The Graphics Pipeline and OpenGL IV:

Stereo Rendering, Depth of Field Rendering, Multi-pass Rendering

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EE 267 Virtual Reality

Lecture 6

stanford.edu/class/ee267/

Lecture Overview

- overview of glasses-based stereo
- stereo rendering with OpenGL
  - projection matrix
  - view matrix
- offscreen frame buffers and multi-render passes
- anaglyph stereo rendering with GLSL
- depth of field rendering

Glasses-based Stereo

1. Anaglyph

2. Polarization

3. Shutter Glasses

4. Chromatic Filters (e.g., Dolby)

Glasses-based Stereo

2. Polarization

Glasses-based Stereo

- passive glasses
- active LC element on projector or interlaced rows/columns on monitor (resolution loss)

2. Polarization

- e.g. RealD – most 3D cinemas use this
- circular polarization to allow for head roll
- inexpensive glasses, little crosstalk
- need polarization-preserving screen!

Glasses-based Stereo

3. Shutter Glasses

Glasses-based Stereo

- active glasses, temporally-multiplexed display
- e.g. StereoGraphics
- somewhat expensive glasses, little crosstalk
- need fast display (at least 120 Hz)
- sync monitor update with glasses

3. Shutter Glasses

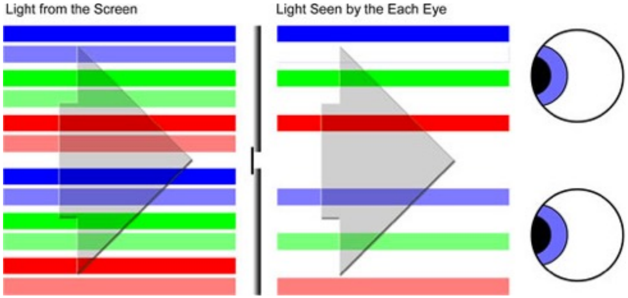
Glasses-based Stereo

4. Chromatic Filters (e.g., Dolby)

Glasses-based Stereo

- passive glasses, usually two projectors with passive color filters
- somewhat expensive glasses (not as widespread in cinemas)
- full color!

www.shortcourses.com/stereo/stereo1-12.html



4. Chromatic Filters (e.g., Dolby)

Glasses-based Stereo

1. Anaglyph

Glasses-based Stereo

1. Anaglyph

- passive, inexpensive glasses (least expensive overall)
- no modifications to display necessary – just render stereo images in different colors
- cannot reproduce correct colors! but not as bad as it sounds

Put on Your 3D Glasses Now!

pintrest.com

Anaglyph Stereo - Monochrome

- render L & R images, convert to grayscale
- merge into red-cyan anaglyph by assigning I(r)=L, I(g,b)=R (I is anaglyph)

from movie “Bick Buck Bunny”

Anaglyph Stereo – Full Color

- render L & R images, do not convert to grayscale
- merge into red-cyan anaglyph by assigning I(r)=L(r), I(g,b)=R(g,b) (I is anaglyph)


from movie “Bick Buck Bunny”

Anaglyph Stereo - Dubois

- paper: Eric Dubois “A Projection Method to Generate Anaglyph Stereo Images”, ICASSP 2001
- optimize color management in CIE XYZ space
- requires spectral transmission of glasses & spectral emission curves of display primaries
- great course project - see previous course projects …

Open Source Movie: Big Buck Bunny

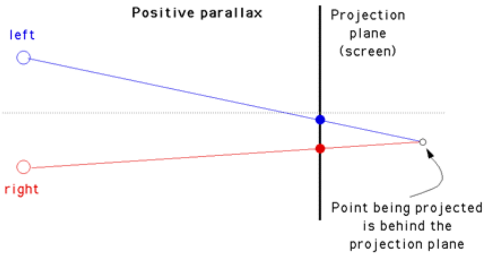
Rendered with Blender (Open Source 3D Modeling Program)

http://bbb3d.renderfarming.net/download.html

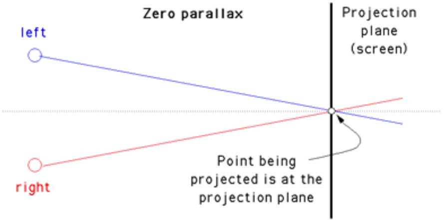
Parallax

http://paulbourke.net/stereographics/stereorender/

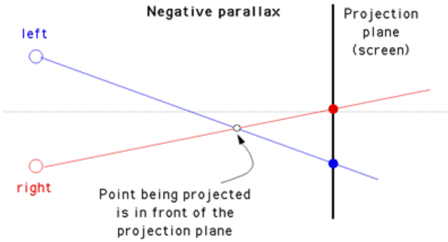
- parallax is the relative distance of a 3D point projected into the 2 stereo images



case 1



case 2

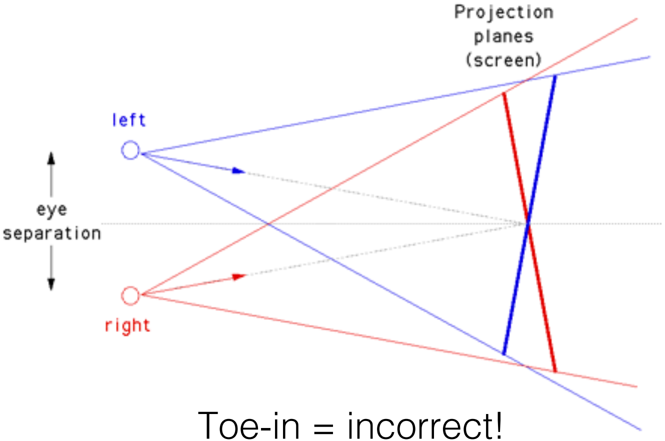


case 3

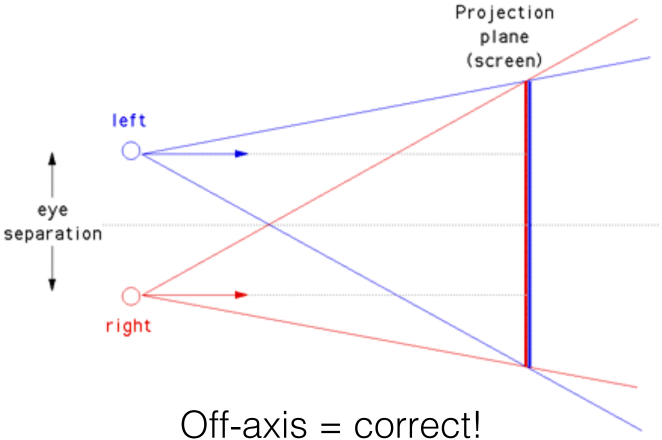
Parallax

http://paulbourke.net/stereographics/stereorender/

- visual system only uses horizontal parallax, no vertical parallax!
- naïve toe-in method creates vertical parallax → visual discomfort

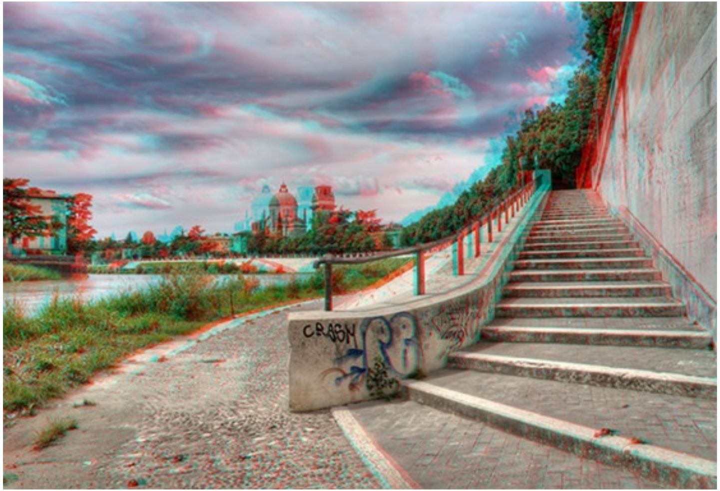


Toe-in = incorrect!



Off-axis = correct!

Parallax – well done



Parallax – well done

1862
“Tending wounded Union soldiers at Savage's Station, Virginia, during the Peninsular Campaign”,
Library of Congress Prints and Photographs Division

Parallax – not well done (vertical parallax = unnatural)

Take Off Your 3D Glasses Now!

