixel shader approaches.
- The Oculus SDK now keeps track of game frame timing and uses this information to accurately predict orientation and motion.
- A new technique called *Timewarp* is introduced to reduce motion-to-photon latency. This technique re-projects the scene based on more recent sensor data during the distortion rendering phase.

The new software components that are being introduced in Oculus SDK 0.4 are:

- **Camera Device Driver** In order to support the machine vision based position tracking, we've developed a custom low latency camera driver.
- **Display Driver** This custom developed driver significantly improves the user experience with regard to managing the Oculus Rift display. The Oculus Rift is now handled as a special display device that VR applications using the Oculus SDK will automatically render to. The user no longer sees the Rift Display as a monitor device, and so avoids the complications of setting it up as part of the PC desktop. To preserve compatibility with applications built against older versions of the SDK, the driver currently features an option for reverting back to the old mode of operation.
- **Service Application** A runtime component which runs as a background service is introduced. This provides several improvements including simplifying device plug/unplug logic, allowing sensor fusion to maintain an estimate of headset orientation for improved start-up performance, and enabling sensor calibration to occur when the headset is not in use. When no VR applications are running, the service consumes a minimal amount of CPU resources (currently less than 0.5% of total CPU on an Intel i7-3820).
- **System Tray Icon** The Oculus System Tray Icon provides access to a control panel for the Oculus Rift. Currently this features a dialog for configuring display driver modes, and a dialog for adding and configuring user profiles which replaces the standalone Oculus Configuration Utility that shipped with previous versions of the Oculus SDK.

The introduction of the Display Driver leads to a more natural handling of the Oculus Rift display, however if you've been working with the Rift for some time, you may be initially surprised by the change in behavior. Most notably, when in the default display mode, the Rift will no longer appear as a new display in the operating system's display configuration panel.

The software components described above are distributed as part of the Oculus Runtime which is a separate download than the Oculus SDK. The latest version of both packages is available at developer.oculusvr.com.

3 Oculus Rift Hardware Setup

3.1 Oculus Rift DK1

Figure 1: The Oculus Rift DK1.

Instructions for setting up DK1 hardware are provided in the *Oculus Rift Development Kit* manual that shipped with the device. Additional instructions are provided in the *Oculus User Guide* which is available at developer.oculusvr.com.

3.2 Oculus Rift DK2

Figure 2: The Oculus Rift DK2.

Instructions for setting up DK2 hardware are provided in the *Development Kit 2 - Quick Start Guide* that shipped with the device. Additional instructions are provided in the *Oculus User Guide* which is part of the Oculus Runtime Package and is available at developer.oculusvr.com.

The main differences when setting up the hardware are that DK2 no longer has the external Control Box, but it does include a camera for position tracking. The camera plugs into one of the USB ports on the computer. It is also necessary to plug a sync cable between the camera and the Cable Connector box found near the end of the main Headset cable.

The camera features an indicator light on the front which is turned off when the camera is not in use, and on

when the device is being used and is correctly receiving sync signals from the headset.

3.3 Monitor Setup

Previously when the Rift was connected to your computer it would be automatically recognized and managed as an additional monitor. With the introduction of the Oculus Display Driver this is no longer necessary, however the Rift Display Mode control panel can still be used to revert back to this mode by selecting the *Extend Desktop* or *DK1 Legacy App Support* modes. The display mode control panel is accessed through the Oculus System Tray Icon.

When the Rift is operating in the *Extend Desktop* legacy mode, in which it appears as an additional monitor, care should be taken to make sure it is configured properly within the Operating System display settings. Oculus DK1 can be set to either mirror or extend your current desktop monitor setup, while with DK2 OS mirroring may not possible. We recommend using the Rift as an extended monitor in most cases, but it's up to you to decide which configuration works best for you. This is covered in more detail in Appendix A.

When configuring the Rift as a display, for DK1 you should set the resolution to 1280×800. For DK2 the resolution should be set to 1920×1080 (may appear as 1080×1920) and it may be necessary to manually adjust the orientation of the display such that it is horizontal. Figure 3 shows the DK2 correctly configured in extended display mode in Windows.

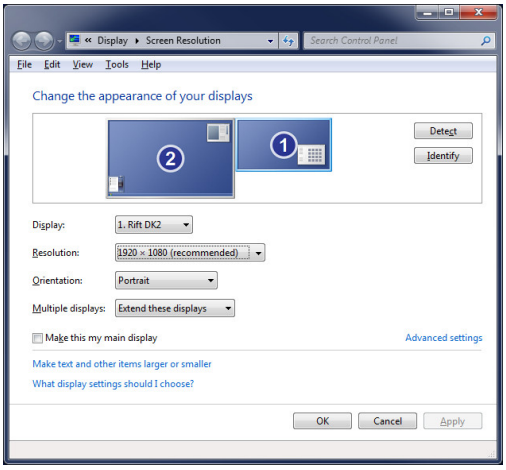


Figure 3: Windows display configuration for DK2.

4 Oculus Rift SDK Setup

4.1 System Requirements

4.1.1 Operating systems

The Oculus SDK 0.4.0 currently supports Windows 7, 8 and 8.1 and MacOS (10.8, 10.9). Linux coming soon.

4.1.2 Minimum system requirements

There are no specific computer hardware requirements for the Oculus SDK, however we recommend that developers use a computer with a modern graphics card. A good benchmark is to try running Unreal Engine 3 and Unity at 60 frames per second (FPS) with vertical sync and stereo 3D enabled. If this is possible without dropping frames, then your configuration should be sufficient for Oculus Rift development.

The following components are provided as a guideline:

- Windows: 7, 8, or 8.1
- MacOS: 10.8+
- Linux: Ubuntu 12.04 LTS
- 2.0+ GHz processor
- 2 GB system RAM
- Direct3D10 or OpenGL 3 compatible video card.

Although many lower end and mobile video cards, such as the Intel HD 5000, have the graphics capabilities to run minimal Rift demos, their rendering throughput may be inadequate for full-scene 75 FPS VR rendering with stereo and distortion. Developers targeting this class of hardware will need to be very conscious of scene geometry because low-latency rendering at 75 FPS is critical for a usable VR experience. Irregular display updates are also particularly apparent in VR so your application must avoid skipping frames.

If you are looking for a portable VR workstation, the Nvidia 650M inside of a MacBook Pro Retina provides minimal graphics power for low end demo development.

4.2 Installation

In order to develop applications using the latest SDK you must download the Oculus SDK package and also install the Oculus Runtime package.

The latest version of both of these packages is available at developer.oculusvr.com.

The naming convention for the Oculus SDK release package is `ovr_type_major.minor.build`. For example, the initial build was `ovr_lib_0.1.1.zip`.

4.3 Directory Structure

The installed Oculus SDK package contains the following subdirectories:

`3rdParty`	Third party SDK components used by samples, such as TinyXml.
`Doc`	SDK Documentation, including this document.
`Firmware`	Firmware files for the Oculus tracker.
`LibOVR`	Libraries, source code, projects, and makefiles for the SDK.
`LibOVR/Include`	Public include header files, including `OVR.h`. Header files here reference other headers in `LibOVR/Src`.
`LibOVR/Lib`	Pre-built libraries for use in your project.
`LibOVR/Src`	Source code and internally referenced headers.
`Samples`	Samples that integrate and leverage the Oculus SDK.
`Tools`	Configuration utility.

4.4 Compiler Settings

The LibOVR libraries do not require exception handling or RTTI support, thereby allowing your game or application to disable these features for efficiency.

4.5 Makefiles, Projects, and Build Solutions

Developers can rebuild the samples and LibOVR using the projects and solutions in the `Samples` and `LibOVR/Projects` directory.

4.5.1 Windows

Solutions and project files for Visual Studo 2010, 2012 and 2013 are provided with the SDK:

- `Samples/LibOVR_with_Samples_VS2010.sln`, or the 2012/2013 equivalent, is the main solution that allows you to build and run all of the samples, and LibOVR itself.

4.5.2 MacOS

The included Xcode workspace `Samples/LibOVR_With_Samples.xcworkspace` allows you to build and run all of the samples, and LibOVR itself. The project is setup to build universal binaries (x86 and x86_64) for all recent MacOS versions (10.8 and newer).

4.5.3 Linux (Coming Soon)

A makefile is provided in the root folder which allows you to build LibOVR and the OculusWorldDemo sample. The code is dependent on the `udev` and `Xinerama` runtime components, so before building, you must install the relevant packages. You must also install a `udev/rules.d` file in order to set the correct access permissions for Oculus HID devices. These steps can be performed by executing the provided script `ConfigurePermissionsAndPackages.sh`, located in the root folder of the SDK.

4.6 Terminology

You should familiarize yourself with the following terms, which are frequently used in the rest of this document:

Head-mounted display (HMD)	A general term for any VR device such as the Rift.
Interpupillary distance (IPD)	The distance between the eye pupils. The default value in the SDK is 64 millimeters, which corresponds to the average human distance, but values of 54 to 72 millimeters are possible.
Field of view (FOV)	The full vertical viewing angle used to configure rendering. This is computed based on the eye distance and display size.
Tan Half FOV	The tangent of half the FOV angle. Thus a FOV of 60 degrees has a half-FOV of 30 degrees, and a tan-half-FOV value of tan(30) or 0.577. Tan half FOV is considered a more usable form in this use case than direct use of FOV angles.
Aspect ratio	The ratio of horizontal resolution to vertical resolution. The aspect ratio for each eye on the Oculus Rift DK1 is 640/800 or 0.8.
Multisampling	Hardware anti-aliasing mode supported by many video cards.

5 Getting Started

Your developer kit is unpacked and plugged in. You have installed the SDK, and you are ready to go. Where is the best place to begin?

If you haven't already, take a moment to adjust the Rift headset so that it's comfortable for your head and eyes. More detailed information about configuring the Rift can be found in the Oculus Rift Hardware Setup section of this document.

After your hardware is fully configured, the next step is to test the development kit. The SDK comes with a set of full-source C++ samples designed to help developers get started quickly. These include:

- **OculusWorldDemo** - A visually appealing Tuscany scene with on-screen text and controls.
- **OculusRoomTiny** - A minimal C++ sample showing sensor integration and rendering on the Rift (only available for D3DX platforms as of 0.4. Support for GL platforms will be added in a future release).

We recommend running the pre-built OculusWorldDemo as a first-step in exploring the SDK. You can find a link to the executable file in the root of the Oculus SDK installation.

5.1 OculusWorldDemo

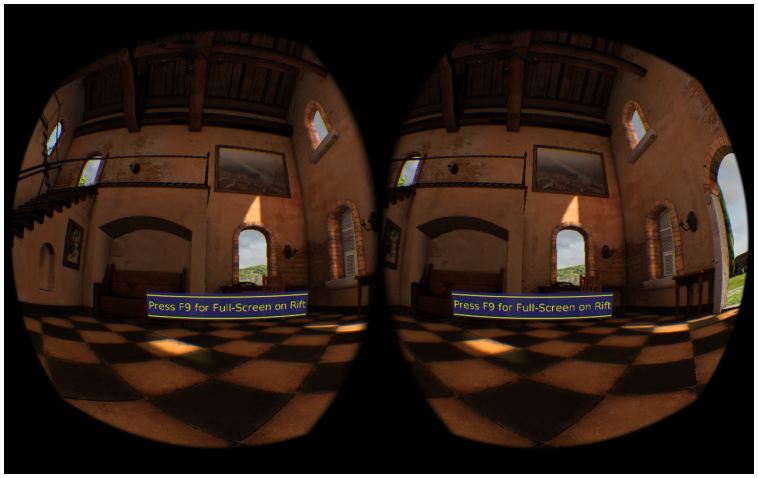


Figure 4: Screenshot of the OculusWorldDemo application.

5.1.1 Controls

Key or Input	Movement	Key	Function
W, S	Move forward, back	F4	Multisampling toggle
A, D	Strafe left, right	F7	Mono/stereo view mode toggle
Mouse move	Look left, right	F9	Hardware full-screen (low latency) ⋆
Left gamepad stick	Move	F11	Windowed full-screen (no blinking) ⋆
Right gamepad stick	Turn	E	Motion relative to head/body

Key(s)	Function	Key(s)	Function
R	Reset sensor orientation	G	Cycle grid overlay mode
Esc	Cancel full-screen	U, J	Adjust second view value
-, +	Adjust eye height	I, K	Adjust third view value
L	Adjust fourth view value	;	Cylce rendered scenes
Tab	Options Menu	+Shift	Adjust values quickly
Spacebar	Toggle debug info overlay	O	Toggle Time-Warp
T	Reset player position	C	Toggle FreezeEyeUpdate
Ctrl+Q	Quit	V	Toggle Vsync

⋆ Only relevant in Extend Desktop display mode.

5.1.2 Using OculusWorldDemo

Once you've launched OculusWorldDemo you should see a window on your PC monitor similar to the screenshot in Figure 4. Depending on the settings chosen in the *Display Mode dialog* of the *Oculus System Tray* you may also see the image displayed inside the Rift. If the chosen setting is *Direct Display* then the *Oculus Display Driver* will be managing the Oculus Rift display and will be automatically displaying the rendered scene inside it. On the other hand, if the chosen setting is *Extended Desktop* or a DK1 is being used and the *DK1 Legacy Support* checkbox is checked, then the Oculus Rift display will appear in extended desktop mode. In this case, you should press F9 or F11 to switch rendering to the Oculus Rift as follows:

- **F9** - Switches to hardware full-screen mode. This will give best possible latency, but may blink monitors as the operating system changes display settings. If no image shows up in the Rift, then press F9 again to cycle to the next monitor.
- **F11** - Instantly switches the rendering window to the Rift portion of the desktop. This mode has higher latency and no vsync, but is convenient for development.

If you're having problems (for example, no image in the headset, no head tracking, and so on), please view the developer forums at developer.oculusvr.com/forums. The forums should help for resolving many common issues.

When the image is correctly displayed inside the Rift then take a moment to look around in VR and double check that all of the hardware is working properly. If you're using a DK2 then you should be able to see that physical head translation is now also recreated in the virtual word as well as rotation.

Important: If you need to move the DK2 external camera for any reason after initial calibration, be sure to minimize the movement of the HMD for a few seconds whilst holding it within the tracking frustum. This will give the system chance to recalibrate the camera pose.

If you would like to explore positional tracking in more detail, you can press the semicolon ';' key to bring the the "sea of cubes" field that we use for debugging. In this mode, cubes are displayed that allow you to easily observe positional tracking behaviour. Cubes are displayed in red when head position is being tracked and in blue when sensor fusion falls back onto the head model.

