Immersive Systems II
HMD Optics

Developing Immersive Applications

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Learning Objectives:

- explain the image formation process in typical XR HMDs
- apply thin lens optics principles to understand HMD design
- describe how IPD affects stereo rendering and user comfort
- explain lens distortion and correction in HMDs

Why VR Optics Matters

1. **See It Right** — Accurate optical design ensures realistic virtual worlds
2. **Render Smarter** — Understanding optics helps optimize graphics rendering
3. **Works Across Devices** — Optics knowledge transfers to all HMD platforms
4. **Comfort = Retention** — Proper optics reduces eye strain and motion sickness
5. **Break the Rules** — Know the principles to innovate beyond them

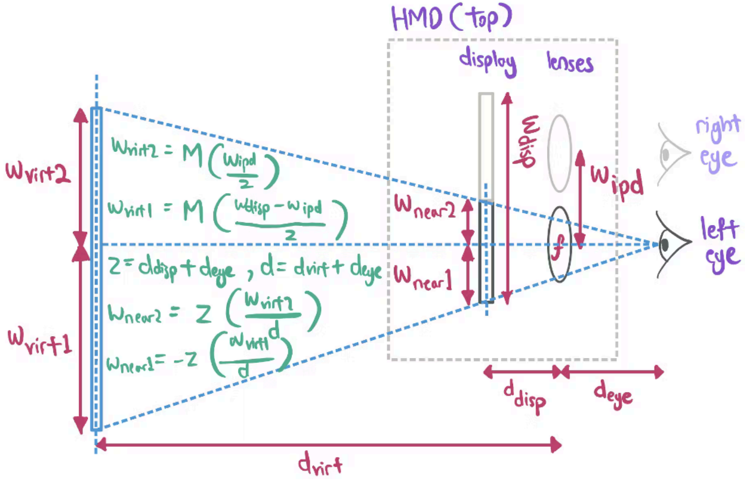
Core Graphics Concepts

The Rendering Pipeline:

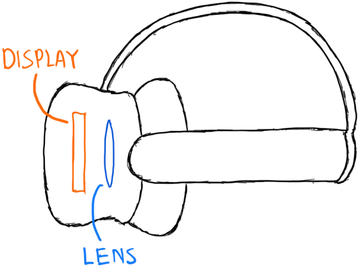
- **Application** — Scene setup, game logic
- **Geometry Processing** — Vertex transformations
- **Rasterization** — Converting vectors to pixels
- **Pixel Processing** — Shading, texturing, lighting
- **Output** — Frame buffer display

VR requires rendering this pipeline **twice per frame** (once for each eye) at high frame rates (90+ FPS).

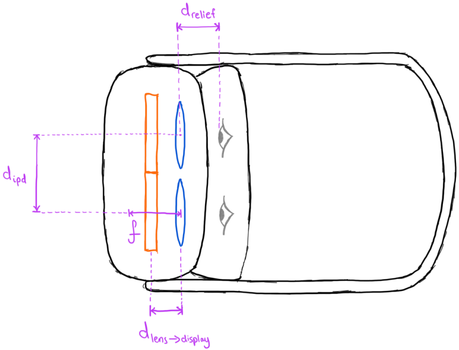
Core Physics: Thin Lens Optics



HMD Optical System



SIDE VIEW



TOP VIEW

Key components: Display screen, magnifying lens, eye position, and eye

Image Formation Process

How HMDs create the virtual image:

1. **Display screen** shows rendered content (close to face)
2. **Magnifying lens** bends light rays from display
3. **Virtual image** appears at comfortable viewing distance (optical infinity)
4. **Eyes** can focus naturally without strain

Key insight: Without lenses, the display would be too close to focus on (< 10cm). The lens makes it appear far away while maintaining wide FOV.

Key Parameter: IPD

Inter-Pupillary Distance:

- Distance between the centers of your pupils
- Typical range: 58-72mm (average: 63mm)
- **Critical for comfortable stereo viewing**
- Mismatch causes eye strain and depth perception issues
- Most modern HMDs have adjustable IPD

Software implications:

- Affects view matrix for each eye (different camera positions)
- Each eye needs separate projection matrix
- IPD offset = stereo baseline for depth perception

Key Parameter: Eye Relief

- Distance from the lens to your eye
- **Affects field of view (FOV)**
- Needs to accommodate glasses wearers
- Typical range: 10-20mm

Trade-off:

- Closer eye relief = wider FOV, more immersive
- Further eye relief = more comfortable, accommodates glasses