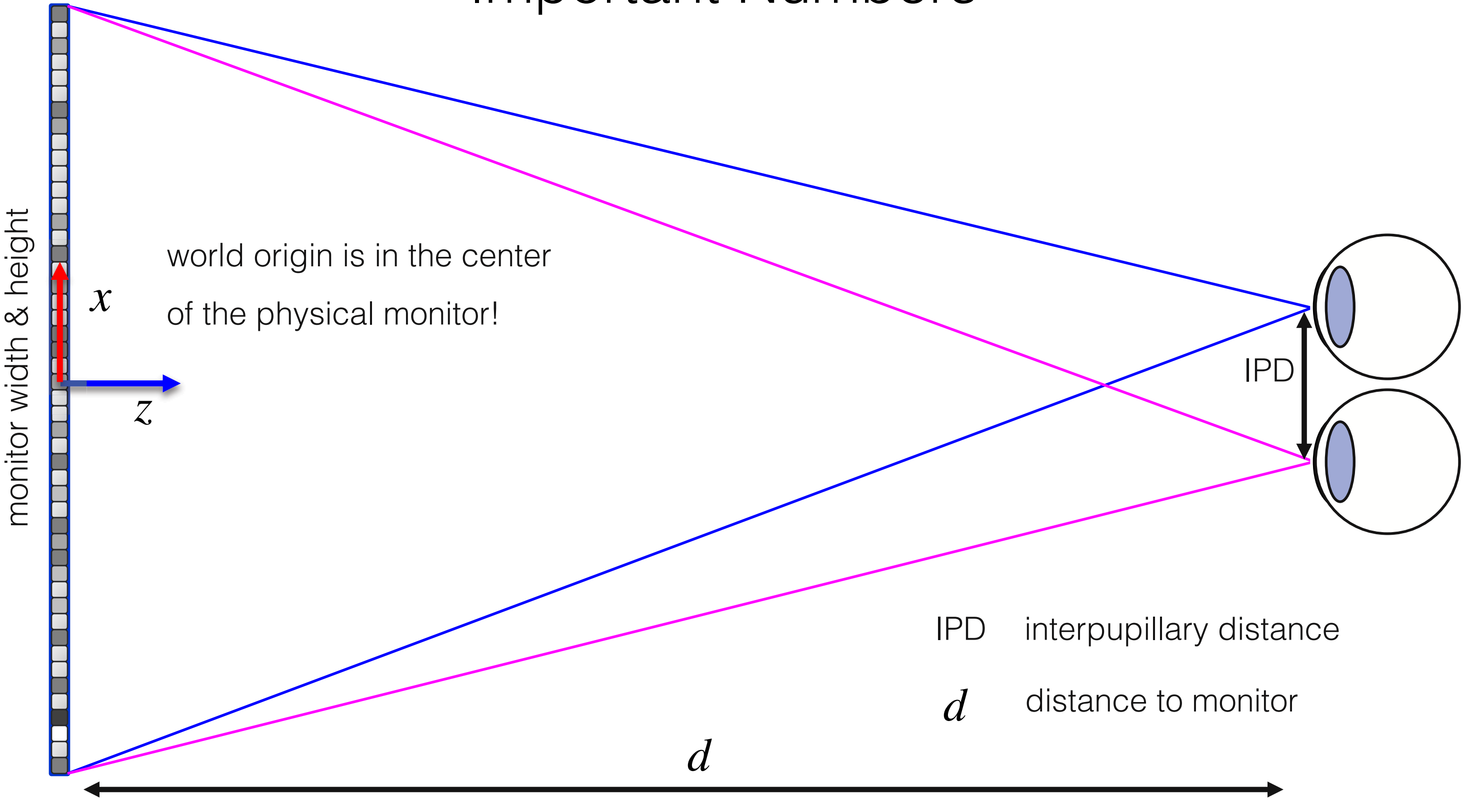
Stereo Rendering with OpenGL/WebGL: View Matrix

- need to modify view matrix and projection matrix
- rendering pipeline does not change – only those two matrices

- however: need to render two images in sequence (more details later)

- look at view matrix first: write your own `lookAt` function that uses rotation & translation matrix to generate view matrix from `eye,center,up` parameters
- do not use `THREE.Matrix4().lookAt()` function – this does not work properly!