There are a number of interesting things to take note of the first time you experience OculusWorldDemo. First, the level is designed "to scale". Thus, everything appears to be roughly the same height as it would be in the real world. The sizes for everything, including the chairs, tables, doors, and ceiling, are based on measurements from real world objects. All of the units are measured in meters.

Depending on your actual height, you may feel shorter or taller than normal. The default eye-height of the player in OculusWorldDemo is 1.61 meters (approximately the average adult eye height), but this can be adjusted using the '+' and '-' keys. Alternatively, you can set your height in the Oculus Configuration Utility (accessed through the Oculus System Tray Icon).

OculusWorldDemo includes code showing how to use values set in the player's profile such as eye height, IPD, and head dimensions, and how to feed them into the SDK to achieve a realistic sense of scale for a wide range of players. The scale of the world and the player is critical to an immersive VR experience. Further information regarding scale can be found in the *Oculus Best Practices Guide* document.

5.2 Using the SDK Beyond the OculusWorldDemo

5.2.1 Software developers and integration engineers

If you're integrating the Oculus SDK into your game engine, we recommend starting by opening the sample projects (`Samples/LibOVR_With_Samples_VS2010.sln` or `Samples/LibOVR_With_Samples.xcworkspace`), building the projects, and experimenting with the provided sample code.

OculusRoomTiny is a good place to start because its source code compactly combines all critical features of the Oculus SDK. It contains logic necessary to initialize LibOVR core, access Oculus devices, use the player's profile, implement head-tracking, sensor fusion, stereoscopic 3D rendering, and distortion processing.

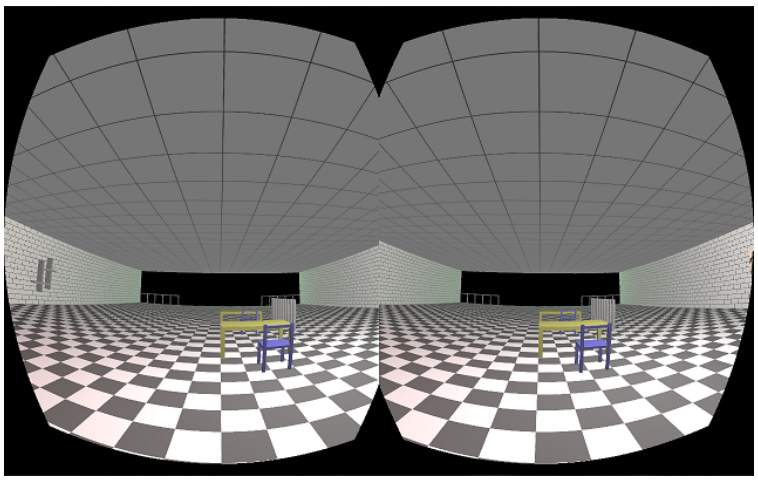


Figure 5: Screenshot of the OculusRoomTiny application.

OculusWorldDemo is a more complex sample. It is intended to be portable and supports many more features including: windowed/full-screen mode switching, XML 3D model and texture loading, movement collision detection, adjustable view size and quality controls, 2D UI text overlays, and so on. This is a good application to experiment with after you are familiar with Oculus SDK basics.

It also includes and overlay menu with options and toggles that customize many aspects of rendering including FOV, render target use, timewarp and display settings. Experimenting with these options may provide developers with insight into what the related numbers mean and how they affect things behind the scenes.

Beyond experimenting with the provided sample code, you should continue to follow this document. We'll cover important topics including the LibOVR initialization, head-tracking, rendering for the Rift, and minimizing latency.

5.2.2 Artists and game designers

If you're an artist or game designer unfamiliar in C++, we recommend downloading UE3, UE4 or Unity along with the corresponding Oculus integration. You can use our out-of-the-box integrations to begin building

Oculus-based content immediately.

The “Unreal Engine 3 Integration Overview” document and the “Unity Integration Overview” document, available from the Oculus Developer Center, detail the steps required to set up your UE3/Unity plus Oculus development environment.

We also recommend reading through the “Oculus Best Practices Guide”, which has tips, suggestions, and research oriented around developing great VR experiences. Topics include control schemes, user interfaces, cut-scenes, camera features, and gameplay. The “Best Practices Guide” should be a go-to reference when designing your Oculus-ready games.

Aside from that, the next step is to get started building your own Oculus-ready game or application. Thousands of other developers like you, are out there building the future of virtual reality gaming. You can reach out to them by visiting developer.oculusvr.com/forums.

6 LibOVR Integration Outline

The Oculus SDK has been designed to be as easy to integrate as possible. This section outlines a basic Oculus integration into a C++ game engine or application. We'll discuss initializing the LibOVR, HMD device enumeration, head tracking, frame timing, and rendering for the Rift.

Many of the code samples below are taken directly from the OculusRoomTiny demo source code (available in `Oculus/LibOVR/Samples/OculusRoomTiny`). OculusRoomTiny and OculusWorldDemo are great places to view sample integration code when in doubt about a particular system or feature.

6.1 Integration tasks

To add Oculus support to a new application, you'll need to do the following:

1. Initialize LibOVR.
2. Enumerate Oculus devices, create the `ovrHmd` object, and start sensor input.
3. Integrate head-tracking into your application's view and movement code. This involves:
   (a) Reading data from the Rift sensors through `ovrHmd_GetTrackingState` or `ovrHmd_GetEyePose`.
   (b) Applying Rift orientation and position to the camera view, while combining it with other application controls.
   (c) Modifying movement and game play to consider head orientation.
4. Initialize rendering for the HMD.
   (a) Select rendering parameters such as resolution and field of view based on HMD capabilities.
   (b) For SDK rendered distortion, configure rendering based on system rendering API pointers and viewports.
   (c) *or* For client rendered distortion, create the necessary distortion mesh and shader resources.
5. Modify application frame rendering to integrate HMD support and proper frame timing:
   (a) Make sure your engine supports multiple rendering views.
   (b) Add frame timing logic into the render loop to ensure that motion prediction and timewarp work correctly.
   (c) Render each eye's view to intermediate render targets.
   (d) Apply distortion correction to render target views to correct for the optical characteristics of the lenses (only necessary for client rendered distortion).
6. Customize UI screens to work well inside of the headset.

We'll first take a look at obtaining sensor data because it's relatively easy to set up, then we'll move on to the more involved subject of rendering.

7 Initialization and Sensor Enumeration

The following example initializes LibOVR and requests information about the first available HMD:

```
// Include the OculusVR SDK
#include "OVR_CAPI.h"

void Initialization()
{
    ovr_Initialize();

    ovrHmd      hmd = ovrHmd_Create(0);

    if (hmd)
    {
        // Get more details about the HMD.
        ovrSizei resolution = hmd->Resolution;

        ...
    }

    // Do something with the HMD.
    ....

    ovrHmd_Destroy(hmd);
    ovr_Shutdown();
}
```

As you can see from the code, `ovr_Initialize` must be called before using any of the API functions, and `ovr_Shutdown` must be called to shut down the library before you exit the program. In between these function calls, you are free to create HMD objects, access sensors, and perform application rendering.

In this example, `ovrHmd_Create(0)` is used to create the first available HMD. `ovrHmd_Create` accesses HMDs by index, which is an integer ranging from 0 to the value returned by `ovrHmd_Detect`. Users can call `ovrHmd_Detect` any time after library initialization to re-enumerate the connected Oculus devices. Finally, `ovrHmd_Destroy` must be called to clear the HMD before shutting down the library.

If no Rift is plugged in during detection, `ovrHmd_Create(0)` will return a null handle. In this case developers can use `ovrHmd_CreateDebug` to create a virtual HMD of the specified type. Although the virtual HMD will not provide any sensor input, it can be useful for debugging Rift compatible rendering code, and doing general development without a physical device.

The `ovrHmd` handle is actually a pointer to an `ovrHmdDesc` struct that contains information about the HMD and its capabilities, and is used to set up rendering. The following table describes the fields:

Type	Field	Description
ovrHmdType	Type	Type of the HMD, such as ovrHmd_DK1 or ovrHmd_DK2.
const char*	ProductName	Name describing the product, such as "Oculus Rift DK1".
const char*	Manufacturer	Name of the manufacturer.
short	VendorId	Vendor ID reported by the headset USB device.
short	ProductId	Product ID reported by the headset USB device.
char[]	SerialNumber	Serial number string reported by the headset USB device.
short	FirmwareMajor	The major version of the sensor firmware.
short	FirmwareMinor	The minor version of the sensor firmware.
float	CameraFrustumHFovInRadians	The horizontal FOV of the position tracking camera frustum.
float	CameraFrustumVFovInRadians	The vertical FOV of the position tracking camera frustum.
float	CameraFrustumNearZInMeters	The distance from the position tracking camera to the near frustum bounds.
float	CameraFrustumFarZInMeters	The distance from the position tracking camera to the far frustum bounds.
unsigned int	HmdCaps	HMD capability bits described by ovrHmdCaps.
unsigned int	TrackingCaps	Tracking capability bits describing whether orientation, position tracking, and yaw drift correction are supported.
unsigned int	DistortionCaps	Distortion capability bits describing whether timewarp and chromatic aberration correction are supported.
ovrSizei	Resolution	Resolution of the full HMD screen (both eyes) in pixels.
ovrVector2i	WindowsPos	Location of the monitor window on the screen. Set to (0,0) if not supported.
ovrFovPort[]	DefaultEyeFov	Recommended optical field of view for each eye.
ovrFovPort[]	MaxEyeFov	Maximum optical field of view that can be practically rendered for each eye.
ovrEyeType[]	EyeRenderOrder	Preferred eye rendering order for best performance. Using this value can help reduce latency on sideways scanned screens.
const char*	DisplayDeviceName	System specific name of the display device.
int	DisplayId	System specific ID of the display device.

7.1 Head tracking and sensors

The Oculus Rift hardware contains a number of MEMS sensors including a gyroscope, accelerometer, and magnetometer. Starting with DK2, there is also an external camera to track headset position. The information from each of these sensors is combined through a process known as *sensor fusion* to determine the motion of the user's head in the real world, and to synchronize the user's virtual view in real-time.

To use the Oculus sensor, you first need to initialize tracking and sensor fusion by calling ovrHmd_ConfigureTracking. This function has the following signature:

```
ovrBool  ovrHmd_ConfigureTracking(ovrHmd hmd, unsigned int supportedTrackingCaps,
                                               unsigned int requiredTrackingCaps);
```

`ovrHmd_ConfigureTracking` takes two sets of capability flags as input. These both use flags declared in `ovrTrackingCaps`. `supportedTrackingCaps` describes the HMD tracking capabilities that the application supports, and hence should be made use of when available. `requiredTrackingCaps` specifies capabilities that must be supported by the HMD at the time of the call in order for the application to operate correctly. If the required capabilities are not present, then `ovrHmd_ConfigureTracking` will return `false`.

After tracking is initialized, you can poll sensor fusion for head position and orientation by calling `ovrHmd_GetTrackingState`. These calls are demonstrated by the following code:

```
    // Start the sensor which provides the Rift's pose and motion.
    ovrHmd_ConfigureTracking(hmd, ovrTrackingCap_Orientation |
                                  ovrTrackingCap_MagYawCorrection |
                                  ovrTrackingCap_Position, 0);

    // Query the HMD for the current tracking state.
    ovrTrackingState ts  = ovrHmd_GetTrackingState(hmd, ovr_GetTimeInSeconds());

    if (ts.StatusFlags & (ovrStatus_OrientationTracked | ovrStatus_PositionTracked))
    {
        Posef pose = ts.HeadPose;
        ...
    }
```

This example initializes the sensors with orientation, yaw correction, and position tracking capabilities enabled if available, while actually requiring that only basic orientation tracking be present. This means that the code will work for DK1, while also enabling camera based position tracking for DK2. If you're using a DK2 headset and the DK2 camera is not available during the time of the call, but is plugged in later, the camera will be enabled automatically by the SDK.

After the sensors are initialized, the sensor state is obtained by calling `ovrHmd_GetTrackingState`. This state includes the predicted head pose and the current tracking state of the HMD as described by `StatusFlags`. This state can change at runtime based on the available devices and user behavior. For example with DK2, the `ovrStatus_PositionTracked` flag will be reported only when `HeadPose` includes the absolute positional tracking data based on the camera.

The reported `ovrPoseStatef` includes full six degrees of freedom (6DoF) head tracking data including orientation, position, and their first and second derivatives. The pose value is reported for a specified absolute point in time using prediction, typically corresponding to the time in the future that this frame's image will be displayed on screen. To facilitate prediction, `ovrHmd_GetTrackingState` takes absolute time, in seconds, as a second argument. The current value of absolute time can be obtained by calling `ovr_GetTimeInSeconds`. If the time passed into `ovrHmd_GetTrackingState` is the current time or earlier then the tracking state returned will be based on the latest sensor readings with no prediction. In a production application, however, you should use one of the real-time computed values returned by `ovrHmd_BeginFrame` or `ovrHmd_BeginFrameTiming`. Prediction is covered in more detail in the section on Frame Timing.

As already discussed, the reported pose includes a 3D position vector and an orientation quaternion. The orientation is reported as a rotation in a right-handed coordinate system, as illustrated in Figure 6. Note that

the x-z plane is aligned with the ground regardless of camera orientation.

As seen from the diagram, the coordinate system uses the following axis definitions:

- Y is positive in the up direction.
- X is positive to the right.
- Z is positive heading backwards.

Rotation is maintained as a unit quaternion, but can also be reported in yaw-pitch-roll form. Positive rotation is counter-clockwise (CCW, direction of the rotation arrows in the diagram) when looking in the negative direction of each axis, and the component rotations are:

- **Pitch** is rotation around X, positive when pitching up.
- **Yaw** is rotation around Y, positive when turning left.
- **Roll** is rotation around Z, positive when tilting to the left in the XY plane.

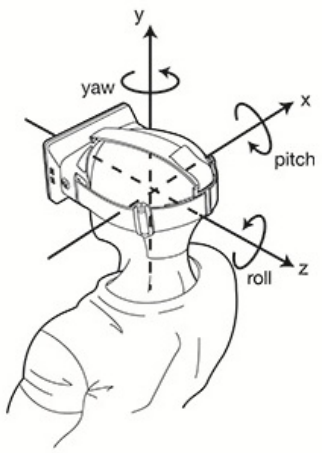


Figure 6: The Rift coordinate system

The simplest way to extract yaw-pitch-roll from `ovrPose` is to use the C++ OVR Math helper classes that are included with the library. The following example uses direct conversion to assign `ovrPosef` to the equivalent C++ `Posef` class. You can then use the `Quatf::GetEulerAngles<>` to extract the Euler angles in the desired axis rotation order.

```
Posef pose = trackingState.HeadPose.ThePose;
float yaw, float eyePitch, float eyeRoll;
pose.Orientation.GetEulerAngles<Axis_Y, Axis_X, Axis_Z>(&yaw, &eyePitch, &eyeRoll);
```

All simple C math types provided by OVR such as `ovrVector3f` and `ovrQuatf` have corresponding C++ types that provide constructors and operators for convenience. These types can be used interchangeably.

