Immersive Systems III — Deep Dive in HMD Simulator

Developing Immersive Applications

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Learning Objectives:

- explain how HMD parameters (IPD, FOV, eye relief, distortion) affect stereo rendering and user comfort
- describe the key components of the HMD simulator codebase and their roles in the rendering pipeline
- troubleshoot common HMD rendering issues using the HMD simulator
- relate optical parameters to rendering artifacts and comfort trade-offs

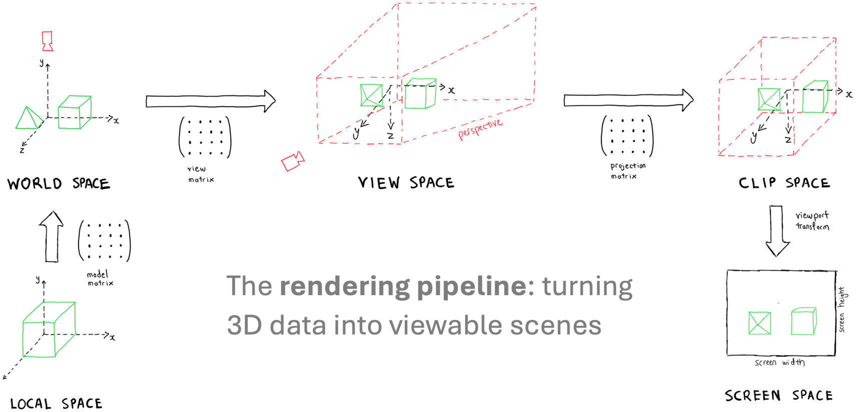
Recap: HMD Optics from Week 06

Key concepts we covered:

- Thin lens equation and image formation
- Eye relief, focal length, and their relationship to FOV
- View frustum parameters (symmetric vs asymmetric)
- Projection and view matrices for stereo rendering

Today we go hands-on with these concepts using the HMD simulator.

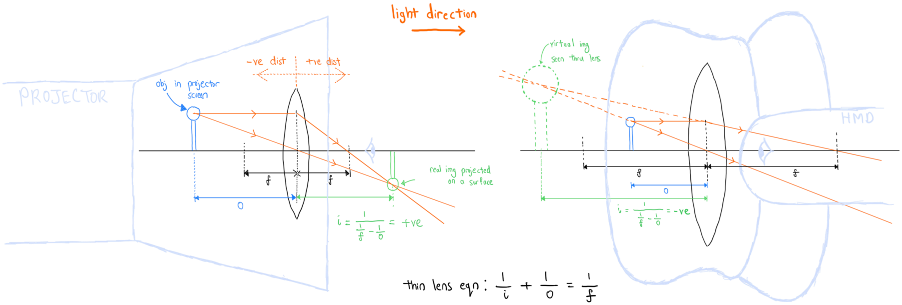
Recap: Core Graphics Concepts



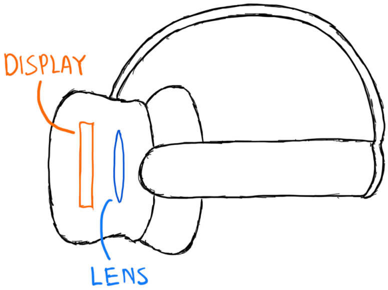
The **rendering pipeline:** turning 3D data into viewable scenes

VR requires rendering this pipeline **twice per frame** at high FPS (e.g., 90+).