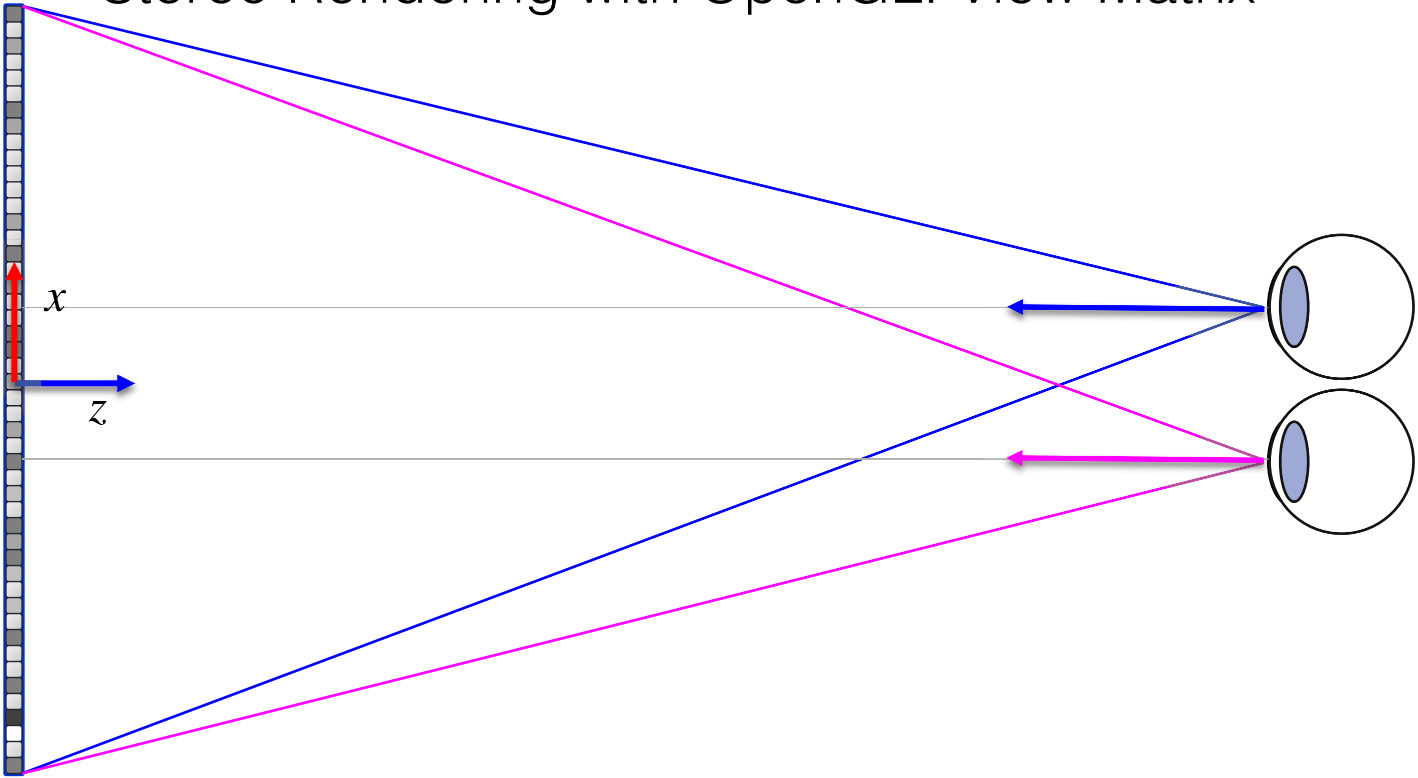
Important Numbers



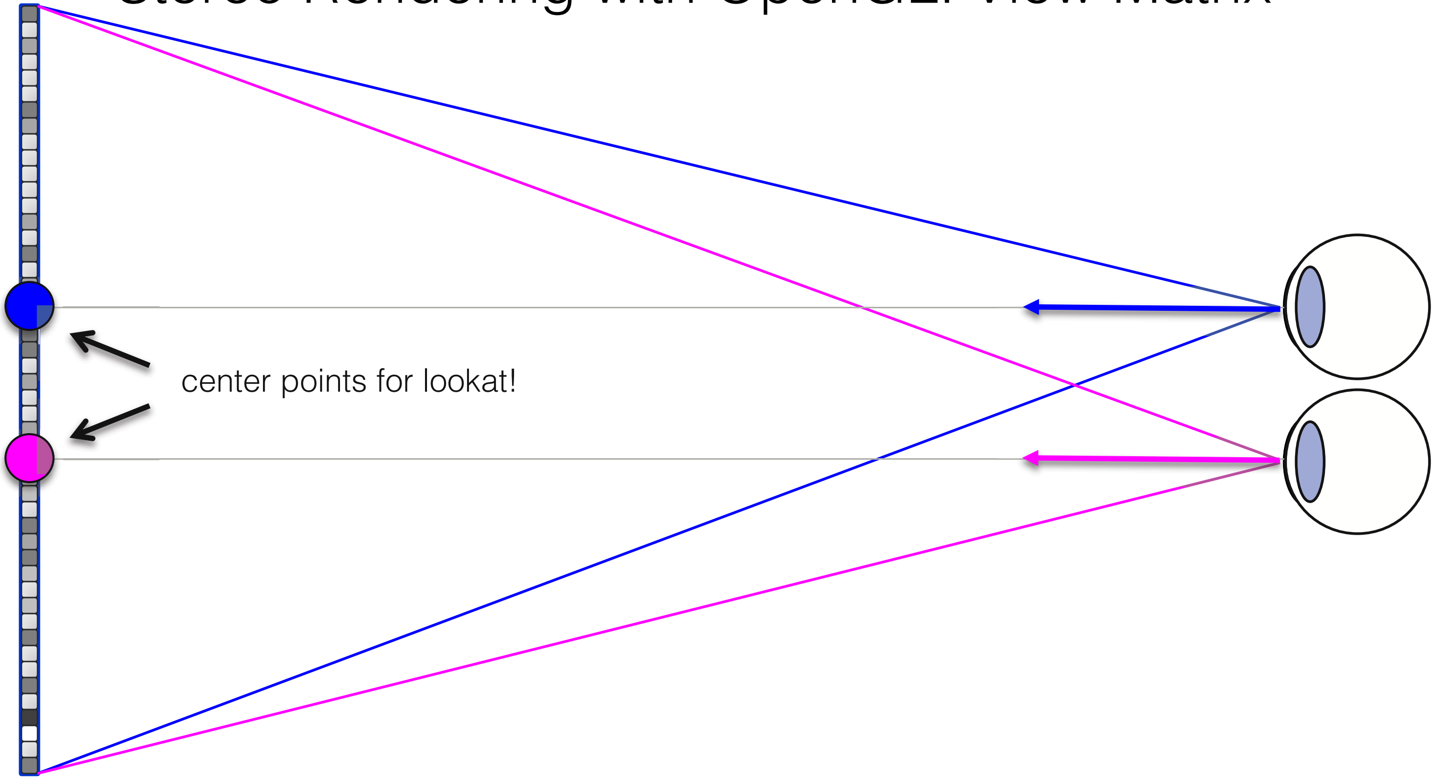
IPD interpupillary distance

d distance to monitor

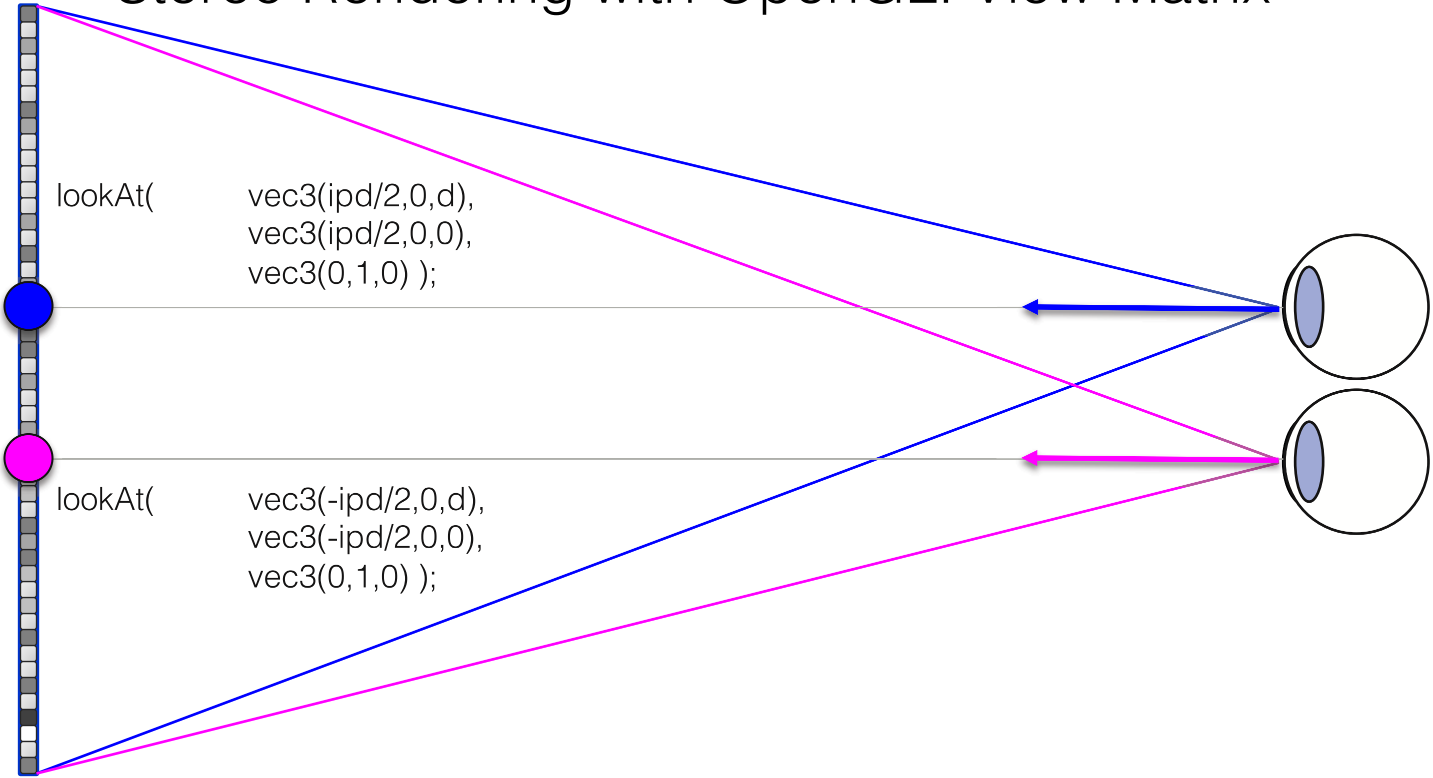
Stereo Rendering with OpenGL: View Matrix