7.1.1 Position Tracking

Figure 7 shows the DK2 position tracking camera mounted on a PC monitor and a representation of the resulting tracking frustum. The frustum is defined by the horizontal and vertical FOV, and the distance to the front and back frustum planes. Approximate values for these parameters can be accessed through the `ovrHmdDesc` struct as follows:

```
ovrHmd       hmd = ovrHmd_Create(0);

if (hmd)
{
    // Extract tracking frustum parameters.
    float frustomHorizontalFOV = hmd->CameraFrustumHFovInRadians;
    ...
```

The relevant parameters and typical values are list below:

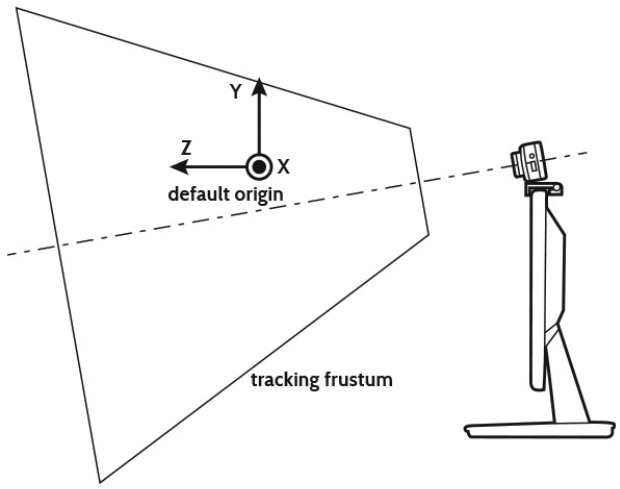


Figure 7: Position tracking camera and tracking frustum.

Type	Field	Typical Value
`float`	CameraFrustumHFovInRadians	1.292 radians (74 degrees)
`float`	CameraFrustumVFovInRadians	0.942 radians (54 degrees)
`float`	CameraFrustumNearZInMeters	0.4m
`float`	CameraFrustumFarZInMeters	2.5m

These parameters are provided to enable application developers to provide a visual representation of the tracking frustum. Figure 7 also shows the default tracking origin and associated coordinate system. Note that although the camera axis (and hence the tracking frustum) are shown tilted downwards slightly, the tracking coordinate system is always oriented horizontally such that the `z` and `x` axes are parallel to the ground.

By default the tracking origin is located one meter away from the camera in the direction of the optical axis but with the same height as the camera. The default origin orientation is level with the ground with the negative `z` axis pointing towards the camera. In other words, a headset yaw angle of zero corresponds to the user looking towards the camera.

This can be modified using the API call `ovrHmd_RecenterPose` which resets the tracking origin to the headset's current location, and sets the yaw origin to the current headset yaw value. Note that the tracking origin is set on a per application basis and so switching focus between different VR apps will switch the tracking origin also.

Determining the head pose is done by calling `ovrHmd_GetTrackingState`. The returned struct `ovrTrackingState` contains several items relevant to position tracking. `HeadPose` includes both head position and orientation. `CameraPose` is the pose of the camera relative to the tracking origin. `LeveledCameraPose` is the pose of the camera relative to the tracking origin but with roll and pitch zeroed out. This can be used as a reference point to render real-world objects in the correct place.

The `StatusFlags` variable contains three status bits relating to position tracking.
`ovrStatus_PositionConnected` is set when the position tracking camera is connected and functioning properly. The `ovrStatus_PositionTracked` flag is set only when the headset is being actively tracked. `ovrStatus_CameraPoseTracked` is set after the initial camera calibration has

taken place. Typically this requires the headset to be reasonably stationary within the view frustum for a second or so at the start of tracking. It may be necessary to communicate this to the user if the `ovrStatus_CameraPoseTracked` flag doesn't become set quickly after entering VR.

There are several conditions that may cause position tracking to be interrupted and hence the `ovrStatus_PositionTracked` flag to become zero:

- The headset moved wholly or partially outside the tracking frustum.
- The headset adopts an orientation that is not easily trackable with the current hardware (for example facing directly away from the camera).
- The exterior of the headset is partially or fully occluded from the tracking camera's point of view (for example by hair or hands).
- The velocity of the headset exceeds the expected range.

Following an interruption, assuming the conditions above are no longer present, tracking normally resumes quickly and the `ovrStatus_PositionTracked` flag will become set.

7.1.2 User input integration

Head tracking will need to be integrated with an existing control scheme for most applications to provide the most comfortable, intuitive, and usable interface for the player.

For example, in a first person shooter (FPS) game, the player generally moves forward, backward, left, and right using the left joystick, and looks left, right, up, and down using the right joystick. When using the Rift, the player can now look left, right, up, and down, using their head. However, players should not be required to frequently turn their heads 180 degrees since this creates a bad user experience. Generally, they need a way to reorient themselves so that they are always comfortable (the same way in which we turn our bodies if we want to look behind ourselves for more than a brief glance).

To summarize, developers should carefully consider their control schemes and how to integrate head-tracking when designing applications for VR. The OculusRoomTiny application provides a source code sample that shows how to integrate Oculus head tracking with the aforementioned standard FPS control scheme.

Read the *Oculus Best Practices Guide* for suggestions and contra-indicated mechanisms.

7.2 Health and Safety Warning

All applications that use the Oculus Rift must integrate code that displays a health and safety warning when the device is used. This warning will appear for a short amount of time when the Rift first displays a VR scene; it can be dismissed by pressing a key or tapping on the headset. Currently, the warning will be displayed for at least 15 seconds for the first time a new profile user puts on the headset and for 6 seconds afterwards.

The warning will be displayed automatically as an overlay in SDK Rendered mode; in App rendered mode it is left for developers to implement. To support timing and rendering the safety warning, we've added two functions to the C API: `ovrHmd_GetHSWDisplayState` and `ovrHmd_DismissHSWDisplay`. `ovrHmd_GetHSWDisplayState` reports the state of the warning described by the `ovrHSWDisplayState` structure, including the displayed flag and how much time is left before it can be dismissed. `ovrHmd_DismissHSWDisplay` should be called in response to a keystroke or gamepad action to dismiss the warning.

The following code snippet illustrates how health and safety warning may be handled:

```
// Health and Safety Warning display state.
ovrHSWDisplayState hswDisplayState;
ovrHmd_GetHSWDisplayState(HMD, &hswDisplayState);

if (hswDisplayState.Displayed)
{
    // Dismiss the warning if the user pressed the appropriate key or if the user
    // is tapping the side of the HMD.
    // If the user has requested to dismiss the warning via keyboard or controller input...
    if (Util_GetAndResetHSWDismissedState())
        ovrHmd_DismissHSWDisplay(HMD);
    else
    {
        // Detect a moderate tap on the side of the HMD.
        ovrTrackingState ts = ovrHmd_GetTrackingState(HMD, ovr_GetTimeInSeconds());

        if (ts.StatusFlags & ovrStatus_OrientationTracked)
        {
            const OVR::Vector3f v(ts.RawSensorData.Accelerometer.x,
                                  ts.RawSensorData.Accelerometer.y,
                                  ts.RawSensorData.Accelerometer.z);

            // Arbitrary value and representing moderate tap on the side of the DK2 Rift.
            if (v.LengthSq() > 250.f)
                ovrHmd_DismissHSWDisplay(HMD);
        }
    }
}
```

8 Rendering to the Oculus Rift

Figure 8: OculusWorldDemo stereo rendering.

The Oculus Rift requires split-screen stereo with distortion correction for each eye to cancel the distortion due to lenses. Setting this up can be tricky, but proper distortion correction is a critical part of achieving an immersive experience.

The Oculus C API provides two ways of doing distortion correction: SDK distortion rendering and Client (application-side) distortion rendering. With both approaches, the application renders stereo views into individual render textures or a single combined one. The differences appear in the way the APIs handle distortion, timing, and buffer swap:

- With the SDK distortion rendering approach, the library takes care of timing, distortion rendering, and buffer swap (the `Present` call). To make this possible, developers provide low level device and texture pointers to the API, and instrument the frame loop with `ovrHmd_BeginFrame` and `ovrHmd_EndFrame` calls that do all of the work. No knowledge of distortion shaders (vertex or pixel-based) is required.
- With Client distortion rendering, distortion must be rendered by the application code. This is similar to the approach used in version 0.2 of the SDK. However, distortion rendering is now mesh-based. In other words, the distortion is encoded in mesh vertex data rather than using an explicit function in the pixel shader. To support distortion correction, the Oculus SDK generates a mesh that includes vertices and UV coordinates used to warp the source render target image to the final buffer. The SDK also provides explicit frame timing functions used to support timewarp and prediction.

The following subsections cover the rendering approaches in greater detail:

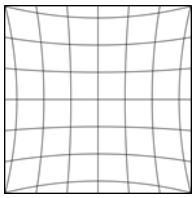
- Section 8.1 introduces the basic concepts behind HMD stereo rendering and projection setup.
- Section 8.2 describes SDK distortion rendering, which is the recommended approach.
- Section 8.3 covers client distortion rendering including timing, mesh creation, and the necessary shader code.

8.1 Stereo rendering concepts

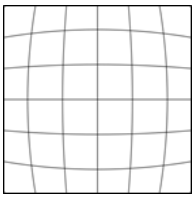
The Oculus Rift requires the scene to be rendered in split-screen stereo with half the screen used for each eye. When using the Rift, the left eye sees the left half of the screen, and the right eye sees the right half. Although varying from person-to-person, human eye pupils are approximately 65 mm apart. This is known as interpupillary distance (IPD). The in-application cameras should be configured with the same separation. Note that this is a translation of the camera, not a rotation, and it is this translation (and the parallax effect that goes with it) that causes the stereoscopic effect. This means that your application will need to render the entire scene twice, once with the left virtual camera, and once with the right.

Note that the *reprojection stereo rendering* technique, which relies on left and right views being generated from a single fully rendered view, is usually not viable with an HMD because of significant artifacts at object edges.

The lenses in the Rift magnify the image to provide a very wide field of view (FOV) that enhances immersion. However, this process distorts the image significantly. If the engine were to display the original images on the Rift, then the user would observe them with pincushion distortion.



Pincushion Distortion



Barrel Distortion

To counteract this distortion, the software must apply post-processing to the rendered views with an equal and opposite barrel distortion so that the two cancel each other out, resulting in an undistorted view for each eye. Furthermore, the software must also correct chromatic aberration, which is a color separation effect at the edges caused by the lens. Although the exact distortion parameters depend on the lens characteristics and eye position relative to the lens, the Oculus SDK takes care of all necessary calculations when generating the distortion mesh.

When rendering for the Rift, projection axes should be parallel to each other as illustrated in Figure 9, and the left and right views are completely independent of one another. This means that camera setup is very similar to that used for normal non-stereo rendering, except that the cameras are shifted sideways to adjust for each eye location.

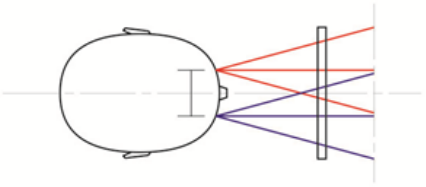


Figure 9: HMD eye view cones.

In practice, the projections in the Rift are often slightly off-center because our noses get in the way! But the point remains, the left and right eye views in the Rift are entirely separate from each other, unlike stereo views generated by a television or a cinema screen. This means you should be very careful if trying to use methods developed for those media because they do not usually apply to the Rift.

The two virtual cameras in the scene should be positioned so that they are pointing in the same direction (determined by the orientation of the HMD in the real world), and such that the distance between them is the same as the distance between the eyes, or interpupillary distance (IPD). This is typically done by adding the `ovrEyeRenderDesc::ViewAdjust` translation vector to the translation component of the view matrix.

Although the Rift's lenses are approximately the right distance apart for most users, they may not exactly match the user's IPD. However, because of the way the optics are designed, each eye will still see the correct view. It is important that the software makes the distance between the virtual cameras match the user's IPD as found in their profile (set in the configuration utility), and *not* the distance between the Rift's lenses.

8.2 SDK distortion rendering

The Oculus SDK provides SDK Distortion Rendering as the recommended path for presenting frames and handling distortion. With SDK rendering, developers render the scene into one or two render textures, passing these textures into the API. Beyond that point, the Oculus SDK handles the rendering of distortion, calling `Present`, GPU synchronization, and frame timing.

Here is an outline of the steps involved with SDK Rendering:

1. Initialization
   (a) Modify your application window and swap chain initialization code to use the data provided in the `ovrHmdDesc` struct e.g. Rift resolution etc.
   (b) Compute the desired FOV and texture sizes based on `ovrHMDDesc` data.
   (c) Allocate textures in an API-specific way.
   (d) Use `ovrHmd_ConfigureRendering` to initialize distortion rendering, passing in the necessary API specific device handles, configuration flags, and FOV data.
   (e) Under Windows, call `ovrHmd_AttachToWindow` to direct back buffer output from the window to the HMD.
2. Frame Handling
   (a) Call `ovrHmd_BeginFrame` to start frame processing and obtain timing information.
   (b) Perform rendering for each eye in an engine-specific way, rendering into render textures.
   (c) Call `ovrHmd_EndFrame` (passing in the render textures from the previous step) to swap buffers and present the frame. This function will also handle timewarp, GPU sync, and frame timing.
3. Shutdown
   (a) You can use `ovrHmd_ConfigureRendering` with a null value for the `apiConfig` parameter to shut down SDK rendering or change its rendering parameters. Alternatively, you can just destroy the ovrHmd object by calling `ovrHmd_Destroy`.