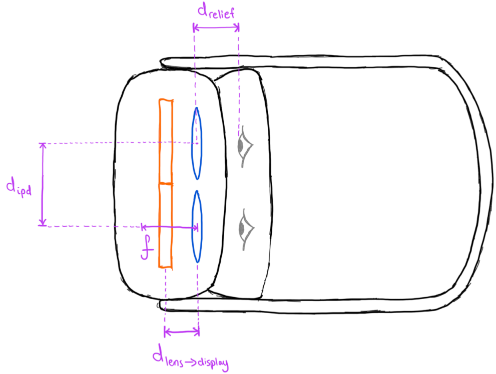
Recap: Core Physics Concepts



Recap: Key HMD Hardware Components

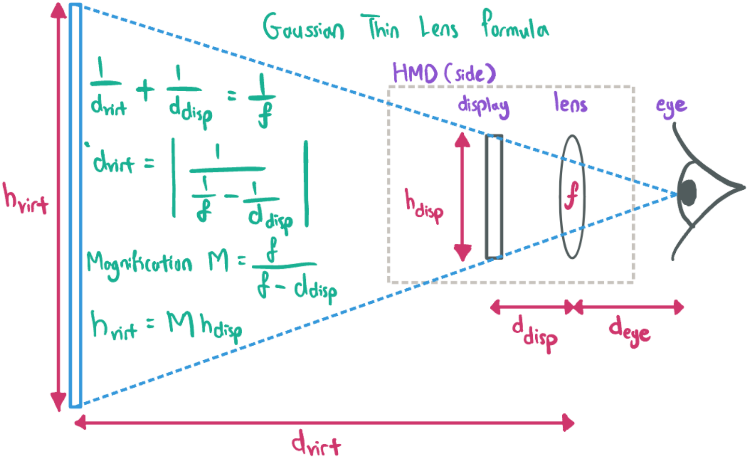


SIDE VIEW



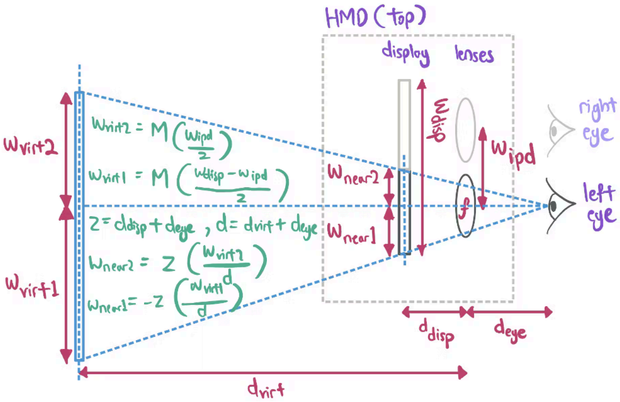
TOP VIEW

Recap: Virtual Image Dist & Height

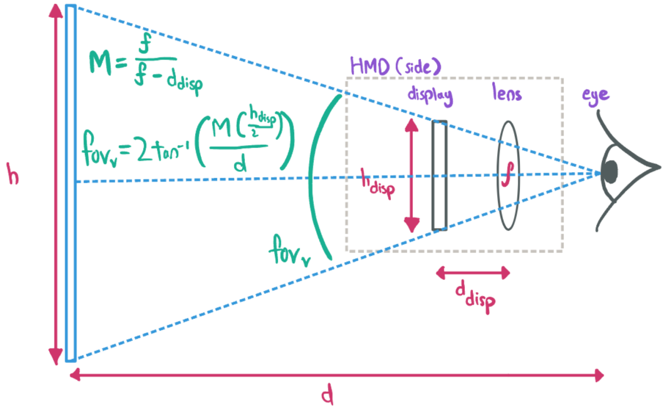


Video segment: `https://youtu.be/OKD4jrnn4WE?t=406`

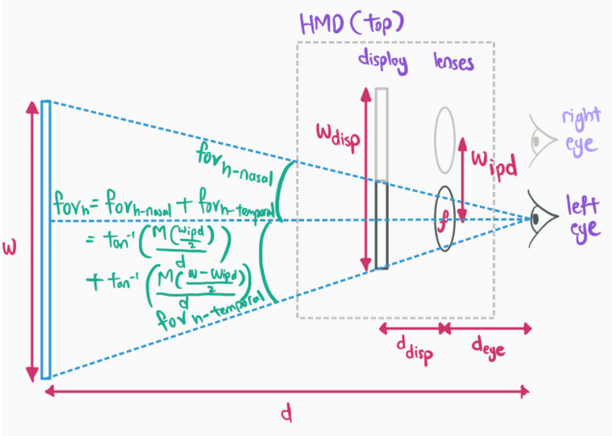
Computation: Virtual Image Width



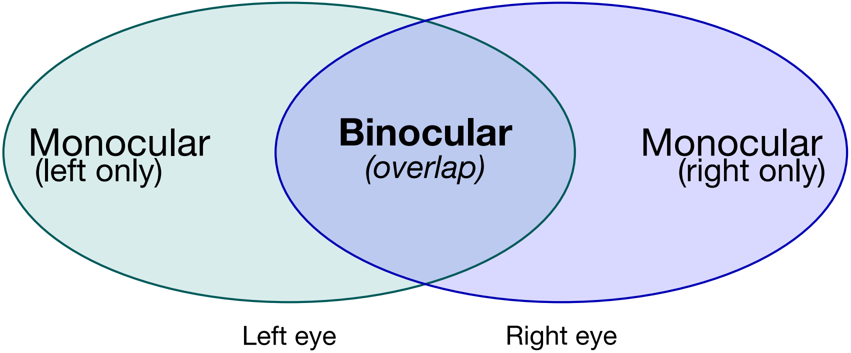
Computation: Vertical FOV



Computation: Horizontal FOV



Binocular and Monocular Regions



HMDs render two views offset by IPD; overlap provides retinal disparity for stereoscopic depth.