Stereo Rendering with OpenGL: View Matrix

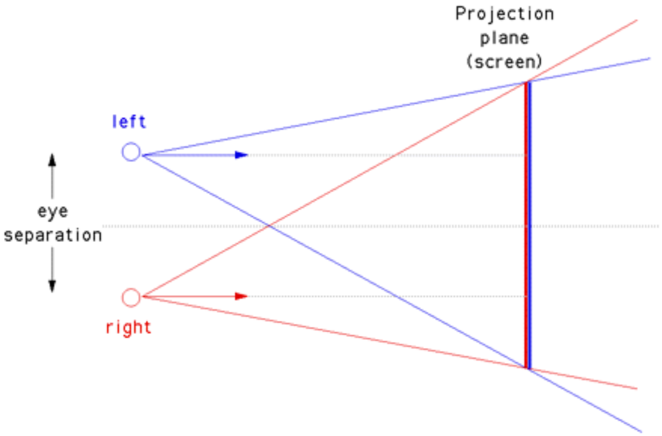


Stereo Rendering with OpenGL: View Matrix



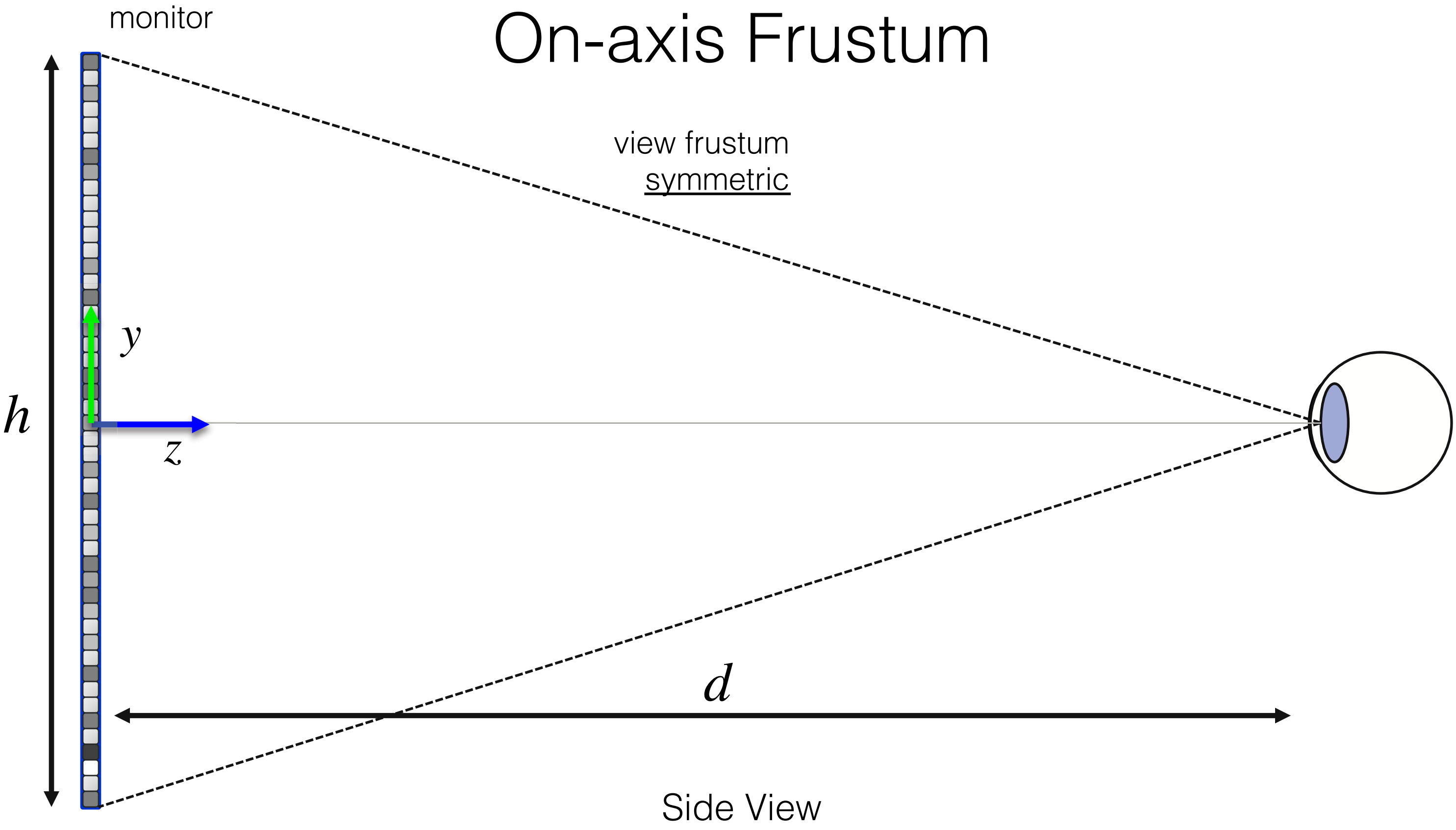
Stereo Rendering with OpenGL: Projection Matrix