8.2.1 Render texture initialization

This section describes the steps involved in initialization. As a first step, you determine the rendering FOV and allocate the required render target textures. The following code sample shows how the OculusRoomTiny demo does this:

```
// Configure Stereo settings.
Sizei recommenedTex0Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Left,
                                                    hmd->DefaultEyeFov[0], 1.0f);
Sizei recommenedTex1Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Right,
                                                    hmd->DefaultEyeFov[1], 1.0f);
```

```
    Sizei renderTargetSize;
    renderTargetSize.w  = recommenedTex0Size.w + recommenedTex1Size.w;
    renderTargetSize.h = max ( recommenedTex0Size.h, recommenedTex1Size.h );

    const int eyeRenderMultisample = 1;
    pRendertargetTexture = pRender->CreateTexture(
                                    Texture_RGBA | Texture_RenderTarget | eyeRenderMultisample,
                                    renderTargetSize.w, renderTargetSize.h, NULL);
    // The actual RT size may be different due to HW limits.
    renderTargetSize.w = pRendertargetTexture->GetWidth();
    renderTargetSize.h = pRendertargetTexture->GetHeight();
```

The code first determines the render texture size based on the FOV and the desired pixel density at the center of the eye. Although both the FOV and pixel density values can be modified to improve performance, in this case the recommended FOV is used (obtained from `hmd->DefaultEyeFov`). The function `ovrHmd_GetFovTextureSize` computes the desired texture size for each eye based on these parameters.

The Oculus API allows the application to use either one shared texture or two separate textures for eye rendering. This example uses a single shared texture for simplicity, making it large enough to fit both eye renderings. The sample then calls `CreateTexture` to allocate the texture in an API-specific way. Under the hood, the returned texture object will wrap either a D3D texture handle or OpenGL texture id. Because video hardware may have texture size limitations, we update `renderTargetSize` based on the actually allocated texture size. Although use of a different texture size may affect rendering quality and performance, it should function properly, provided that the viewports are set up correctly. The Frame Rendering section later in this document describes details of viewport setup.

8.2.2 Configure rendering

With the FOV determined, you can now initialize SDK rendering by calling `ovrHmd_ConfigureRendering`. This also generates the `ovrEyeRenderDesc` structure that describes all of the details needed when you come to perform stereo rendering. Note that in client-rendered mode the call `ovrHmd_GetRenderDesc` should be used instead.

In addition to the input `eyeFovIn[]` structures, this requires a render-API dependent version of `ovrRenderAPIConfig` that provides API and platform specific interface pointers. The following code shows an example of what this looks like for Direct3D 11:

```
// Configure D3D11.
RenderDevice* render = (RenderDevice*)pRender;
ovrD3D11Config d3d11cfg;
d3d11cfg.D3D11.Header.API         = ovrRenderAPI_D3D11;
d3d11cfg.D3D11.Header.RTSize      = Sizei(backBufferWidth, backBufferHeight);
d3d11cfg.D3D11.Header.Multisample = backBufferMultisample;
d3d11cfg.D3D11.pDevice            = pRender->Device;
d3d11cfg.D3D11.pDeviceContext     = pRender->Context;
d3d11cfg.D3D11.pBackBufferRT      = pRender->BackBufferRT;
d3d11cfg.D3D11.pSwapChain         = pRender->SwapChain;

if (!ovrHmd_ConfigureRendering(hmd, &d3d11cfg.Config, ovrDistortionCap_Chromatic |
                                                      ovrDistortionCap_TimeWarp |
                                                      ovrDistortionCap_Overdrive,
                               eyeFov, EyeRenderDesc))
    return(1);
```

With D3D11, `ovrHmd_ConfigureRendering` requires the device, context, back buffer and swap chain pointers. Internally, it uses these to allocate the distortion mesh, shaders, and any other resources necessary to correctly output the scene to the Rift display.

Similar code is used to configure rendering with OpenGL. The following code shows how this is done under Windows:

```
// Configure OpenGL.
ovrGLConfig cfg;
cfg.OGL.Header.API         = ovrRenderAPI_OpenGL;
cfg.OGL.Header.RTSize      = Sizei(hmd->Resolution.w, hmd->Resolution.h);
cfg.OGL.Header.Multisample = backBufferMultisample;
cfg.OGL.Window             = window;
cfg.OGL.DC                 = dc;

ovrBool result = ovrHmd_ConfigureRendering(hmd, &cfg.Config, distortionCaps,
                                                eyesFov, EyeRenderDesc);
```

In addition to setting up rendering, staring with Oculus SDK 0.4.0 Windows users will need to call `ovrHmd_AttachToWindow` to direct its swap-chain output to the HMD through the Oculus display driver. This is easily done with once call:

```
// Direct rendering from a window handle to the Hmd.
// Not required if ovrHmdCap_ExtendDesktop flag is set.
ovrHmd_AttachToWindow(hmd, window, NULL, NULL);
```

Going forward, we plan to introduce direct rendering support on all platforms. With the window attached, we are ready to render to the HMD.

8.2.3 Frame rendering

When used in the SDK distortion rendering mode, the Oculus SDK handles frame timing, motion prediction, distortion rendering, end frame buffer swap (known as `Present` in Direct3D), and GPU synchronization. To do this, it makes use of three functions that must be called on the render thread:

- `ovrHmd_BeginFrame`, `ovrHmd_EndFrame`
- `ovrHmd_GetEyePose`

As suggested by their names, calls to `ovrHmd_BeginFrame` and `ovrHmd_EndFrame` enclose the body of the frame rendering loop. `ovrHmd_BeginFrame` is called at the beginning of the frame, returning frame timing information in the `ovrFrameTiming` struct. Values within this structure are useful for animation and correct sensor pose prediction. `ovrHmd_EndFrame` should be called at the end of the frame, in the same place that you would typically call `Present`. This function takes care of the distortion rendering, buffer swap, and GPU synchronization. The function also ensures that frame timing is matched with the video card VSync.

In between `ovrHmd_BeginFrame` and `ovrHmd_EndFrame` you will render both of the eye views to a render texture. Before rendering each eye you should get the latest predicted head pose by calling `ovrHmd_GetEyePose`. This will ensure that each predicted pose is based on the latest sensor data. We also recommend that you use the `ovrHMDDesc::EyeRenderOrder` variable to determine which eye to render first for that HMD, since that can also produce better pose prediction on HMDs with eye-independent scanout.

The `ovrHmd_EndFrame` function submits the eye images for distortion processing. Because the texture data is passed in an API-specific format, the `ovrTexture` structure needs some platform-specific initialization.

The following code shows how `ovrTexture` initialization is done for D3D11 in OculusRoomTiny:

```
ovrD3D11Texture EyeTexture[2];

// Pass D3D texture data, including ID3D11Texture2D and ID3D11ShaderResourceView pointers.
Texture* rtt = (Texture*)pRendertargetTexture;
EyeTexture[0].D3D11.Header.API            = ovrRenderAPI_D3D11;
EyeTexture[0].D3D11.Header.TextureSize    = RenderTargetSize;
EyeTexture[0].D3D11.Header.RenderViewport = EyeRenderViewport[0];
EyeTexture[0].D3D11.pTexture              = pRendertargetTexture->Tex.GetPtr();
EyeTexture[0].D3D11.pSRView               = pRendertargetTexture->TexSv.GetPtr();

// Right eye uses the same texture, but different rendering viewport.
EyeTexture[1]                             = EyeTexture[0];
EyeTexture[1].D3D11.Header.RenderViewport = EyeRenderViewport[1];
```

Alternatively, here is OpenGL code:

```
ovrGLTexture EyeTexture[2];
...
EyeTexture[0].OGL.Header.API            = ovrRenderAPI_OpenGL;
EyeTexture[0].OGL.Header.TextureSize    = RenderTargetSize;
EyeTexture[0].OGL.Header.RenderViewport = eyes[0].RenderViewport;
EyeTexture[0].OGL.TexId                 = textureId;
```

Note that in addition to specifying the texture related pointers, we are also specifying the rendering viewport. Storing this value within the texture structure that is submitted every frame allows applications to change render target size dynamically, if desired. This is useful for optimizing rendering performance. In the sample code a single render texture is used with each eye mapping to half of the render target size. As a result the same `pTexture` pointer is used for both `EyeTexture` structures but the render viewports are different.

With texture setup complete, you can set up a frame rendering loop as follows:

```
ovrFrameTiming hmdFrameTiming = ovrHmd_BeginFrame(hmd, 0);

pRender->SetRenderTarget ( pRendertargetTexture );
pRender->Clear();

ovrPosef headPose[2];

for (int eyeIndex = 0; eyeIndex < ovrEye_Count; eyeIndex++)
{
    ovrEyeType eye         = hmd->EyeRenderOrder[eyeIndex];
    headPose[eye]          = ovrHmd_GetEyePose(hmd, eye);

    Quatf      orientation = Quatf(headPose[eye].Orientation);
    Matrix4f   proj        = ovrMatrix4f_Projection(EyeRenderDesc[eye].Fov,
                                                    0.01f, 10000.0f, true);

    // * Test code *
    // Assign quaternion result directly to view (translation is ignored).
    Matrix4f   view = Matrix4f(orientation.Inverted()) * Matrix4f::Translation(-WorldEyePos);

    pRender->SetViewport(EyeRenderViewport[eye]);
    pRender->SetProjection(proj);
    pRoomScene->Render(pRender, Matrix4f::Translation(EyeRenderDesc[eye].ViewAdjust) * view);
}

// Let OVR do distortion rendering, Present and flush/sync.
ovrHmd_EndFrame(hmd, headPose, eyeTextures);
```

As described earlier, frame logic is enclosed by the begin frame and end frame calls. In this example both eyes share the render target. Rendering is straightforward, although there a few points worth noting:

- We use `hmd->EyeRenderOrder[eyeIndex]` to select the order of eye rendering. Although not required, this can improve the quality of pose prediction.
- The projection matrix is computed based on `EyeRenderDesc[eye].Fov`, which are the same FOV values used for the rendering configuration.
- The view matrix is adjusted by the `EyeRenderDesc[eye].ViewAdjust` vector, which accounts for IPD in meters.
- This sample uses only the Rift orientation component, whereas real applications should make use of position as well. Please refer to the OculusRoomTiny or OculusWorldDemo source code for a more comprehensive example.

8.2.4 Frame timing

Accurate frame and sensor timing are required for accurate head motion prediction which is essential for a good VR experience. Prediction requires knowing exactly when in the future the current frame will appear on the screen. If we know both sensor and display scanout times, we can predict the future head pose and

improve image stability. Miscomputing these values can lead to under or over-prediction, degrading perceived latency and potentially causing overshoot "wobbles".

To ensure accurate timing, the Oculus SDK uses absolute system time, stored as a `double`, to represent sensor and frame timing values. The current absolute time is returned by `ovr_GetTimeInSeconds`. However, it should rarely be necessary because simulation and motion prediction should rely completely on the frame timing values.

Render frame timing is managed at a low level by two functions: `ovrHmd_BeginFrameTiming` and `ovrHmd_EndFrameTiming`. `ovrHmd_BeginFrameTiming` should be called at the beginning of the frame, and returns a set of timing values for the frame. `ovrHmd_EndFrameTiming` implements most of the actual frame vsync tracking logic. It must be called at the end of the frame after swap buffers and GPU Sync. With SDK Distortion Rendering, `ovrHmd_BeginFrame` and `ovrHmd_EndFrame` call the timing functions internally, and so these do not need to be called explicitly. Nevertheless you will still use the `ovrFrameTiming` values returned by `ovrHmd_BeginFrame` to perform motion prediction and maybe waits.

`ovrFrameTiming` provides a set of absolute times values associated with the current frame. These are:

`float DeltaSeconds`	The amount of time passed since the previous frame (useful for animation).
`double ThisFrameSeconds`	Time that this frame's rendering started.
`double TimewarpPointSeconds`	Time point, during this frame, when timewarp should start.
`double NextFrameSeconds`	Time when the next frame's rendering is expected to start.
`double ScanoutMidpointSeconds`	Midpoint time when this frame will show up on the screen. This can be used to obtain head pose prediction for simulation and rendering.
`double EyeScanoutSeconds[2]`	Times when each eye of this frame is expected to appear on screen. This is the best pose prediction time to use for rendering each eye.

Some of the timing values are used internally by the SDK and may not need to be used directly by your application. The `EyeScanoutSeconds[]` values, for example, is used internally by `ovrHmd_GetEyePose` to report the predicted head pose when rendering each eye. There are, however, some cases in which timing values are useful:

- When using timewarp, the `ovrHmd_EndFrame` implementation will pause internally to wait for the timewarp point, in order to ensure the lowest possible latency. If the application frame rendering is finished early, the developer can instead decide to execute other processing, and then manage waiting until the `TimewarpPointSeconds` time is reached.
- If both simulation and rendering are performed on the same thread, then simulation may need an earlier head `Pose` value that is not specific to either eye. This can be obtained by calling `ovrHmd_GetSensorState` with `ScanoutMidpointSeconds` for absolute time.
- `EyeScanoutSeconds[]` values are useful when accessing pose from a non-rendering thread. This is discussed later in this document.

8.3 Client distortion rendering

In the client distortion rendering mode, the application applies the distortion to the rendered image and makes the final Present call. This mode is intended for application developers who may wish to combine the Rift distortion shader pass with their own post-process shaders for increased efficiency, or if they wish to retain fine control over the entire rendering process. Several API calls are provided which enable this while hiding much of the internal complexity.

8.3.1 Setting up rendering

The first step is to create the render texture that the application will render the undistorted left and right eye images to. The process here is essentially the same as for the SDK distortion rendering approach. Use the `ovrHmdDesc` struct to obtain information about the HMD configuration and allocate the render texture (or a different render texture for each eye) in an API-specific way. This was described previously in the *Render Texture Initialization* section of this document.

The next step is to obtain information regarding how the rendering and distortion should be performed for each eye. This is described using the `ovrEyeRenderDesc` struct. The following table describes the fields:

Type	Field	Description
`ovrEyeType`	Eye	The eye that these values refer to (`ovrEye_Left` or `ovrEye_Right`).
`ovrFovPort`	Fov	The field of view to use when rendering this eye view.
`ovrRecti`	DistortedViewport	Viewport to use when applying the distortion to the render texture.
`ovrVector2f`	PixelsPerTanAngleAtCenter	Density of render texture pixels at the center of the distorted view.
`ovrVector3f`	ViewAdjust	Translation to be applied to the view matrix.

Call `ovrHmd_GetRenderDesc` for each eye to fill in `ovrEyeRenderDesc` as follows:

```
// Initialize ovrEyeRenderDesc struct.
ovrFovPort eyeFov[2];

...

ovrEyeRenderDesc eyeRenderDesc[2];

EyeRenderDesc[0] = ovrHmd_GetRenderDesc(hmd, ovrEye_Left, eyeFov[0]);
EyeRenderDesc[1] = ovrHmd_GetRenderDesc(hmd, ovrEye_Right, eyeFov[1]);
```

8.3.2 Setting up distortion

In client distortion rendering mode, the application is responsible for executing the necessary shaders to apply the image distortion and chromatic aberration correction. In previous SDK versions, the SDK used a fairly complex pixel shader running on every pixel of the screen. However, after testing many methods, Oculus now recommends rendering a mesh of triangles to perform the corrections. The shaders used are simpler and therefore run faster, especially when you use higher resolutions. The shaders also have a more flexible

distortion model that allows us to use higher-precision distortion correction.