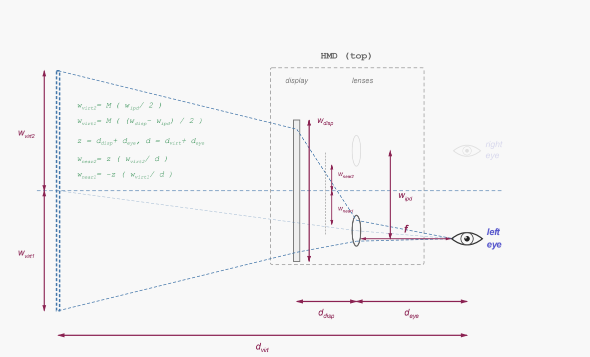
- **Binocular region:** overlap seen by both eyes; provides depth cues
- **Monocular region:** peripheral areas visible to one eye only

HMD Simulator Architecture

The HMD simulator (`https://github.com/singaporetech/hmd`) consists of these modules:

- `main.ts` — Entry point: WebGPU/WebGL engine init, render loop
- `app.ts` — Scene management: 5 cameras, environment loading, PIP viewports, display mode toggling
- `hmd.ts` — Core HMD class: optical parameters, off-axis projection matrix, barrel distortion shader, render targets
- `ui.ts` — Babylon.js GUI: parameter sliders, stats panel, toggle buttons
- `constants.ts` — Layer masks, Cardboard V2 presets, DisplayMode enum
- `frustumVisualizer.ts` — Frustum edge rendering as tubes, per-frame updates

HMD Optics: Image Formation



Key measurements (widths):

- $w_{\text{virt1}}, w_{\text{virt2}}$: Virtual image widths
- w_{disp}: Display width
- w_{ipd}: Inter-pupillary distance
- $w_{\text{near1}}, w_{\text{near2}}$: Near-plane widths

Distances:

- d_{disp}: Lens to display
- d_{eye}: Eye relief (eye to lens)
- d_{virt}: Virtual image distance
- f: Focal length

Code: Magnification and Virtual Image

From `hmd.ts` — `calcProjectionMatrix()`

```
^^I^^I// magnification (f must be > distLens2Display)
^^I^^Ithis.magnification = this.f / (this.f - this.distLens2Display);
^^I^^I// virtual image height
^^I^^Ithis.imgHeight = this.displayHeight * this.magnification;
^^I^^I// aspect ratio
^^I^^Ithis.aspectRatio = this.displayWidth / this.displayHeight;
^^I^^I// thin lens: 1/f = 1/do + 1/di  =>  di
^^I^^Ithis.distLens2Img = Math.abs(1/(1/this.f - 1/this.distLens2Display));
^^I^^I// distance from eye to virtual image
^^I^^Ithis.distEye2Img = this.distLens2Img + this.eyeRelief;
^^I^^Ithis.near = this.distEye2Display;
^^I^^I// vertical FOV from virtual image height
^^I^^Ithis.fovVertical = 2 * Math.atan(this.imgHeight / 2 / this.distEye2Img);
^^I
```

Source: `hmd.ts` — `calcProjectionMatrix()`. Based on thin lens equations (see Week 06 recap).

Code: Off-Axis Projection Matrix

From `hmd.ts` — asymmetric frustum for Babylon.js (LHS)

```
^^I^^I// Off-axis projection (left eye shown)
^^I^^Ilet x = (2*this.near) / (this.rightForLeftEye - this.leftForLeftEye);
^^I^^Iconst y = (2*this.near) / (this.top-this.bottom);
^^I^^Ilet a = (this.rightForLeftEye+this.leftForLeftEye) / (this.rightForLeftEye-this.
    leftForLeftEye);
^^I^^Iconst b = (this.top+this.bottom)/(this.top-this.bottom);
^^I^^Iconst c = (this.far+this.near)/(this.far-this.near);
^^I^^Iconst d = (-2*this.far*this.near)/(this.far-this.near);
^^I^^Ithis.projMatL = Matrix.FromValues( x,0,0,0,
^^I^^I0,y,0,0,
^^I^^Ia,b,c,1,
^^I^^I0,0,d,0); // LHS col-major
^^I
```

Left/right bounds differ per eye (offset by IPD/2), creating an **asymmetric** horizontal frustum.