- perspective projection we have discussed so far is on-axis=symmetric
- we need a different way to set up the asymmetric, off-axis frustum
- use `THREE.Matrix4().makePerspective(left,right,top,bottom,znear,zfar)`

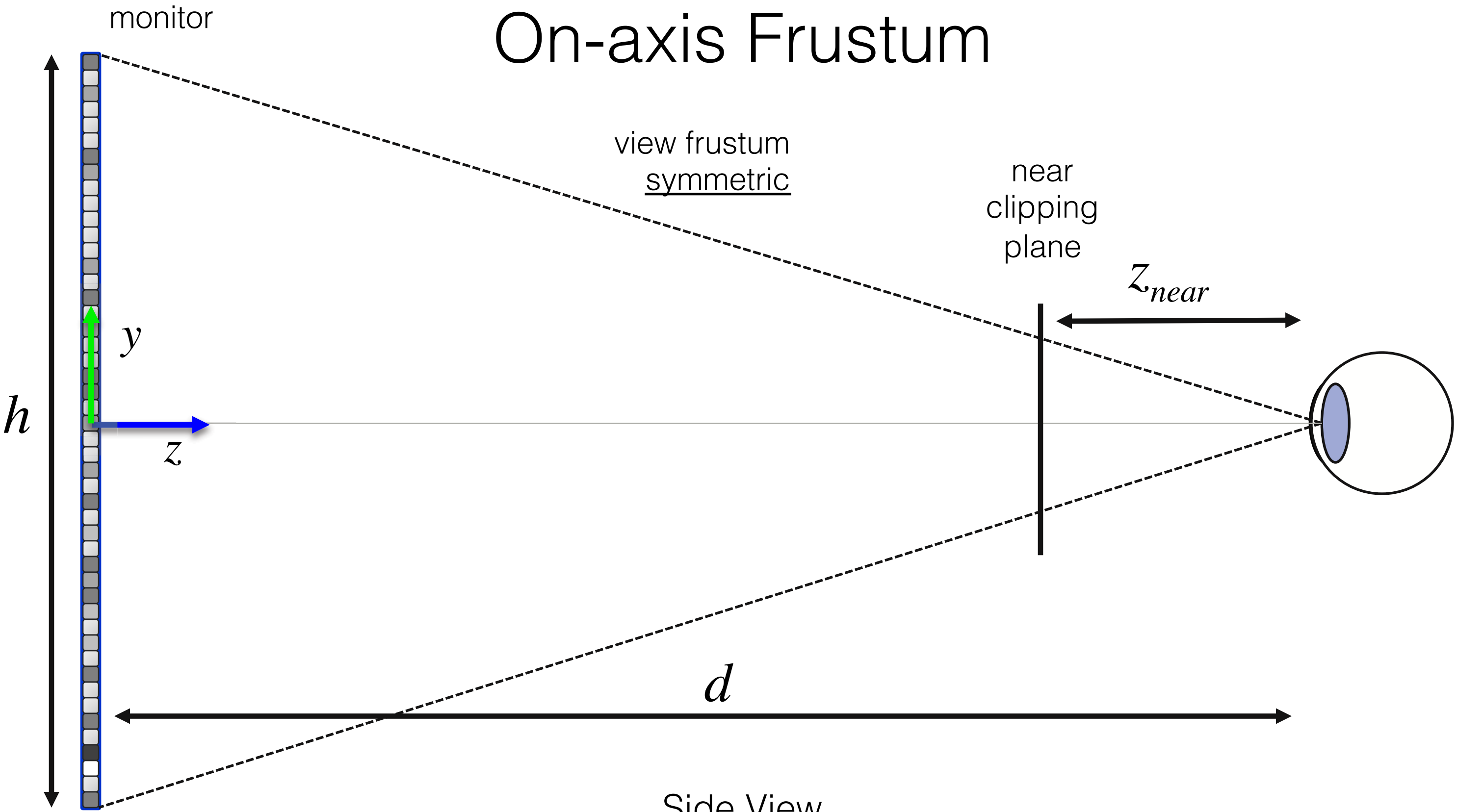


http://paulbourke.net/stereographics/stereorender/

On-axis Frustum

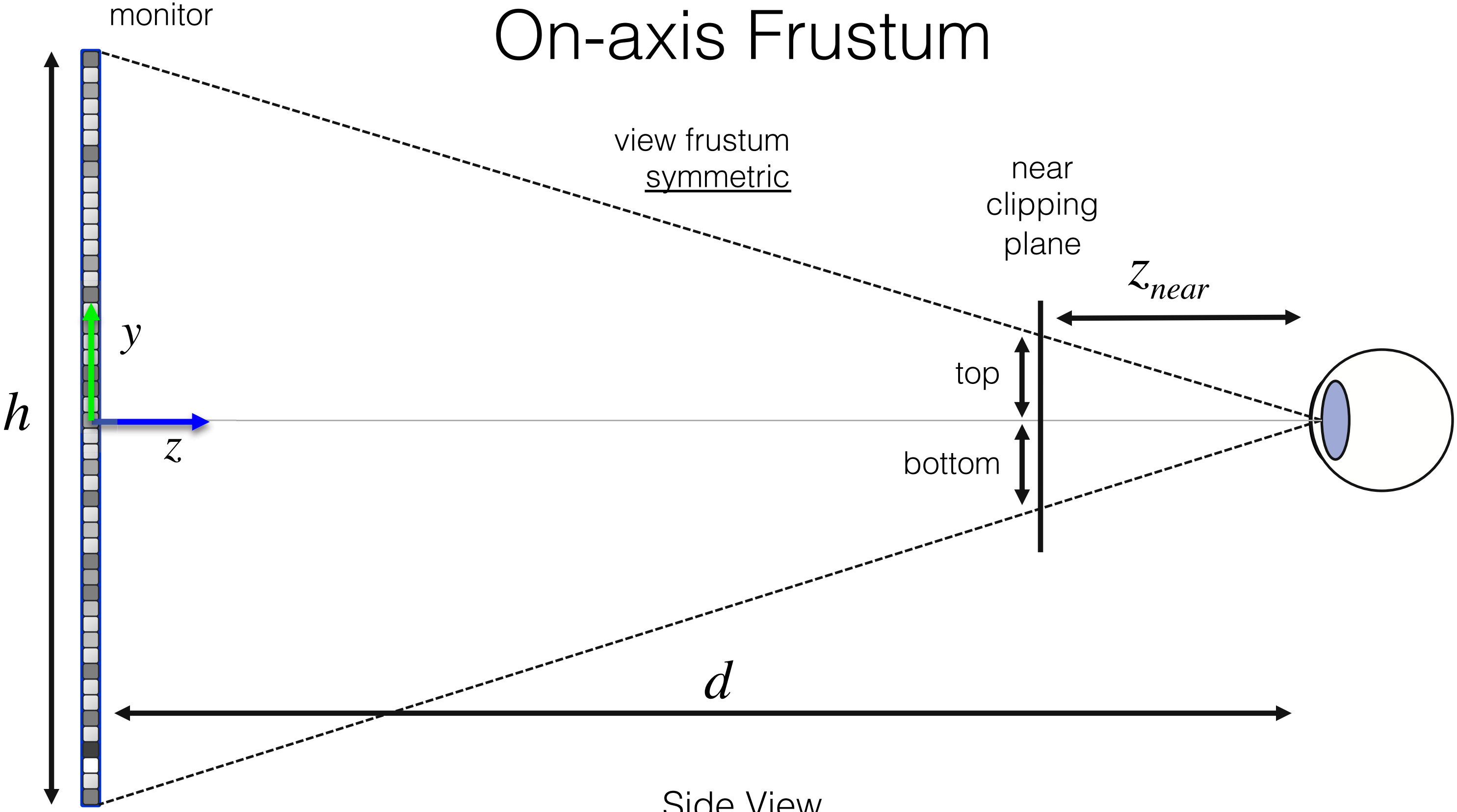


On-axis Frustum



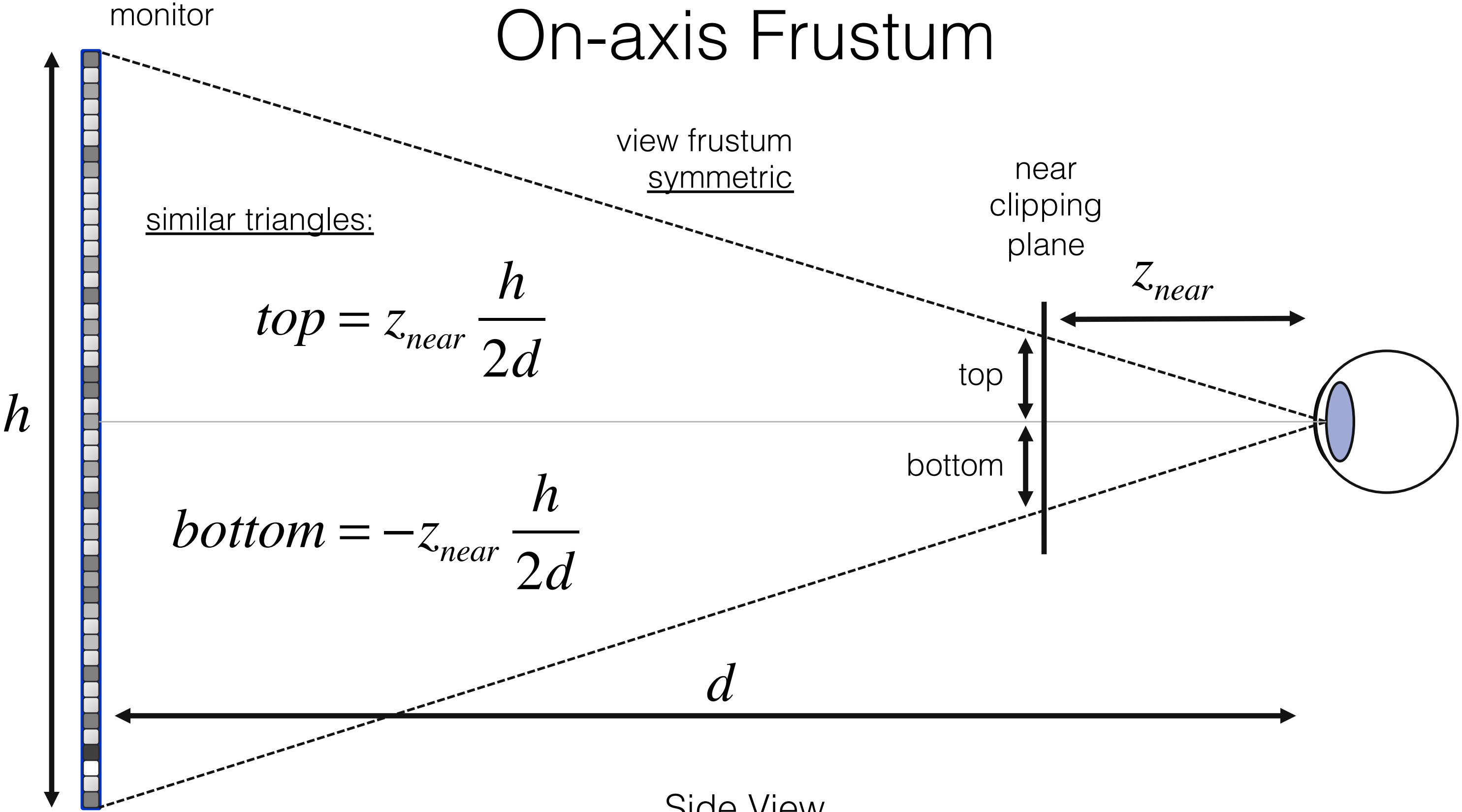
Side View

On-axis Frustum



Side View

On-axis Frustum



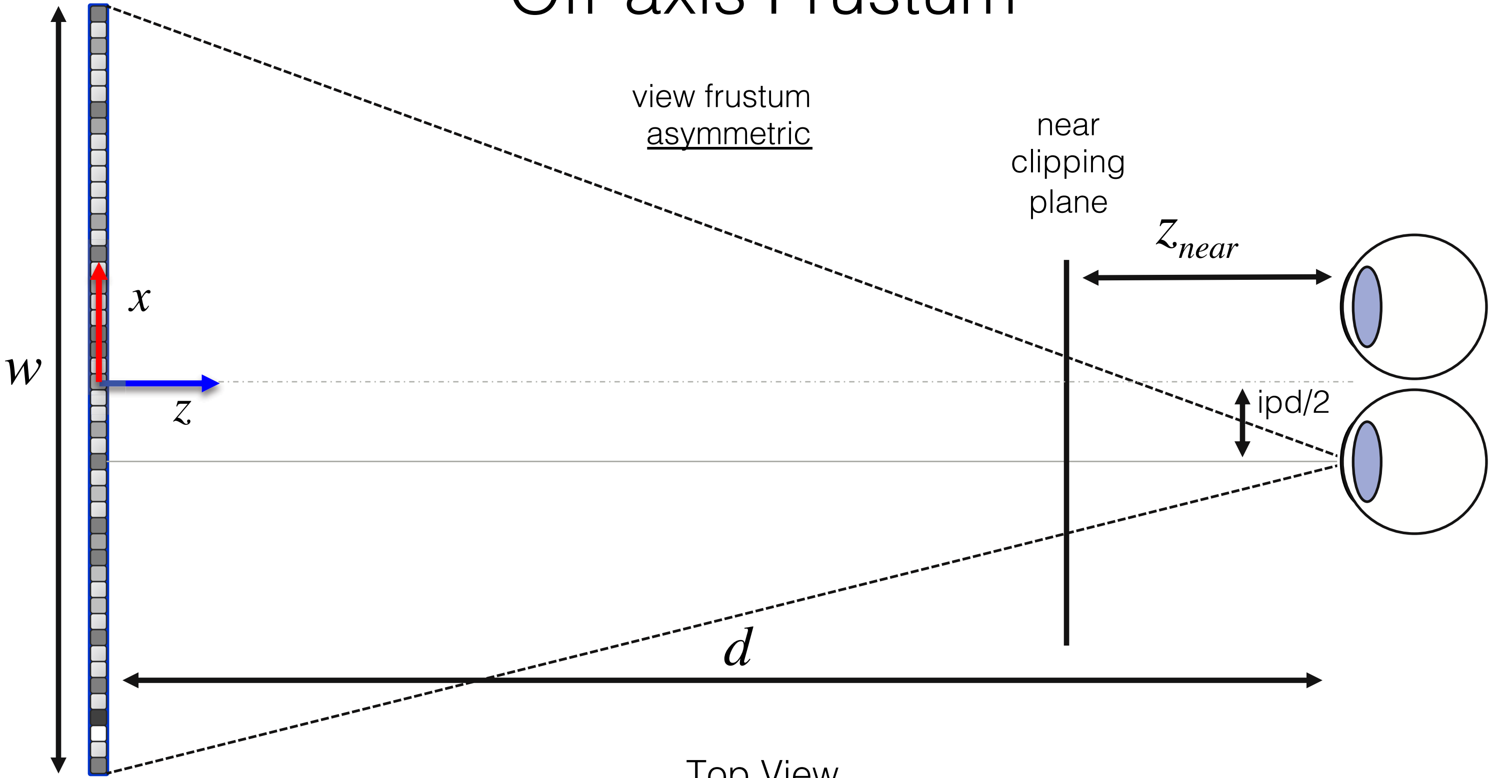
similar triangles:

$$top = z_{near}\frac{h}{2d}$$

$$bottom = -z_{near}\frac{h}{2d}$$

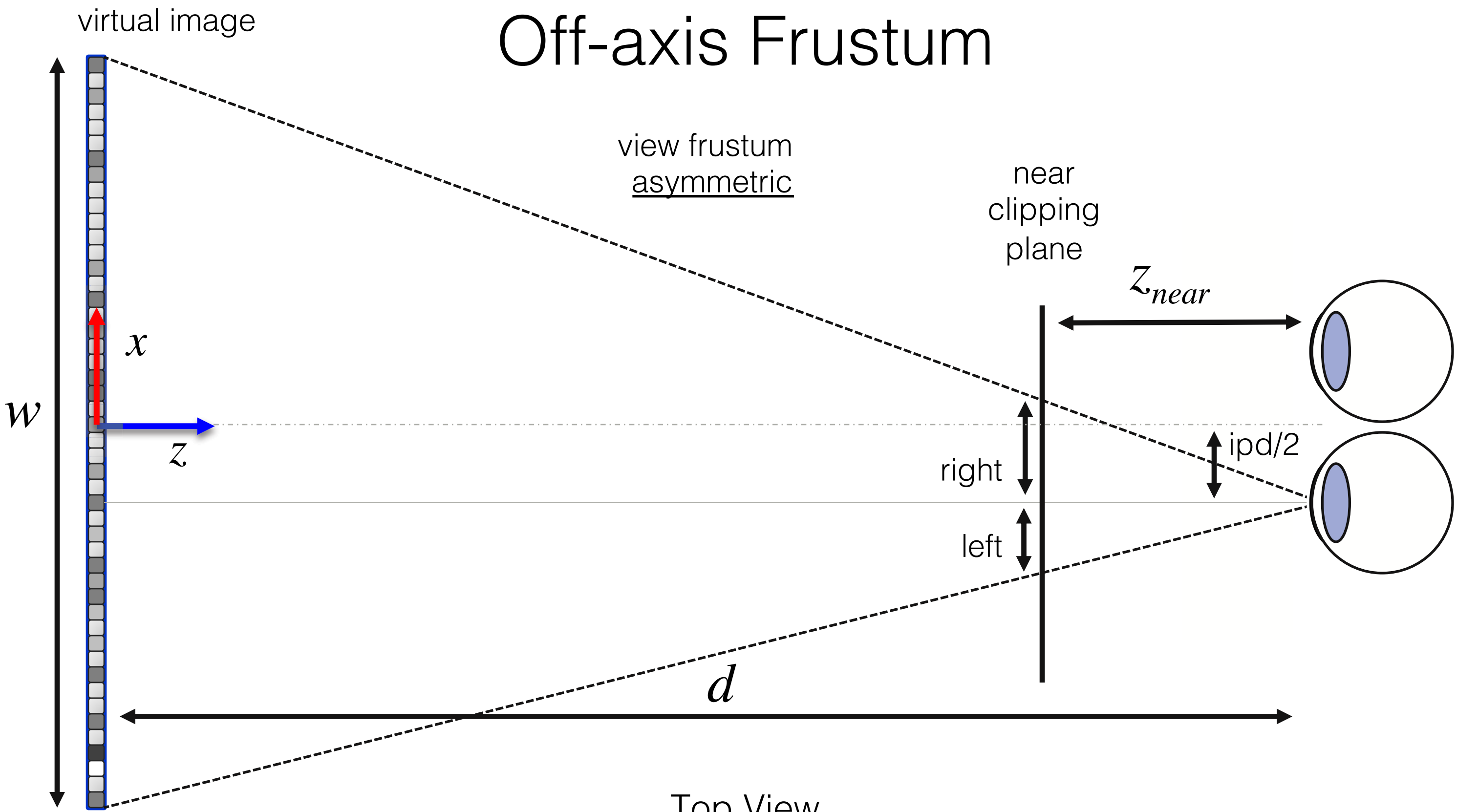
Side View

Off-axis Frustum



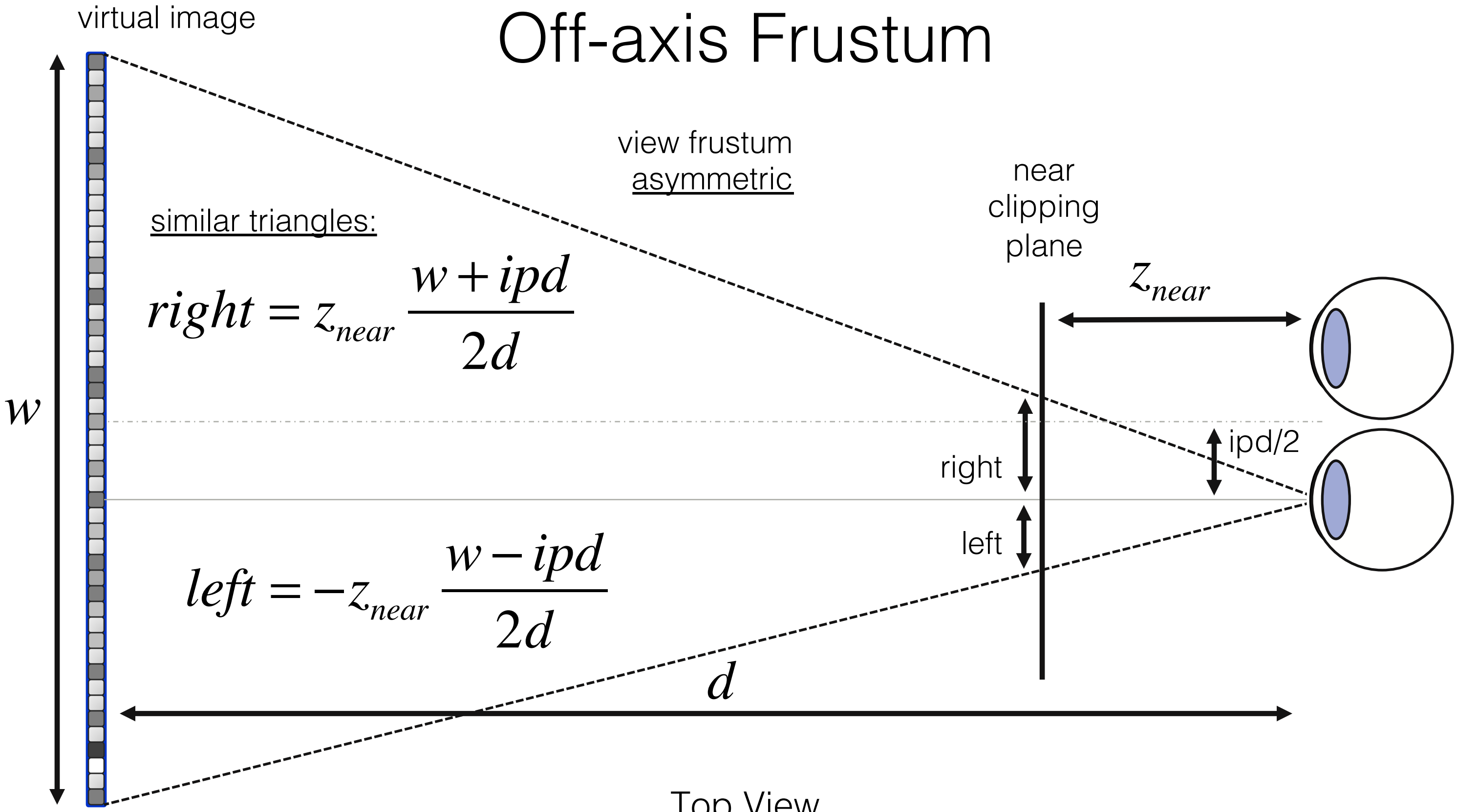
Top View

Off-axis Frustum



Top View

Off-axis Frustum

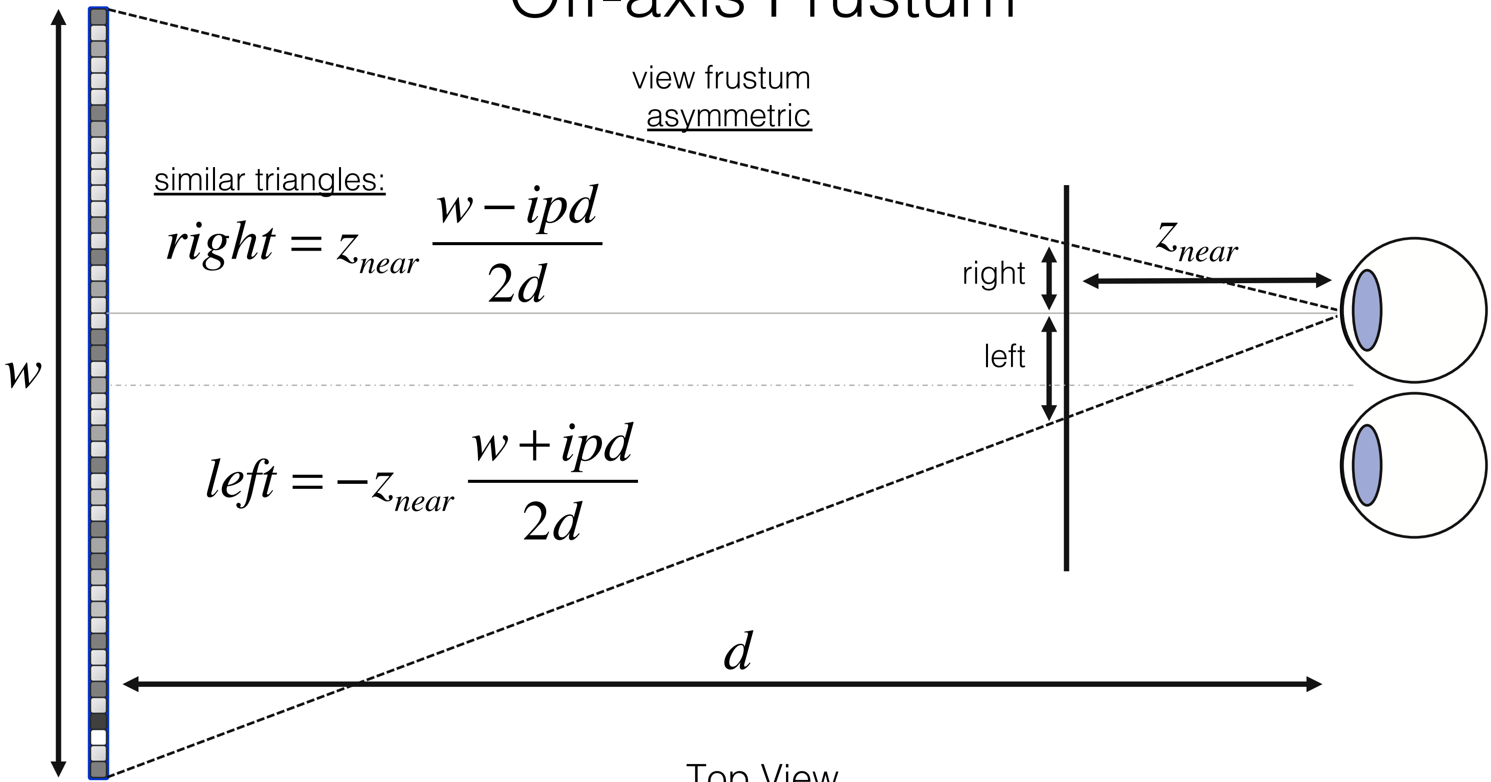


$$right = z_{near}\frac{w+ipd}{2d}$$

$$left = -z_{near}\frac{w-ipd}{2d}$$

Top View

Off-axis Frustum



$$right = z_{near} \frac{w - ipd}{2d}$$

$$left = -z_{near} \frac{w + ipd}{2d}$$

Top View

Anaglyph with OpenGL

- most efficient way:
  1. clear color and depth buffer
  2. set left modelview and project matrix, render scene only into red channel
  3. clear depth buffer
  4. set right modelview and project matrix, render scene only into green & blue channels

- we'll do it in a slightly more complicated way (need for other tasks anyway):
  - multiple render passes
  - render into offscreen (frame) buffers

OpenGL Frame Buffers

- usually (frame) buffers are provided by the window manager (i.e., your browser)

- for most mono applications, two (double) buffers: back buffer and front buffer
  → render into back buffer; swap buffers when done (WebGL does this for you!)
- advantage: rendering takes time, you don't want the user to see how triangles get drawn onto the screen; only show final image

- in many stereo applications, 4 (quad) buffers: front/back left and right buffer
- render left and right images into back buffers, then swap both together