OculusRoomTiny is a simple demonstration of how to apply this distortion. The vertex shader looks like the following:

```
float2 EyeToSourceUVScale, EyeToSourceUVOffset;
float4x4 EyeRotationStart, EyeRotationEnd;
float2 TimewarpTexCoord(float2 TexCoord, float4x4 rotMat)
{
    // Vertex inputs are in TanEyeAngle space for the R,G,B channels (i.e. after chromatic
    // aberration and distortion). These are now "real world" vectors in direction (x,y,1)
    // relative to the eye of the HMD. Apply the 3x3 timewarp rotation to these vectors.
    float3 transformed = float3( mul ( rotMat, float4(TexCoord.xy, 1, 1) ).xyz);

    // Project them back onto the Z=1 plane of the rendered images.
    float2 flattened = (transformed.xy / transformed.z);

    // Scale them into ([0,0.5],[0,1]) or ([0.5,0],[0,1]) UV lookup space (depending on eye)
    return(EyeToSourceUVScale * flattened + EyeToSourceUVOffset);
}

void main(in float2 Position    : POSITION,    in float timewarpLerpFactor : POSITION1,
          in float Vignette     : POSITION2,   in float2 TexCoord0         : TEXCOORD0,
          in float2 TexCoord1   : TEXCOORD1,   in float2 TexCoord2         : TEXCOORD2,
          out float4 oPosition  : SV_Position, out float2 oTexCoord0       : TEXCOORD0,
          out float2 oTexCoord1 : TEXCOORD1,   out float2 oTexCoord2       : TEXCOORD2,
          out float  oVignette  : TEXCOORD3)
{
    float4x4 lerpedEyeRot = lerp(EyeRotationStart, EyeRotationEnd, timewarpLerpFactor);
    oTexCoord0  = TimewarpTexCoord(TexCoord0,lerpedEyeRot);
    oTexCoord1  = TimewarpTexCoord(TexCoord1,lerpedEyeRot);
    oTexCoord2  = TimewarpTexCoord(TexCoord2,lerpedEyeRot);
    oPosition = float4(Position.xy, 0.5, 1.0);
    oVignette = Vignette;   /* For vignette fade */
}
```

The position XY data is already in Normalized Device Coordinates (NDC) space (-1 to +1 across the entire framebuffer). Therefore, the vertex shader simply adds a 1 to W and a default Z value (which is unused because depth buffering is not enabled during distortion correction). There are no other changes. `EyeToSourceUVScale` and `EyeToSourceUVOffset` are used to offset the texture coordinates based on how the eye images are arranged in the render texture.

The pixel shader is as follows:

```
Texture2D Texture   : register(t0);
SamplerState Linear : register(s0);

float4 main(in float4 oPosition  : SV_Position, in float2 oTexCoord0 : TEXCOORD0,
            in float2 oTexCoord1 : TEXCOORD1, in float2 oTexCoord2 : TEXCOORD2,
            in float oVignette : TEXCOORD3)   : SV_Target
{
    // 3 samples for fixing chromatic aberrations
    float R = Texture.Sample(Linear, oTexCoord0.xy).r;
    float G = Texture.Sample(Linear, oTexCoord1.xy).g;
    float B = Texture.Sample(Linear, oTexCoord2.xy).b;
    return (oVignette*float4(R,G,B,1));
}
```

The pixel shader samples the red, green, and blue components from the source texture where specified, and combines them with a shading. The shading is used at the edges of the view to give a smooth fade-to-black effect rather than an abrupt cut-off. A sharp edge triggers the motion-sensing neurons at the edge of our

vision and can be very distracting. Using a smooth fade-to-black reduces this effect substantially.

As you can see, the shaders are very simple, and all the math happens during the generation of the mesh positions and UV coordinates. To generate the distortion mesh, call `ovrHmd_CreateDistortionMesh`. This function generates the mesh data in the form of an indexed triangle list, which you can then convert to the data format required by your graphics engine. It is also necessary to call `ovrHmd_GetRenderScaleAndOffset` in order to retrieve values for the constants `EyeToSourceUVScale` and `EyeToSourceUVOffset` used in the vertex shader. For example, in OculusRoomTiny:

```
//Generate distortion mesh for each eye
for ( int eyeNum = 0; eyeNum < 2; eyeNum++ )
{
    // Allocate & generate distortion mesh vertices.
    ovrDistortionMesh meshData;
    ovrHmd_CreateDistortionMesh(hmd,
                                eyeRenderDesc[eyeNum].Eye, eyeRenderDesc[eyeNum].Fov,
                                distortionCaps, &meshData);

    ovrHmd_GetRenderScaleAndOffset(eyeRenderDesc[eyeNum].Fov,
                                   textureSize, viewports[eyeNum],
                                   (ovrVector2f*) DistortionData.UVScaleOffset[eyeNum]);

    // Now parse the vertex data and create a render ready vertex buffer from it
    DistortionVertex * pVBVerts = (DistortionVertex*)OVR_ALLOC(
                                        sizeof(DistortionVertex) * meshData.VertexCount );
    DistortionVertex * v        = pVBVerts;
    ovrDistortionVertex * ov    = meshData.pVertexData;
    for ( unsigned vertNum = 0; vertNum < meshData.VertexCount; vertNum++ )
    {
        v->Pos.x = ov->Pos.x;
        v->Pos.y = ov->Pos.y;
        v->TexR  = (*(Vector2f*)&ov->TexR);
        v->TexG  = (*(Vector2f*)&ov->TexG);
        v->TexB  = (*(Vector2f*)&ov->TexB);
        v->Col.R = v->Col.G = v->Col.B = (OVR::UByte)( ov->VignetteFactor * 255.99f );
        v->Col.A = (OVR::UByte)( ov->TimeWarpFactor * 255.99f );
        v++; ov++;
    }

    //Register this mesh with the renderer
    DistortionData.MeshVBs[eyeNum] = *pRender->CreateBuffer();
    DistortionData.MeshVBs[eyeNum]->Data ( Buffer_Vertex, pVBVerts,
                                           sizeof(DistortionVertex) * meshData.VertexCount );

    DistortionData.MeshIBs[eyeNum] = *pRender->CreateBuffer();
    DistortionData.MeshIBs[eyeNum]->Data ( Buffer_Index, meshData.pIndexData,
                                           sizeof(unsigned short) * meshData.IndexCount );

    OVR_FREE ( pVBVerts );
    ovrHmd_DestroyDistortionMesh( &meshData );
}
```

For extra performance, this code can be merged with existing post-processing shaders, such as exposure correction or color grading. However, you should do so before and after pixel-exact checking, to ensure that the shader and mesh still calculate the correct distortion. It is very common to get something that looks plausible, but even a few pixels of error can cause discomfort for users.

8.3.3 Game rendering loop

The game render loop must now process the render timing information for each frame, render the scene for the left and right eyes, render the distortion mesh, call present, and wait as necessary to achieve minimum perceived latency. The following code demonstrates this:

```
ovrHmd hmd;
ovrPosef headPose[2];

ovrFrameTiming frameTiming = ovrHmd_BeginFrameTiming(hmd, 0);

pRender->SetRenderTarget ( pRendertargetTexture );
pRender->Clear();

for (int eyeIndex = 0; eyeIndex < ovrEye_Count; eyeIndex++)
{
    ovrEyeType eye = hmd->EyeRenderOrder[eyeIndex];
    headPose[eye] = ovrHmd_GetEyePose(hmd, eye);

    Quatf orientation = Quatf(eyePose.Orientation);
    Matrix4f proj = ovrMatrix4f_Projection(EyeRenderDesc[eye].Fov,
                                           0.01f, 10000.0f, true);

    // * Test code *
    // Assign quaternion result directly to view (translation is ignored).
    Matrix4f view = Matrix4f(orientation.Inverted()) * Matrix4f::Translation(-WorldEyePosition);

    pRender->SetViewport(EyeRenderViewport[eye]);
    pRender->SetProjection(proj);

    pRoomScene->Render(pRender, Matrix4f::Translation(EyeRenderDesc[eye].ViewAdjust) * view);
}

// Wait till time-warp point to reduce latency.
ovr_WaitTillTime(frameTiming.TimewarpPointSeconds);


// Prepare for distortion rendering.
pRender->SetRenderTarget(NULL);
pRender->SetFullViewport();
pRender->Clear();

ShaderFill distortionShaderFill(DistortionData.Shaders);
distortionShaderFill.SetTexture(0, pRendertargetTexture);
distortionShaderFill.SetInputLayout(DistortionData.VertexIL);

for (int eyeIndex = 0; eyeIndex < 2; eyeIndex++)
{
    // Setup shader constants
    DistortionData.Shaders->SetUniform2f("EyeToSourceUVScale",
    DistortionData.UVScaleOffset[eyeIndex][0].x, DistortionData.UVScaleOffset[eyeIndex][0].y);
    DistortionData.Shaders->SetUniform2f("EyeToSourceUVOffset",
    DistortionData.UVScaleOffset[eyeIndex][1].x, DistortionData.UVScaleOffset[eyeIndex][1].y);

    ovrMatrix4f timeWarpMatrices[2];
    ovrHmd_GetEyeTimewarpMatrices(hmd, (ovrEyeType) eyeIndex, headPose[eyeIndex],
                                  timeWarpMatrices);

    DistortionData.Shaders->SetUniform4x4f("EyeRotationStart", Matrix4f(timeWarpMatrices[0]));
    DistortionData.Shaders->SetUniform4x4f("EyeRotationEnd",   Matrix4f(timeWarpMatrices[1]));

    // Perform distortion
    pRender->Render(&distortionShaderFill,
                    DistortionData.MeshVBs[eyeIndex], DistortionData.MeshIBs[eyeIndex]);
}
```

```
pRender->Present( VSyncEnabled );
pRender->WaitUntilGpuIdle();  //for lowest latency
ovrHmd_EndFrameTiming(hmd);
```

8.4 Multi-threaded engine support

Modern applications, particularly video game engines, often distribute processing over multiple threads. When integrating the Oculus SDK, care needs to be taken to ensure that the API functions are called in the appropriate manner, and that timing is being managed correctly for accurate HMD pose prediction. This section describes two multi-threaded scenarios that might be used. Hopefully the insight provided will enable you to handle these issues correctly even if your application's multi-threaded approach differs from those presented. As always if you require guidance please visit developer.oculusvr.com.

One of the factors that dictates API policy is our use of the application rendering API inside of the SDK e.g. Direct3D. Generally, rendering API's impose their own multi-threading restrictions. For example it's common that core rendering functions must be called from the same thread that was used to create the main rendering device. These limitations in turn impose restrictions on the use of the Oculus API.

These rules apply:

- All tracking interface functions are thread-safe, allowing tracking state to be sampled from different threads.
- All of rendering functions including the configure and frame functions are **not thread safe**. It is ok to use ConfigureRendering on one thread and handle frames on another thread, but explicit synchronization must be done since functions that depend on configured state are not reentrant.
- All of the following calls must be done on the render thread. This is the thread used by the application to create the main rendering device. `ovrHmd_BeginFrame` (or `ovrHmd_BeginFrameTiming` and `ovrHmd_EndFrame`, `ovrHmd_GetEyePose`, `ovrHmd_GetEyeTimewarpMatrices`.

8.4.1 Update and render on different threads

It is common for video game engines to separate the actions of updating the state of the world and rendering a view of it. In addition, executing these on separate threads (mapped onto different cores) allows them to execute concurrently and utilize a greater amount of the available CPU resources. Typically the update operation will execute AI logic and player character animation which, in VR, will require the current headset pose. In the case of the rendering operation, this needs to determine the view transform when rendering the left and right eyes and hence also needs the head pose. The main difference between the two is the level of accuracy required. Head pose for AI purposes usually on has to be moderately accurate. When rendering, on the other hand, it's critical that the head pose used to render the scene matches the head pose at the time that the image is displayed on the screen as closely as possible. The SDK employs two techniques to try and ensure this. The first is prediction whereby the application can request the predicted head pose at a future point in time. The `ovrFrameTiming` struct provides accurate timing information for this purpose. The second technique is Timewarp in which we wait until a very short time before the presentation of the next frame to the display, perform another head pose reading, and re-project the rendered image to take account of any changes in predicted headpose that occured since the head pose was read during rendering.

Generally the closer we are to the time that the frame is displayed, the better the prediction of head pose at that time will be. It's perfectly fine to read head pose several times during the render operation, each time passing in the same future time that the frame will be displayed (in the case of calling `ovrHmd_GetFrameTiming`), and each time receiving a more accurate estimate of future head pose. However, in order for Timewarp to function correctly, you must pass in the actual head pose that was used to determine the view matrices

when you come to make the call to `ovrHmd_EndFrame` (in the case of SDK distortion rendering) or `ovrHmd_GetEyeTimewarpMatrices` (for client distortion rendering).

When obtaining the head pose for the update operation it will typically suffice to get the current head pose (rather than the predicted one). This can be obtained with:

```
    ovrTrackingState ts  = ovrHmd_GetTrackingState(hmd, ovr_GetTimeInSeconds());
```

The next section deals which a scenario where we need to get the final head pose used for rendering from a non render thread, and hence also need to use prediction.

8.4.2 Render on different threads

In some engines render processing is distributed across more than one thread. For example, one thread may perform culling and render setup for each object in the scene (we shall refer to this as the "main" thread), while a second thread makes the actual D3D or OpenGL API calls (referred to as the "render" thread). The difference between this and the former scenario is that now the non-render thread needs to obtain accurate predictions of head pose, and in order to do this needs an accurate estimate of the time until the frame being processed will appear on the screen. Furthermore, due to the asynchronous nature of this approach, while a frame is being rendered by the render thread, the next frame frame might be being processed by the main thread. As a result it's necessary for the application to associate the head poses that were obtained in the main thread with the frame, such that when that frame is being rendered by the render thread the application is able to pass in the correct head pose transforms into `ovrHmd_EndFrame` or `ovrHmd_GetEyeTimewarpMatrices`. For this purpose we introduce the concept of a `frameIndex` which is created by the application, incremented each frame, and passed into several of the API functions.