Design challenge: Balance immersion vs comfort for diverse users

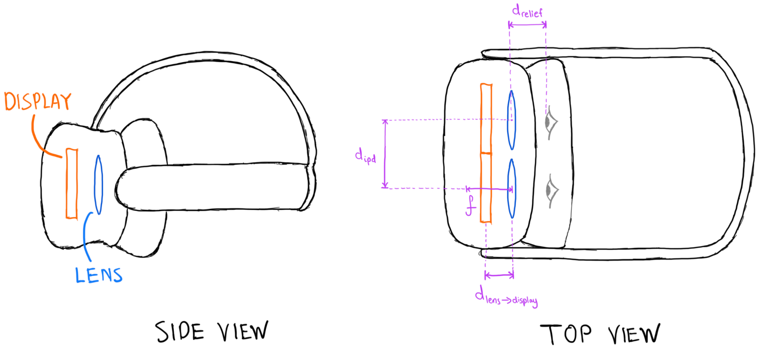
Key Parameter: Field of View

- Angular extent of the visible world
- Human vision: 210° horizontal, 150° vertical
- VR HMDs: typically 90-110° diagonal
- **Wider FOV = more immersive**, but harder to render
- Depends on lens design, focal length, and eye relief

FOV calculations:

- **Binocular FOV** — overlap region both eyes see
- **Monocular FOV** — total extent including peripheral
- **Nasal FOV** — towards nose (limited by nose bridge)
- **Temporal FOV** — towards temples (wider)

View Frustum in VR



The view frustum defines what portion of the 3D world is visible, bounded by near and far clipping planes.

View Frustum: Key Concepts

Near and far clipping planes:

- **Near plane** — objects closer than this are clipped
- **Far plane** — objects further than this are clipped
- Adjusting near plane affects interaction (e.g., grabbing close objects)

Asymmetry in VR:

- Each eye has **different projection matrix**
- Horizontal asymmetry due to IPD offset
- Vertical symmetry maintained
- This asymmetry is critical for correct stereo rendering

Common issue: Objects clipped when too close? → Adjust near clipping plane in code

Lens Distortion

The Challenge:

- Real lenses introduce distortion (pincushion/barrel)
- Makes straight lines appear curved
- Reduces image quality at edges

The Solution:

- Pre-distort the rendered image
- Lens distortion “undoes” the pre-distortion
- Result: straight lines appear straight to the user

This is why VR content looks distorted on phone screens without cardboard viewers!

Chromatic Aberration

The phenomenon:

- Different wavelengths of light refract differently
- Causes color fringing at edges
- Red, green, blue channels focus at different distances

Correction approach:

- Render each color channel with slight offset
- Shader-based correction in real-time
- Part of the lens distortion correction pipeline

Reference: Stanford EE267 lecture notes cover the detailed math

stanford.edu/class/ee267

Stereo Rendering

Key Concepts:

- Render scene **twice**: once for each eye
- Left and right cameras offset by IPD
- Each eye sees slightly different perspective
- Brain fuses images to perceive depth
- Vergence and accommodation cues

Performance impact:

Doubling the rendering workload requires optimization strategies:

- Foveated rendering (render center sharper than periphery)
- Fixed foveated rendering (hardware-level optimization)
- Multiview rendering (single pass stereo)

Projection & View Matrices

Are projection matrices the same for both eyes?

FALSE — Each eye has different projection matrix due to asymmetric frustum

Are view matrices the same for both eyes?

FALSE — IPD offset means different eye positions → different view matrices

Software implementation:

- WebXR provides separate matrices via `XRView` objects
- `leftView.projectionMatrix` ≠ `rightView.projectionMatrix`
- `leftView.transform` ≠ `rightView.transform`
- Babylon.js handles this automatically when WebXR session is active

Common Issues & Fixes

Scene looks shrunk/distant?

→ Adjust FOV or focal length in HMD settings

Scene inverted or blurry?

→ Check lens placement and screen-to-lens distance

Cannot sense depth (two separate images)?

→ IPD mismatch — adjust IPD setting to match user’s actual IPD

Objects clipped when too close?

→ Reduce near clipping plane distance in rendering code

Objects appear flat, hard to judge distance?

→ IPD too small or incorrect stereo camera setup

Summary

Today we covered:

- Why VR optics matters for immersive experiences
- Thin lens optics and image formation process
- Key HMD parameters: IPD, eye relief, FOV
- View frustum properties (asymmetric in VR)
- Lens distortion and chromatic aberration correction
- Stereo rendering requirements and performance impact
- Projection and view matrix differences per eye
- Common issues and troubleshooting approaches

Deeper dive: Stanford EE267 lectures on rendering matrices

stanford.edu/class/ee267/lectures/