OpenGL Frame Buffers

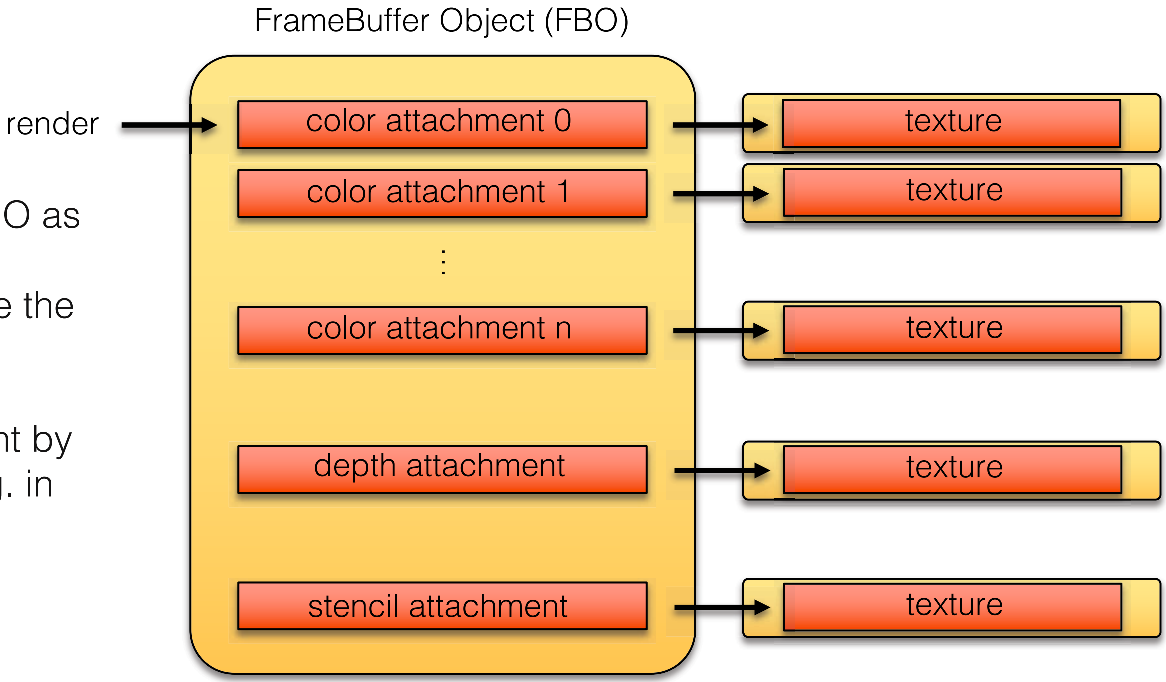
- more generic model: offscreen buffer
- most common form of offscreen buffer in OpenGL: framebuffer object

- concept of "render-to-texture" but with multiple "attachments" for color, depth, and other important per-fragment information

- as many framebuffer objects as desired, they all "live" on the GPU (no memory transfer)

- bit depth per color: 8 bits, 16 bits, 32 bits for color attachments; 24 bits for depth

OpenGL Frame Buffers



- render into FBO as usual, just enable/disable the FBO
- access content by texture ID (e.g. in GLSL shader)

OpenGL Frame Buffers

- FBOs are crucial for multiple render passes!
- 1st pass: render color and depth into FBO
- 2nd pass: render textured rectangle – access FBO in fragment shader
- we'll provide a simple-to-use interface that shields you from the details of FBOs
- in JavaScript FBOs are wrapped by *WebGLRenderTarget* in Three.js
- more details in lab / homework starter code on Friday …

Anaglyph Rendering with OpenGL & GLSL

1. activate FBO1
2. set *left* modelview & projection matrix
3. render scene
4. deactivate FBO1

render pass 1

5. activate FBO2
6. set *right* modelview & projection matrix
7. render scene
8. deactivate FBO2

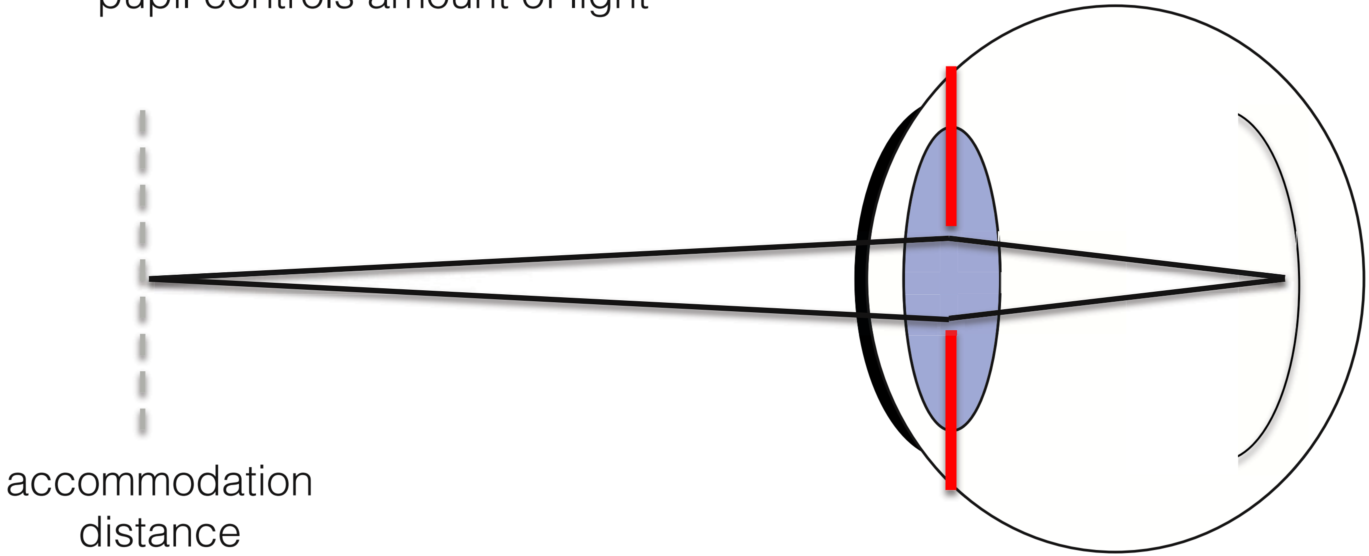
render pass 2

9. render rectangle, pass FBO1 and FBO2 into fragment shader as textures
10. merge stereo images in fragment shader