Essentially, there are three additional things to consider:

1. The main thread needs to assign a frame index to the current frame being processed for rendering. This is used in the call to `ovrHmd_GetFrameTiming` to return the correct timing for pose prediction etc.
2. The main thread should call the thread safe function `ovrHmd_GetTrackingState` with the predicted time value.
3. When the rendering commands generated on the main thread are executed on the render thread, then pass in the corresponding value of `frameIndex` when calling `ovrHmd_BeginFrame`. Similarly, when calling `ovrHmd_EndFrame`, pass in the actual pose transform used when that frame was processed on the main thread (from the call to `ovrHmd_GetTrackingState`).

The following code illustrates this in more detail:

```
void MainThreadProcessing()
{
    frameIndex++;

    // Ask the API for the times when this frame is expected to be displayed.
    ovrFrameTiming frameTiming = ovrHmd_GetFrameTiming(hmd, frameIndex);

    // Get the corresponding predicted pose state.
    ovrTrackingState state = ovrHmd_GetTrackingState(hmd, frameTiming.ScanoutMidpointSeconds);
```

```
    ovrPosef pose = state.HeadPose.ThePose;

    SetFrameHMDData(frameIndex, pose);

    // Do render pre-processing for this frame.

    ...

}

void RenderThreadProcessing()
{

    int frameIndex;
    ovrPosef pose;

    GetFrameHMDData(&frameIndex, &pose);

    // Call begin frame and pass in frameIndex.
    ovrFrameTiming hmdFrameTiming = ovrHmd_BeginFrame(hmd, frameIndex);

    // Execute actual rendering to eye textures.
    ovrTexture eyeTexture[2]);

    ...

    ovrPosef renderPose[2] = {pose, pose};

    ovrHmd_EndFrame(hmd, pose, eyeTexture);
}
```

8.5 Advanced rendering configuration

By default, the SDK generates configuration values that optimize for rendering quality, however it also provides a degree of flexibility, for example when creating render target textures. This section discusses changes that you may wish to make in order to trade-off rendering quality versus performance, or if the engine you are integrating with imposes various constraints.

8.5.1 Render target size

The SDK has been designed with the assumption that you want to use your video memory as carefully as possible, and that you can create exactly the right render target size for your needs. However, real video cards and real graphics APIs have size limitations (all have a maximum size, some also have a minimum size). They may also have granularity restrictions, for example only being able to create render targets that are a multiple of 32 pixels in size, or having a limit on possible aspect ratios. As an application developer, you may also choose to impose extra restrictions to avoid using too much graphics memory.

In addition to the above, the size of the actual render target surface in memory may not necessarily be the same size as the portion that is rendered to. The latter may be slightly smaller. However, since it's specified as a viewport it typically does not have any granularity restrictions. When you bind the render target as a texture, however, it is the full surface that is used, and so the UV coordinates must be corrected for the difference between the size of the rendering and the size of the surface it is on. The API will do this for you but you need to tell it the relevant information.

The following code shows a two-stage approach for settings render target resolution. The code first calls `ovrHmd_GetFovTextureSize` to compute the ideal size of the render target. Next, the graphics library is called to create a render target of the desired resolution. In general, due to idiosyncrasies of the platform and hardware, the resulting texture size may be different from that requested.

```
// Get recommended left and right eye render target sizes.
Sizei recommenedTex0Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Left,
                           hmd->DefaultEyeFov[0], pixelsPerDisplayPixel);
Sizei recommenedTex1Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Right,
                           hmd->DefaultEyeFov[1], pixelsPerDisplayPixel);

// Determine dimensions to fit into a single render target.
Sizei renderTargetSize;
renderTargetSize.w = recommenedTex0Size.w + recommenedTex1Size.w;
renderTargetSize.h = max ( recommenedTex0Size.h, recommenedTex1Size.h );

// Create texture.
pRendertargetTexture = pRender->CreateTexture(renderTargetSize.w, renderTargetSize.h);

// The actual RT size may be different due to HW limits.
renderTargetSize.w = pRendertargetTexture->GetWidth();
renderTargetSize.h = pRendertargetTexture->GetHeight();

// Initialize eye rendering information.
// The viewport sizes are re-computed in case RenderTargetSize changed due to HW limitations.
ovrFovPort eyeFov[2] = { hmd->DefaultEyeFov[0], hmd->DefaultEyeFov[1] };

EyeRenderViewport[0].Pos  = Vector2i(0,0);
EyeRenderViewport[0].Size = Sizei(renderTargetSize.w / 2, renderTargetSize.h);
EyeRenderViewport[1].Pos  = Vector2i((renderTargetSize.w + 1) / 2, 0);
EyeRenderViewport[1].Size = EyeRenderViewport[0].Size;
```

In the case of SDK distortion rendering this data is passed into `ovrHmd_ConfigureRendering` as follows (code shown is for the D3D11 API):

```
ovrEyeRenderDesc eyeRenderDesc[2];

ovrBool result = ovrHmd_ConfigureRendering(hmd, &d3d11cfg.Config,
                                           ovrDistortion_Chromatic | ovrDistortion_TimeWarp,
                                           eyeFov, eyeRenderDesc);
```

Alternatively, in the case of client distortion rendering, you would call `ovrHmd_GetRenderDesc` as follows:

```
ovrEyeRenderDesc eyeRenderDesc[2];

eyeRenderDesc[0] = ovrHmd_GetRenderDesc(hmd, ovrEye_Left, eyeFov[0]);
eyeRenderDesc[1] = ovrHmd_GetRenderDesc(hmd, ovrEye_Right, eyeFov[1]);
```

You are free to choose the render target texture size and left and right eye viewports as you wish, provided that you specify these values when calling `ovrHmd_EndFrame` (in the case of SDK rendering using the `ovrTexture` structure) or `ovrHmd_GetRenderScaleAndOffset` (in the case of client rendering). However, using `ovrHmd_GetFovTextureSize` will ensure that you allocate the optimum size for the particular HMD in use. Sections 8.5.3 and 8.5.4 below consider various modifications to the default configuration that can be made to trade-off quality versus improved performance. You should also note that the API supports using different render targets for each eye if that is required by your engine (although using a single render target is likely to perform better since it will reduce context switches). OculusWorldDemo allows you to toggle between using a single combined render target versus separate ones for each eye, by navigating to the settings menu (press the Tab key) and selecting the "Share RenderTarget" option.

8.5.2 Forcing a symmetrical field of view

Typically the API will return an FOV for each eye that is not symmetrical, meaning the left edge is not the same distance from the centerline as the right edge. This is because humans, as well as the Rift, have a wider FOV when looking outwards. When you look inwards, towards your nose, your nose is in the way! We are also better at looking down than we are at looking up. For similar reasons, the Rift's view is not symmetrical. It is controlled by the shape of the lens, various bits of plastic, and the edges of the screen. The exact details depend on the shape of your face, your IPD, and where precisely you place the Rift on your face, and all this is set up in the configuration tool and stored in the user profile. It all means that almost nobody has all four edges of their FOV set to the same angle, and so the frustum produced will be an off-center projection frustum. In addition, most people will not have the same fields of view for both their eyes. They will be close, but usually not identical.

As an example, on DK1 the author's left eye has the following FOV:

- 53.6 degrees up
- 58.9 degrees down
- 50.3 degrees inwards (towards the nose)
- 58.7 degrees outwards (away from the nose)

In the code and documentation these are referred to as 'half angles' because traditionally a FOV is expressed as the total edge-to-edge angle. In this example the total horizontal FOV is 50.3+58.7 = 109.0 degrees, and the total vertical FOV is 53.6+58.9 = 112.5 degrees.

The recommended and maximum fields of view can be accessed from the HMD as shown below:

```
ovrFovPort defaultLeftFOV = hmd->DefaultEyeFov[ovrEye_Left];

ovrFovPort maxLeftFOV = hmd->MaxEyeFov[ovrEye_Left];
```

`DefaultEyeFov` refers to the recommended FOV values based on the current user's profile settings (IPD, eye relief etc). `MaxEyeFov` refers to the maximum FOV that the headset can possibly display, regardless of profile settings.

Choosing the default values will provide a good user experience with no unnecessary additional GPU load. Alternatively, if your application does not consume significant GPU resources then you may consider using the maximum FOV settings in order to reduce reliance on profile settings being correct. One option might be to provide a slider in the application control panel which enables the user to choose interpolated FOV settings somewhere between default and maximum. On the other hand, if your application is heavy on GPU usage you may wish to consider reducing the FOV below the default values as discussed in section 8.5.4.

The chosen FOV values should be passed into `ovrHmd_ConfigureRendering` in the case of SDK side distortion or `ovrHmd_GetRenderDesc` in the case of client distortion rendering.

The FOV angles for up, down, left, and right (expressed as the tangents of the half-angles), is the most convenient form if you need to set up culling or portal boundaries in your graphics engine. The FOV values are also used to determine the projection matrix used during left and right eye scene rendering. We provide an API utility function `ovrMatrix4f_Projection` that can be used for this purpose:

```
ovrFovPort fov;

// Determine fov.
...

ovrMatrix4f projMatrix = ovrMatrix4f_Projection(fov, znear, zfar, isRightHanded);
```

It is common for the top and bottom edges of the FOV to not be the same as the left and right edges when viewing a PC monitor. This is commonly called the 'aspect ratio' of the display, and very few displays are square. However, some graphics engines do not support off-center frustums. To be compatible with these engines, you will need to modify the FOV values reported by the `ovrHmdDesc` struct. In general, it is better to grow the edges than to shrink them. This will put a little more strain on the graphics engine, but will give the user the full immersive experience, even if they won't be able to see some of the pixels being rendered.

Some graphics engines require that you express symmetrical horizontal and vertical fields of view, and some need an even less direct method such as a horizontal FOV and an aspect ratio. Some also object to having frequent changes of FOV, and may insist that both eyes be set to the same. Here is some code for handling this most restrictive case:

```
ovrFovPort fovLeft = hmd->DefaultEyeFov[ovrEye_Left];
ovrFovPort fovRight = hmd->DefaultEyeFov[ovrEye_Right];

ovrFovPort fovMax = FovPort::Max(fovLeft, fovRight);
```

```
float combinedTanHalfFovHorizontal = max ( fovMax.LeftTan, fovMax.RightTan );
float combinedTanHalfFovVertical = max ( fovMax.UpTan, fovMax.DownTan );

ovrFovPort fovBoth;
fovBoth.LeftTan = fovBoth.RightTan = combinedTanHalfFovHorizontal;
fovBoth.UpTan = fovBoth.DownTan = combinedTanHalfFovVertical;


// Create render target.
Sizei recommenedTex0Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Left,
                                                    fovBoth, pixelsPerDisplayPixel);
Sizei recommenedTex1Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Right,
                                                    fovBoth, pixelsPerDisplayPixel);

...


// Initialize rendering info.
ovrFovPort eyeFov[2];
eyeFov[0]                       = fovBoth;
eyeFov[1]                       = fovBoth;

...


// Compute the parameters to feed to the rendering engine.
// In this case we are assuming it wants a horizontal FOV and an aspect ratio.
float horizontalFullFovInRadians = 2.0f * atanf ( combinedTanHalfFovHorizontal );
float aspectRatio = combinedTanHalfFovHorizontal / combinedTanHalfFovVertical;

GraphicsEngineSetFovAndAspect ( horizontalFullFovInRadians, aspectRatio );
...
```

Note that you will need to determine FOV before creating the render targets since FOV affects the size of the recommended render target required for a given quality.

8.5.3 Improving performance by decreasing pixel density

The first Rift development kit, DK1, has a fairly modest resolution of 1280x800 pixels, split between the two eyes. However because of the wide FOV of the Rift and the way perspective projection works, the size of the intermediate render target required to match the native resolution in the center of the display is significantly higher. For example, to achieve a 1:1 pixel mapping in the center of the screen for the author's field-of-view settings on DK1 requires a render target that is 2000x1056 pixels in size, surprisingly large!

Even if modern graphics cards are able to render this resolution at the required 60Hz, future HMDs may have significantly higher resolutions. For virtual reality, dropping below 60Hz gives a terrible user experience, and it is always better to drop resolution in order to maintain framerate. This is a similar problem to a user having a high resolution 2560x1600 monitor. Very few 3D games can run at this native resolution at full speed, and so most allow the user to select a lower resolution which the monitor then upscales to fill the screen.

It is perfectly possible to do the same thing on the HMD. That is, to run it at a lower video resolution and let the hardware upscale for you. However this introduces two steps of filtering, one by the distortion processing, and a second one by the video upscaler. This double filtering introduces significant artifacts. It is usually more effective to leave the video mode at the native resolution, but limit the size of the intermediate render target. This gives a similar increase in performance, but preserves more of the detail.

One way the application might choose to expose this control to the user is with a traditional resolution selector.

However, it's a little odd because the actual resolution of the render target depends on the user's configuration, rather than directly on a fixed hardware setting, which means that the 'native' resolution is different for different people. In addition, presenting resolutions higher than the physical hardware resolution may be confusing to the user. They may not understand that selecting 1280x800 is a significant drop in quality, even though this is the resolution reported by the hardware.

A better option for you is to modify the `pixelsPerDisplayPixel` value that is passed into the function `ovrHmd_GetFovTextureSize`. This could also be based on a slider presented in the applications render settings. This determines the relative size of render targetpixels as they map to pixels at the center of the display surface. For example, a value of 0.5 would reduce the render target size from 2000x1056 to 1000x528 pixels, which may allow mid-range PC graphics cards to maintain 60Hz.

```
float pixelsPerDisplayPixel = GetPixelsPerDisplayFromApplicationSettings();

Sizei recommenedTexSize = ovrHmd_GetFovTextureSize(hmd, ovrEye_Left,  fovLeft,
                                                   pixelsPerDisplayPixel);
```

Although it is perfectly possible to set the parameter to a value larger than 1.0, thereby producing a higher-resolution intermediate render target, we have not observed any useful increase in quality by doing this, and it has a large performance cost.

OculusWorldDemo allows you to experiment with changing the render target pixel density. Navigate to the settings menu (press the Tab key) and select "Pixel Density". By pressing the up and down arrow keys you can adjust the pixel density at the center of the eye projection. Specifically, a value of 1.0 means that the render target pixel density matches the display surface 1:1 at this point on the display, whereas a value of 0.5 means that the density of render target pixels is only half that of the display surface. As an alternative, you may select the option "Dynamic Res Scaling" which will cause the pixel density to change continuously from 0 to 1.