Refs: three.js Matrix4.makePerspective; Scratchapixel: Projection Matrix

Code: Barrel Distortion Shader (GLSL)

From `hmd.ts` — post-process fragment shader

```
^^I^^Iconst float k1 = 0.34; // Cardboard V2
^^I^^Iconst float k2 = 0.55;
^^I^^Iconst vec2 center = vec2(0.5, 0.5);
^^I^^Ivoid main() {
^^I^^I^^I^^Ivec2 uv = vUV;
^^I^^I^^I^^Ivec2 delta = uv - center;
^^I^^I^^I^^Ifloat r2 = dot(delta, delta);
^^I^^I^^I^^Ivec2 distorted = delta*(1.0+k1*r2+k2*r2*r2);
^^I^^I^^I^^Ivec2 corrected = center + distorted;
^^I^^I^^I^^Ivec4 texColor = texture2D(textureSampler, corrected);
^^I^^I^^I^^Ifloat inBounds = step(0.0, corrected.x) * step(corrected.x, 1.0) * step(0.0,
    corrected.y)
^^I^^I^^I^^I* step(corrected.y, 1.0);
^^I^^I^^I^^Igl_FragColor = mix(vec4(0.55,0.38,0.4,1.0),texColor,inBounds);
^^I^^I^^I}
^^I
```

Barrel distortion: $r' = r(1 + k_1 r^2 + k_2 r^4)$. Google Cardboard V2.

IPD and Depth Perception

Inter-Pupillary Distance (IPD)

- Software IPD controls the separation between virtual cameras
- Mismatch with physical IPD causes depth distortion
- Too large: world appears miniaturized (hyperstereopsis)
- Too small: world appears flat, reduced depth cues

In the simulator, the IPD slider adjusts this value and the stats panel shows the resulting nasal/temporal FOV split.

Lens Distortion Correction

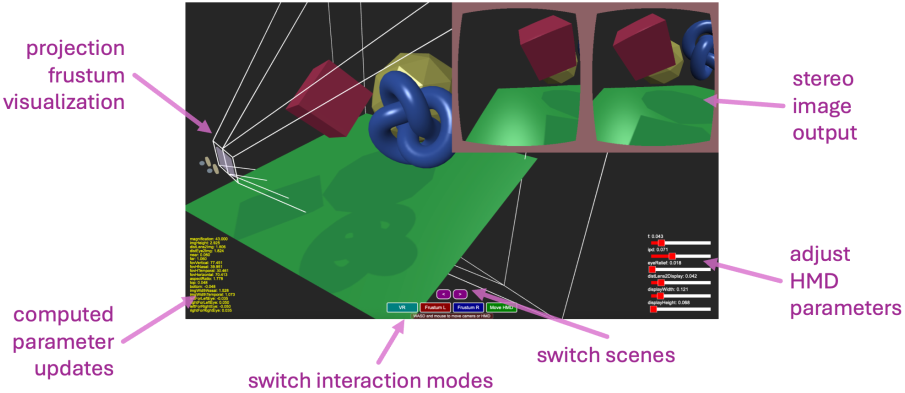
HMD lenses introduce **pincushion distortion** — straight lines bow inward.

- The simulator applies **barrel distortion** (inverse) as a GLSL post-process shader on each eye's render target
- This pre-compensates so the image looks correct through the lenses
- Distortion coefficients k1=0.34, k2=0.55 are hardcoded from Google Cardboard V2 specifications
- The distortion is always active — there is no toggle to disable it

The greyish-pink border visible in VR mode is the out-of-bounds fallback region from the shader.