8.5.4 Improving performance by decreasing field of view

As well as reducing the number of pixels in the intermediate render target, you can increase performance by decreasing the FOV that those pixels are stretched across. This does have an obvious problem in that it reduces the sense of immersion for the player since it literally gives them 'tunnel vision'. Nevertheless, reducing the FOV does increase performance in two ways. The most obvious is fillrate. For a fixed pixel density on the retina, a lower FOV is overall fewer pixels, and because of the properties of projective math, the outermost edges of the FOV are the most expensive in terms of numbers of pixels. The second reason is that there are fewer objects visible in each frame which implies less animation, fewer state changes, and fewer draw calls.

Reducing the FOV set by the player is a very painful choice to make. One of the key experiences of virtual reality is being immersed in the simulated world, and a large part of that is the wide FOV. Losing that aspect is not a thing we would ever recommend happily. However, if you have already sacrificed as much resolution as you can, and the application is still not running at 60Hz on the user's machine, this is an option of last resort.

We recommend giving players a 'maximum FOV' slider to play with, and this will define the maximum of the four edges of each eye's FOV.

```
ovrFovPort defaultFovLeft = hmd->DefaultEyeFov[ovrEye_Left];
ovrFovPort defaultFovRight = hmd->DefaultEyeFov[ovrEye_Right];

float maxFovAngle = ...get value from game settings panel...;
float maxTanHalfFovAngle = tanf ( DegreeToRad ( 0.5f * maxFovAngle ) );

ovrFovPort newFovLeft  = FovPort::Min(defaultFovLeft, FovPort(maxTanHalfFovAngle));
ovrFovPort newFovRight = FovPort::Min(defaultFovRight, FovPort(maxTanHalfFovAngle));


// Create render target.
Sizei recommenedTex0Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Left  newFovLeft,
                                                    pixelsPerDisplayPixel);
Sizei recommenedTex1Size = ovrHmd_GetFovTextureSize(hmd, ovrEye_Right, newFovRight,
                                                    pixelsPerDisplayPixel);

...


// Initialize rendering info.
ovrFovPort eyeFov[2];
eyeFov[0]                       = newFovLeft;
eyeFov[1]                       = newFovRight;

...


// Determine projection matrices.
ovrMatrix4f projMatrixLeft = ovrMatrix4f_Projection(newFovLeft, znear, zfar, isRightHanded);
ovrMatrix4f projMatrixRight = ovrMatrix4f_Projection(newFovRight, znear, zfar, isRightHanded);
```

It may be interesting to experiment with non-square fields of view, for example clamping the up and down ranges significantly (e.g. 70 degrees FOV) while retaining the full horizontal FOV for a 'Cinemascope' feel.

OculusWorldDemo allows you to experiment with reducing the FOV below the defaults. Navigate to the settings menu (press the Tab key) and select the "Max FOV" value. Pressing the up and down arrows allows you to change the maximum angle in degrees.

8.5.5 Improving performance by rendering in mono

A significant cost of stereo rendering is rendering two views, one for each eye. For some applications, the stereoscopic aspect may not be particularly important, and a monocular view may be acceptable in return for some performance. In other cases, some users may get eye strain from a stereo view and wish to switch to a monocular one. However, they still wish to wear the HMD as it gives them a high FOV and head-tracking ability.

OculusWorldDemo allows the user to toggle mono render mode by pressing the `F7` key.

Your code should have the following changes:

- Set the FOV to the maximum symmetrical FOV based on both eyes.
- Call `ovhHmd_GetFovTextureSize` with this FOV to determine the recommended render target size.
- Configure both eyes to use the same render target and the same viewport when calling `ovrHmd_EndFrame` or `ovrHmd_GetRenderScaleAndOffset`.

- Render the scene only once to this shared render target.

This merges the FOV of the left and right eyes into a single intermediate render. This render is still distorted twice, once per eye, because the lenses are not exactly in front of the user's eyes. However, this is still a significant performance increase.

Setting a virtual IPD to zero means that everything will seem gigantic and infinitely far away, and of course the user will lose much of the sense of depth in the scene. Note that it is important to scale virtual IPD and virtual head motion together, so if the virtual IPD is set to zero, all virtual head motion due to neck movement should also be eliminated. Sadly, this loses much of the depth cues due to parallax, but if the head motion and IPD do not agree it can cause significant disorientation and discomfort. Experiment with caution!

A Oculus API Changes

A.1 Changes since release 0.2

The Oculus API has been significantly redesigned since the 0.2.5 release, with the goals of improving ease of use, correctness and supporting a new driver model. The following is the summary of changes in the API:

- All of the HMD and sensor interfaces have been organized into a C API. This makes it easy to bind from other languages.
- The new Oculus API introduces two distinct approaches to rendering distortion: *SDK Rendered* and *Client Rendered*. As before, the application is expected to render stereo scenes onto one or more render targets. With the SDK rendered approach, the Oculus SDK then takes care of distortion rendering, frame present, and timing within the SDK. This means that developers don't need to setup pixel and vertex shaders or worry about the details of distortion rendering, they simply provide the device and texture pointers to the SDK. In client rendered mode, distortion rendering is handled by the application as with previous versions of the SDK. SDK Rendering is the preferred approach for future versions of the SDK.
- The method of rendering distortion in client rendered mode is now mesh based. The SDK returns a mesh which includes vertices and UV coordinates which are then used to warp the source render target image to the final buffer. Mesh based distortion is more efficient and flexible than pixel shader approaches.
- The Oculus SDK now keeps track of game frame timing and uses this information to accurately predict orientation and motion.
- A new technique called *Timewarp* is introduced to reduce motion-to-photon latency. This technique re-projects the scene to a more recently measured orientation during the distortion rendering phase.

The table on the next page briefly summarizes differences between the 0.2.5 and 0.4 API versions.

Functionality	0.2 SDK APIs	0.4 SDK C APIs
Initialization	`OVR::System::Init`, `DeviceManager`, `HMDDevice`, `HMDInfo`.	`ovr_Initialize`, `ovrHmd_Create`, `ovrHmd` handle and `ovrHmdDesc`.
Sensor Interaction	`OVR::SensorFusion` class, with `GetOrientation` returning `Quatf`. Prediction amounts are specified manually relative to the current time.	`ovrHmd_ConfigureTracking`, `ovrHmd_GetTrackingState` returning `ovrTrackingState`. `ovrHmd_GetEyePose` returns head pose based on correct timing.
Rendering Setup	`Util::Render::StereoConfig` helper class creating `StereoEyeParams`, or manual setup based on members of `HMDInfo`.	`ovrHmd_ConfigureRendering` populates `ovrEyeRenderDesc` based on the field of view. Alternatively, `ovrHmd_GetRenderDesc` supports rendering setup for client distortion rendering.
Distortion Rendering	App-provided pixel shader based on distortion coefficients.	Client rendered: based on the distortion mesh returned by `ovrHmd_CreateDistortionMesh`. *(or)* SDK rendered: done automatically in `ovrHmd_EndFrame`.
Frame Timing	Manual timing with current-time relative prediction.	Frame timing is tied to vsync with absolute values reported by `ovrHmd_BeginFrame` or `ovr_BeginFrameTiming`.

A.2 Changes since release 0.3

A number of changes were made to the API since the 0.3.2 Preview release. These are summarized as follows:

- Removed the method `ovrHmd_GetDesc`. The `ovrHmd` handle is now a pointer to a `ovrHmdDesc` struct.
- The sensor interface has been simplified. Your application should now call `ovrHmd_ConfigureTracking` at initialization and `ovrHmd_GetTrackingState` or `ovrHmd_GetEyePose` to get the head pose.
- `ovrHmd_BeginEyeRender` and `ovrHmd_EndEyeRender` have been removed. You should now use `ovrHmd_GetEyePose` to determine predicted head pose when rendering each eye. Render poses and `ovrTexture` info is now passed into `ovrHmd_EndFrame` rather than `ovrHmd_EndEyeRender`.
- `ovrSensorState` struct is now `ovrTrackingState`. The predicted pose `Predicted` is now named `HeadPose`. `CameraPose` and `LeveledCameraPose` have been added. Raw sensor data can be obtained through `RawSensorData`.
- `ovrSensorDesc` struct has been merged into `ovrHmdDesc`.

- Addition of `ovrHmd_AttachToWindow`. This is a platform specific function to specify the application window whose output will be displayed on the HMD. Only used if the `ovrHmdCap_ExtendDesktop` flag is false.
- Addition of `ovr_GetVersionString`. Returns a string representing the libOVR version.

There have also been a number of minor changes:

- Renamed `ovrSensorCaps` struct to `ovrTrackingCaps`.
- Addition of `ovrHmdCaps::ovrHmdCap_Captured` flag. Set to 'true' if the application captured ownership of the HMD.
- Addition of `ovrHmdCaps::ovrHmdCap_ExtendDesktop` flag. Means the display driver is in compatibility mode (read only).
- Addition of `ovrHmdCaps::ovrHmdCap_NoMirrorToWindow` flag. Disables mirroring of HMD output to the window. This may improve rendering performance slightly (only if 'ExtendDesktop' is off).
- Addition of `ovrHmdCaps::ovrHmdCap_DisplayOff` flag. Turns off HMD screen and output (only if 'ExtendDesktop' is off).
- Removed `ovrHmdCaps::ovrHmdCap_LatencyTest` flag. Was used to indicate support of pixel reading for continuous latency testing.
- Addition of `ovrDistortionCaps::ovrDistortionCap_Overdrive` flag. Overdrive brightness transitions to reduce artifacts on DK2+ displays.
- Addition of `ovrStatusBits::ovrStatus_CameraPoseTracked` flag. Indicates that the camera pose has been successfully calibrated.

B Display Device Management

NOTE This section was original written when management of the Rift display as part of the desktop was the only option. With the introduction of the Oculus Display Driver the standard approach is now to select *Direct HMD Access From Apps* mode and let the SDK manage the device. However, until the driver matures it may still be necessary to switch to one of the legacy display modes which require managing the display as part of the desktop. For that reason this section has been left in the document as reference.

B.1 Display Identification

Display devices identify themselves and their capabilities using EDID[1]. When the device is plugged into a PC, the display adapter reads a small packet of data from it. This includes the manufacturer code, device name, supported display resolutions, and information about video signal timing. When running an OS that supports multiple monitors, the display is identified and added to a list of active display devices which can be used to show the desktop or fullscreen applications.

The display within the Oculus Rift interacts with the system in the same way as a typical PC monitor. It too provides EDID information which identifies it as having a manufacturer code of 'OVR', a model ID of 'Rift DK1', and support for several display resolutions including its native 1280×800 at 60Hz.

B.2 Display Configuration

After connecting a Rift to the PC it is possible to modify the display settings through the Windows Control Panel. In Windows 7 ,select **Control Panel, All Control Panel Items, Display, Screen Resolution**. In MacOS, use the **System Preferences, Display** panel In Ubuntu Linux, use the **System Settings, Displays** control panel.

Figure 10 shows the Windows "Screen Resolution" dialog for a PC with the Rift display and a PC monitor connected. In this configuration, there are four modes that can be selected as show in the figure. These are duplicate mode, extended mode, and standalone mode for either of the displays.

B.2.1 Duplicate display mode

In duplicate display mode the same portion of the desktop is shown on both displays, and they adopt the same resolution and orientation settings. The OS attempts to choose a resolution which is supported by both displays, while favoring the native resolutions described in the EDID information reported by the displays. Duplicate mode is a potentially viable mode in which to configure the Rift, however it suffers from vsync issues.

B.2.2 Extended display mode

In extended mode the displays show different portions of the desktop. The Control Panel can be used to select the desired resolution and orientation independently for each display. Extended mode suffers from shortcomings related to the fact that the Rift is not a viable way to interact with the desktop. Nevertheless, it

[1] Extended Display Identification Data

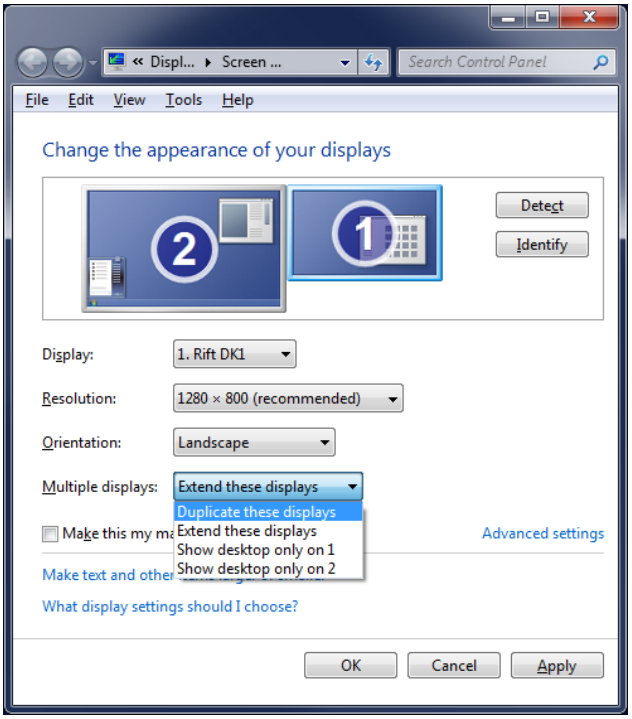


Figure 10: Screenshot of the Windows "Screen Resolution" dialog.

is the current recommended configuration option. The shortcomings are discussed in more detail in the B.4 section of this document.

B.2.3 Standalone display mode

In standalone mode the desktop is displayed on just one of the plugged in displays. It is possible to configure the Rift as the sole display, however this becomes impractical due to issues interacting with the desktop.

B.3 Selecting A Display Device

Reading of EDID information from display devices can occasionally be slow and unreliable. In addition, EDID information may be cached, leading to problems with old data. As a result, display devices may sometimes become associated with incorrect display names and resolutions, with arbitrary delays before the information becomes current.

Because of these issues we adopt an approach which attempts to identify the Rift display name among the attached display devices, however we do not require that it be found for an HMD device to be created using the API.

If the Rift display device is not detected but the Rift is detected through USB, then an empty display name string is returned. In this case, your application could attempt to locate it using additional information, such as display resolution.

In general, due to the uncertainty associated with identifying the Rift display device, it may make sense to

incorporate functionality into your application to allow the user to choose the display manually, such as from a drop-down list of enumerated display devices. One additional root cause of the above scenario, aside from EDID issues, is that the user failed to plug in the Rift video cable. You should make sure you have appropriate assistance within your application to help users troubleshoot an incorrectly connected Rift device.

B.3.1 Windows

If there are no EDID issues and we detect the Rift display device successfully, then we return the display name corresponding to that device, for example `\\.\DISPLAY1\Monitor0`.

To display the video output on the Rift, the application needs to match the display name determined above to an object used by the rendering API. Unfortunately, each rendering system used on Windows (OpenGL, Direct3D 9, Direct3D 10-11) uses a different approach. OpenGL uses the display device name returned in HMDInfo, while in Direct3D the display name must be matched against a list of displays returned by D3D. The DesktopX and DesktopY members of HMDInfo can be used to position a window on the Rift if you do not want to use fullscreen mode.

When using Direct3D 10 or 11, the following code shows how to obtain an IDXGIOutput interface using the DXGI API:

```
IDXGIOutput* searchForOculusDisplay(char* oculusDisplayName)
{
    IDXGIFactory* pFactory;
    CreateDXGIFactory(__uuidof(IDXGIFactory), (void**)(&pFactory));

    UInt32 adapterIndex = 0;
    IDXGIAdapter* pAdapter;

    // Iterate through adapters.
    while (pFactory->EnumAdapters(adapterIndex, &pAdapter) !=
                                DXGI_ERROR_NOT_FOUND)
    {
        UInt32 outputIndex = 0;
        IDXGIOutput* pOutput;

        // Iterate through outputs.
        while (pAdapter->EnumOutputs(outputIndex, &pOutput) !=
                                DXGI_ERROR_NOT_FOUND)
        {
            DXGI_OUTPUT_DESC outDesc;
            pOutput->GetDesc(&outDesc);
            char* outputName = outDesc.DeviceName;

            // Try and match the first part of the display name.
            // For example an outputName of "\\.\DISPLAY1" might
            // correspond to a displayName of "\\.\DISPLAY1\Monitor0".
            // If two monitors are setup in 'duplicate' mode then they will
            // have the same 'display' part in their display name.
            if (strstr(oculusDisplayName, outputName) == oculusDisplayName)
            {
                return pOutput;
            }
        }
    }

    return NULL;
}
```

After you've successfully obtained the IDXGIOutput interface, you can set your Direct3D swap-chain to render to it in fullscreen mode using the following:

```
IDXGIOutput* pOculusOutputDevice = searchForOculusDisplay(oculusDisplayName);
pSwapChain->SetFullscreenState(TRUE, pOculusOutputDevice);
```

When using Direct3D 9, you must create the Direct3DDevice with the "adapter" number corresponding to the Rift (or other display that you want to output to). This next function shows how to find the adapter number:

```
unsigned searchForOculusDisplay(const char* oculusDisplayName)
{
    for (unsigned Adapter=0; Adapter < Direct3D->GetAdapterCount(); Adapter++)
    {
        MONITORINFOEX Monitor;
        Monitor.cbSize = sizeof(Monitor);
        if (::GetMonitorInfo(Direct3D->GetAdapterMonitor(Adapter), &Monitor) && Monitor.szDevice[0])
        {
            DISPLAY_DEVICE DispDev;
            memset(&DispDev, 0, sizeof(DispDev));
            DispDev.cb = sizeof(DispDev);
            if (::EnumDisplayDevices(Monitor.szDevice, 0, &DispDev, 0))
            {
                if (strstr(DispDev.DeviceName, oculusDisplayName))
                {
                    return Adapter;
                }
            }
        }
    }
    return D3DADPATER_DEFAULT;
}
```

Unfortunately, you must re-create the device to switch fullscreen displays. You can use a fullscreen device for windowed mode without recreating it (although it still has to be reset).

B.3.2 MacOS

When running on MacOS, the `ovrHMDDesc` struct contains a `DisplayID` which you should use to target the Rift in fullscreen. If the Rift is connected (and detected by libovr), its DisplayId is stored, otherwise DisplayId contains 0. The following is an example of how to use this to make a Cocoa `NSView` fullscreen on the Rift:

```
CGDirectDisplayId RiftDisplayId = (CGDirectDisplayId) hmd->DisplayId;

NSScreen* usescreen = [NSScreen mainScreen];
NSArray* screens = [NSScreen screens];
for (int i = 0; i < [screens count]; i++)
{
    NSScreen* s = (NSScreen*)[screens objectAtIndex:i];
    CGDirectDisplayID disp = [NSView displayFromScreen:s];

    if (disp == RiftDisplayId)
        usescreen = s;
}

[View enterFullScreenMode:usescreen withOptions:nil];
```

The `WindowPos` member of `ovrHMDDesc` can be used to position a window on the Rift if you do not want to use fullscreen mode.

B.4 Rift Display Considerations

There are several considerations when it comes to managing the Rift display on a desktop OS.

B.4.1 Duplicate mode VSync

In duplicate monitor mode it is common for the supported video timing information to be different across the participating monitors, even when displaying the same resolution. When this occurs the video scans on each display will be out of sync and the software vertical sync mechanism will be associated with only one of the displays. In other words, swap-chain buffer switches (for example following a `glSwapBuffers` or Direct3D `Present` call) will only occur at the correct time for one of the displays, and 'tearing' will occur on the other display. In the case of the Rift, tearing is very distracting, and so ideally we'd like to force it to have vertical sync priority. Unfortunately, the ability to do this is not something that we've found to be currently exposed in system APIs.

B.4.2 Extended mode problems

When extended display mode is used in conjunction with the Rift, the desktop will extend partly onto the regular monitors and partly onto the Rift. Since the Rift displays different portions of the screen to the left and right eyes, it is not suited to displaying the desktop in a usable form, and confusion may arise if icons or windows find their way onto the portion of the desktop displayed on the Rift.

B.4.3 Observing Rift output on a monitor

Sometimes it's desirable to be able to see the same video output on the Rift and on an external monitor. This can be particularly useful when demonstrating the device to a new user, or during application development. One way to achieve this is through the use of duplicate monitor mode as described above, however we don't currently recommend this approach due to the vertical sync priority issue. An alternative approach is through the use of a DVI or HDMI splitter. These take the video signal coming from the display adapter and duplicate it such that it can be fed to two or more display devices simultaneously. Unfortunately this can also cause problems depending on how the EDID data is managed. Specifically, with several display devices connected to a splitter, which EDID information should be reported back to the graphics adapter? Low cost HDMI splitters have been found to exhibit unpredictable behavior. Typically they pass on EDID information from one of the attached devices, but exactly how the choice is determined is often unknown. Higher cost devices may have explicit schemes (for example they report the EDID from the display plugged into output port one), but these can cost more than the Rift itself! Generally, the use of third party splitters and video switching boxes means that Rift EDID data may not be reliably reported to the OS, and therefore libovr will not be able to identify the Rift.

B.4.4 Windows: Direct3D enumeration

As described above the nature of the Rift display means that it is not suited to displaying the Windows desktop. As a result you might be inclined to set standalone mode for your regular monitor to remove the Rift from the list of devices displaying the Windows desktop. Unfortunately this also causes the device to no longer be enumerated when querying for output devices during Direct3D setup. As a result, the only viable option currently is to use the Rift in extended display mode.

C Chromatic Aberration

Chromatic aberration is a visual artifact seen when viewing images through lenses. The phenomenon causes colored fringes to be visible around objects, and is increasingly more apparent as our view shifts away from the center of the lens. The effect is due to the refractive index of the lens varying for different wavelengths of light (shorter wavelengths towards the blue end of the spectrum are refracted less than longer wavelengths towards the red end). Since the image being displayed on the Rift is composed of individual red, green, and blue pixels,[2] it too is susceptible to the unwanted effects of chromatic aberration. The manifestation, when looking through the Rift, is that the red, green, and blue components of the image appear to be scaled out radially, and by differing amounts. Exactly how apparent the effect is depends on the image content and to what degree users are concentrating on the periphery of the image versus the center.

C.1 Correction

Fortunately, programmable GPUs provide the means to significantly reduce the degree of visible chromatic aberration, albeit at some additional GPU expense. This is done by pre-transforming the image so that after the lens causes chromatic aberration, the end result is a more normal looking image. This is exactly analogous to the way in which we pre-distort the image to cancel out the distortion effects generated by the lens.

C.2 Sub-channel aberration

Although we can reduce the artifacts through the use of distortion correction, it's important to note that this approach cannot remove them completely for an LCD display panel. This is due to the fact that each color channel is actually comprised of a range of visible wavelengths, each of which is refracted by a different amount when viewed through the lens. As a result, although we're able to distort the image for each channel to bring the peak frequencies back into spatial alignment, it's not possible to compensate for the aberration that occurs within a color channel. Typically, when designing optical systems, chromatic aberration across a wide range of wavelengths is managed by carefully combining specific optical elements (in other texts, for example, look for "achromatic doublets").

[2] In a typical LCD display, pixel color is achieved using red, green, and blue dyes, which selectively absorb wavelengths from the back-light.

D SDK Samples and Gamepad Usage

Some of the Oculus SDK samples use gamepad controllers to enable movement around the virtual world. This section describes the devices that are currently supported and setup instructions.

Xbox 360 wired controller for Windows

1. Plug the device into a USB port.
2. Windows should recognize the controller and install any necessary drivers automatically.

Logitech F710 Wireless Gamepad

Windows

1. Put the controller into 'XInput' mode by moving the switch on the front of the controller to the 'X' position.
2. Press a button on the controller so that the green LED next to the 'Mode' button begins to flash.
3. Plug the USB receiver into the PC while the LED is flashing.
4. Windows should recognize the controller and install any necessary drivers automatically.

Mac

1. Put the controller into 'DirectInput' mode by moving the switch on the front of the controller to the 'D' position.
2. Press a button on the controller so that the green LED next to the 'Mode' button begins to flash.
3. Plug the USB receiver into the PC while the LED is flashing.
4. OSX should recognize the controller and install any necessary drivers automatically.

Sony PlayStation DUALSHOCK3 Controller

Mac

1. Turn off any nearby PS3 consoles.
2. Go to the Bluetooth section of 'System Preferences...'.
3. Make sure the 'On' and 'Discoverable' check boxes are checked.
4. Plug the controller into the Mac using the USB cable.
5. Press the 'PS' Button in the middle of the controller for 3 seconds and then remove the USB cable.
6. After removing the cable, the controller should immediately appear in the device list. If a dialog appears requesting a passcode enter 'xxxx' and then press 'Pair'.
7. Click on the 'gear' symbol beneath the list of Bluetooth devices and select 'Add to Favorites'.

8. Click on the ‘gear’ symbol once more and select ‘Update Services’.
9. Quickly turn Bluetooth off and then immediately back on again.
10. Press the ‘PS’ Button on the controller. The controller status should now appear as ‘Connected’.

E Low-Level Sensor Details

NOTE The following section is left for reference although parts of it may be out of date after the introduction of the external position tracking camera with DK2.

In normal use, applications will use the API functions which handle sensor fusion, correction, and prediction for them. This section is provided purely for interest.

Developers can read the raw sensor data directly from `ovrTrackingState::RawSensorData`. This contains the following data:

```
ovrVector3f Accelerometer;  // Acceleration reading in m/s^2.
ovrVector3f Gyro;           // Rotation rate in rad/s.
ovrVector3f Magnetometer;   // Magnetic field in Gauss.
float       Temperature;    // Temperature of the sensor in degrees Celsius.
float       TimeInSeconds;  // Time when the reported IMU reading took place, in seconds.
```

Over long periods of time, a discrepancy will develop between `Q` (the current head pose estimate) and the true orientation of the Rift. This problem is called *drift error*, which described more in the following section. Errors in pitch and roll are automatically reduced by using accelerometer data to estimate the gravity vector.

Errors in yaw are reduced by magnetometer data. For many games, such as a standard First Person Shooter (FPS), the yaw direction is frequently modified by the game controller and there is no problem. However, in many other games or applications, the yaw error will need to be corrected. For example, if you want to maintain a cockpit directly in front of the player. It should not unintentionally drift to the side over time. Yaw error correction is enabled by default.

E.0.1 Sensor Fusion Details

The most important part of sensor fusion is the integration of angular velocity data from the gyroscope. In each tiny interval of time, a measurement of the angular velocity arrives:

$$\omega = (\omega_x, \omega_y, \omega_z). \tag{1}$$

Each component is the rotation rate in radians per second about its corresponding axis. For example, if the sensor were sitting on the center of a spinning hard drive disk that sits in the XZ plane, then ω_y is the rotation rate about the Y axis, and $\omega_x = \omega_z = 0$.

What happens when the Rift is rotating around some arbitrary axis? Let

$$\ell = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} \tag{2}$$

be the length of ω. It turns out that the angular velocity vector ω decomposes in the following useful way:

- The current axis of rotation (unit length) is the normalized gyro reading: $\frac{1}{\ell}\omega$
- The length ℓ is the rate of rotation about that axis.

Because of the high sampling rate of the Rift sensor and the accuracy of the gyroscope, the orientation is well maintained over a long time (several minutes). However, *drift error* eventually accumulates. Without a perfect reference orientation, the calculated Rift orientation gradually drifts away from the true orientation.

Fortunately, the other Rift sensors provide enough reference data to compensate for the drift error. The drift error can be considered as a rotation that relates the true orientation to the calculated orientation. Based on the information provided by the Rift sensors, it is helpful to decompose the drift error into two independent components:

1. **Tilt error:** An orientation change in either pitch or roll components (recall Figure 6). Imagine orientations that would cause a ball to start rolling from an otherwise level surface. A tilt error causes confusion about whether the floor is level in a game.
2. **Yaw error:** An orientation change about the Y axis only. A yaw drift error causes uncertainty about which way you are facing.

These distinctions are relative to a fixed, global coordinate system in which Y is always "up". Because you will presumably be using the Rift on Earth, this is naturally defined as the vector outward from the center of the planet. This is sufficient for defining tilt (how far is the perceived Y from the actual Y?). The choice of Z is arbitrary, but remains fixed for the discussion of yaw error. (X is determined automatically by the cross product of Z and Y.)

Tilt error is reduced using the accelerometer's measurement of the gravity vector. The accelerometer simultaneously measures both linear head acceleration and gravity. However, if averaged over a long period of time, it can reliably estimate the direction of gravity. When a difference between the measured Y axis and the calculated Y axis is detected, tiny rotational corrections are made about a rotation axis that lies in the XZ plane and is perpendicular to both the measured and perceived Y axes. The accelerometer cannot sense yaw error because its rotation axis (Y) is aligned perfectly with gravity.

The magnetometer inside of the Rift has the ability to provide yaw error correction by using the Earth's magnetic field, which provides a fixed 3D vector at every location. Unfortunately, this field is corrupted by interference from materials around the sensor, both inside of the Rift and in the surrounding environment. Therefore, the magnetometer has to be calibrated before it becomes useful.

After the calibration information is available, the sensor fusion system will automatically assign *reference points* that are well spaced among the set of possible magnetometer readings. Whenever the magnetometer output is close to a reference point, yaw correction is performed.