The HMD Simulator

Live: `https://hmd.diaversity.org` **Source:** `https://github.com/singaporetech/hmd`



Activity 1: Exploring the Simulator

Get oriented:

1. Open `https://hmd.diaversity.org` and use **left/right arrow keys** to switch scenes
2. Click **Move HMD** to enable it (also enables mouse rotation)
3. Use **WASD** to translate and **mouse** to rotate the HMD
4. Watch the frustum tubes and PIP viewports update in real-time

Observe:

- The frustum visualization follows the HMD position
- PIP viewport content changes as the HMD "looks" at different scene areas
- Move the HMD close to objects — notice how nearby objects **clip** (disappear) when they cross the near plane
- Toggle Move HMD off to return to orbiting the main camera

Activity 2: IPD and Frustum Overlap

Try this in the simulator:

1. Toggle **Frustum L** and **Frustum R** on
2. Move the **IPD** slider; watch frustum separation and the PIP viewports
3. Orbit the main camera to a **top-down** view; compare each frustum's shape
4. Push IPD to an extreme and observe the asymmetry

Observe:

- How does the binocular overlap region change with IPD?
- Each frustum is wider on the temporal side (off-axis projection)
- Check `fovHNasal` and `fovHTemporal` in the stats panel

Activity 3: Eye Relief and FOV

Try this in the simulator:

1. Keep frustum visualization on
2. Move the `eyeRelief` slider from low to high
3. Set eye relief to a high value and note FOV, then reduce to minimum
4. Check `fovVertical` and `fovHorizontal` in the stats panel

Observe:

- Reducing eye relief **widens** the FOV — why?
- Real HMDs need minimum eye relief for comfort and glasses clearance
- This is a key design trade-off: wider FOV vs physical comfort
- Wider FOV increases immersion but may increase distortion at edges

Activity 4: Focal Length

Focal length — try this in the simulator:

1. Move the **f** (focal length) slider slowly
2. Watch `distEye2Img` and `magnification` in the stats panel
3. Try setting f very close to `distLens2Display` — what happens?

Observe:

- When f approaches `distLens2Display`, magnification goes toward infinity
- If f < `distLens2Display`, the image inverts (real image, not virtual)
- In a real HMD, this inversion is invisible: the real image forms too close to the eye
- `distEye2Img` determines where the eye must **accommodate** (focus)
- Mismatch between accommodation and vergence causes discomfort (VAC)

Optics Explorer: `https://optics.diaversity.org` — visualize ray changes with focal length

Activity 5: Lens-to-Display Distance

Building on Activity 4:

Now see how lens-to-display distance interacts with focal length.

Try this:

1. Move the `distLens2Display` slider
2. Watch `magnification` and `near` in the stats panel
3. Bring it close to the focal length value

Observe:

- As `distLens2Display` approaches f, magnification grows rapidly
- Near plane (= eye-to-display distance) shifts accordingly
- If `distLens2Display` > f, image inverts (projector mode)

Activity 6: VR Mode & Cardboard

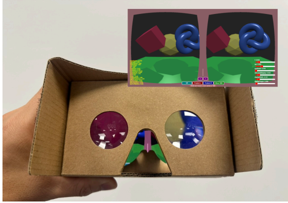
Building on Activities 4 and 5:
You explored how focal length and lens-to-display distance affect the rendered image. Now see the full stereo pipeline in action.

Try this:

1. Click the **VR** toggle to see side-by-side stereo output
2. Note how barrel distortion appear on each eye
3. Open the simulator on your **phone** at `https://hmd.diaversity.org`
4. Toggle **VR mode** and place the phone in a Google Cardboard viewer
5. Adjust IPD and eye relief; observe **stereopsis** — the perception of depth from binocular disparity

Observe:

- Barrel distortion should be mitigated through the lenses
- Compare depth perception (stereopsis) with different IPD settings



Activity 7: Impossible Rendering

Try creative or “impossible” configurations:

1. Set `f` **below** `distLens2Display` — observe the inverted (real) image
2. Push IPD to an extreme value (very large or negative if possible)
3. Set `distLens2Display` very close to `f` — watch magnification spike
4. Try extreme display dimensions (very wide, very tall) and observe the FOV

Advanced (code modification):

- Clone the HMD repo and add a **skew** term to the projection matrix in `calcProjectionMatrix()` to create an Escher-inspired impossible viewpoint
- What happens when left and right eyes see geometrically contradictory perspectives?

Slido: Describe what impossible or creative configuration you tried and what effect you observed.

Summary

Today we covered:

- HMD simulator codebase: 6 modules (`main.ts`, `app.ts`, `hmd.ts`, `ui.ts`, `constants.ts`, `frustumVisualizer.ts`)
- Key code: magnification/virtual image, off-axis projection matrix, barrel distortion shader
- How IPD, eye relief, focal length, display dimensions, and `distLens2Display` affect the visual output
- Troubleshooting rendering issues by adjusting simulator parameters

Next: Week 09 — Interaction theory and implementation