render pass 3

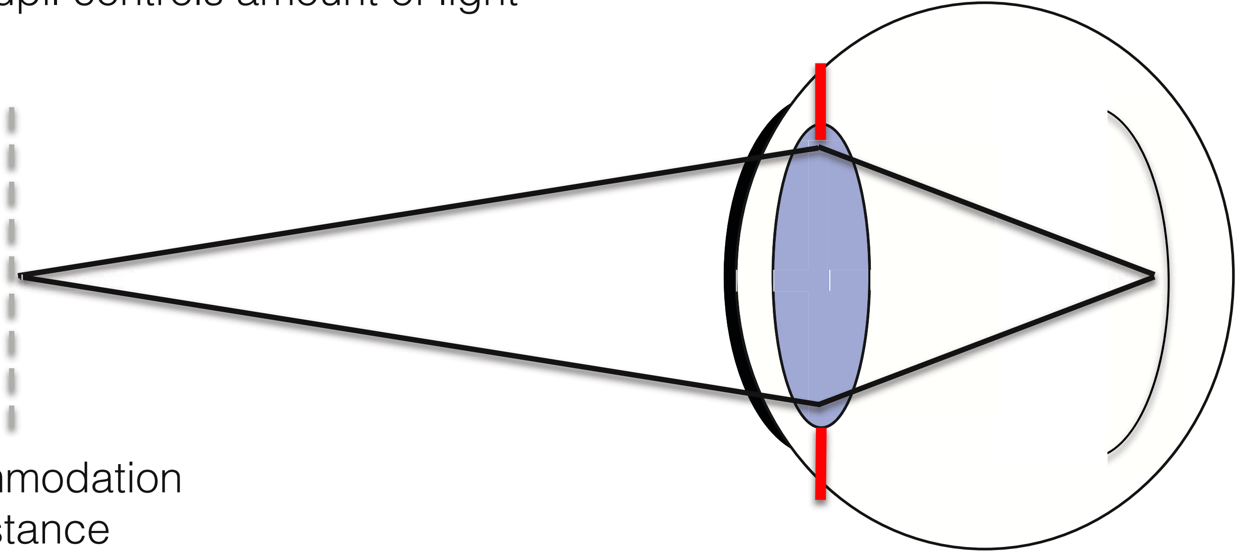
Retinal Blur / Depth of Field Rendering

- pupil controls amount of light



Retinal Blur / Depth of Field Rendering

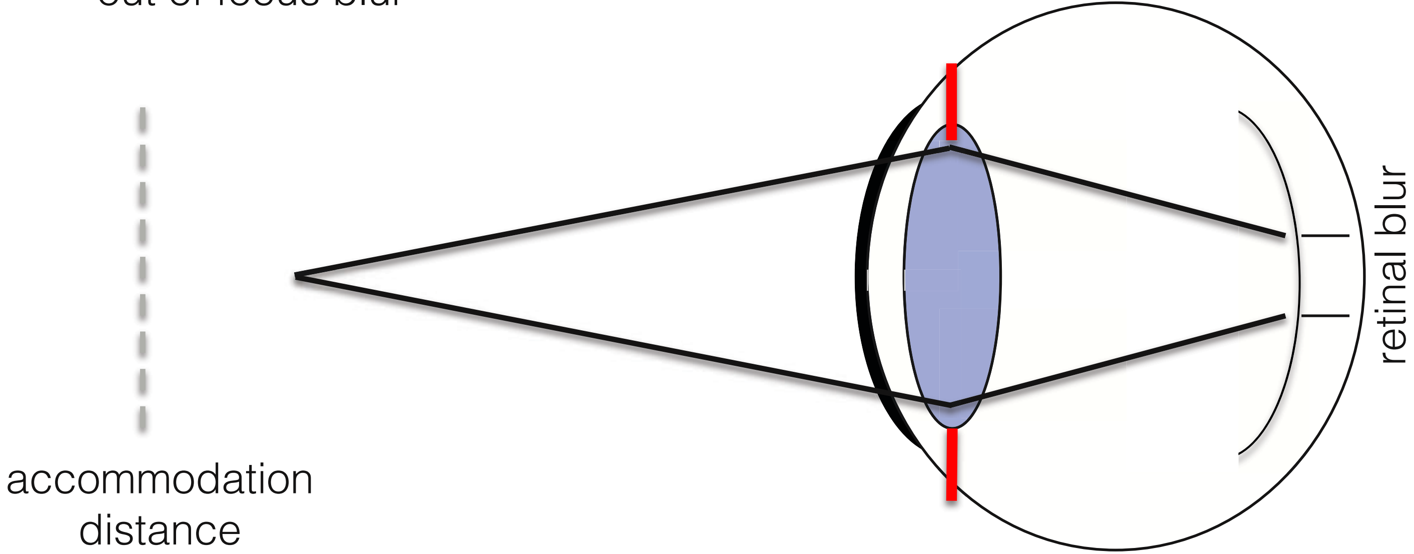
- pupil controls amount of light



accommodation
distance

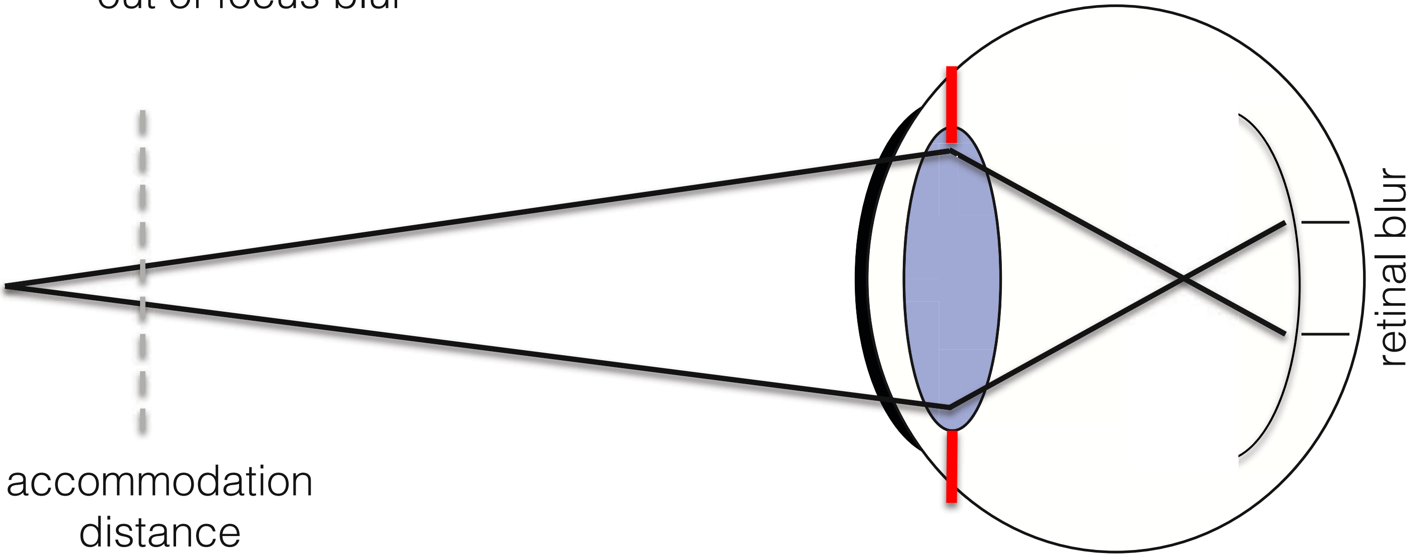
Retinal Blur / Depth of Field Rendering

- out of focus blur



Retinal Blur / Depth of Field Rendering

- out of focus blur

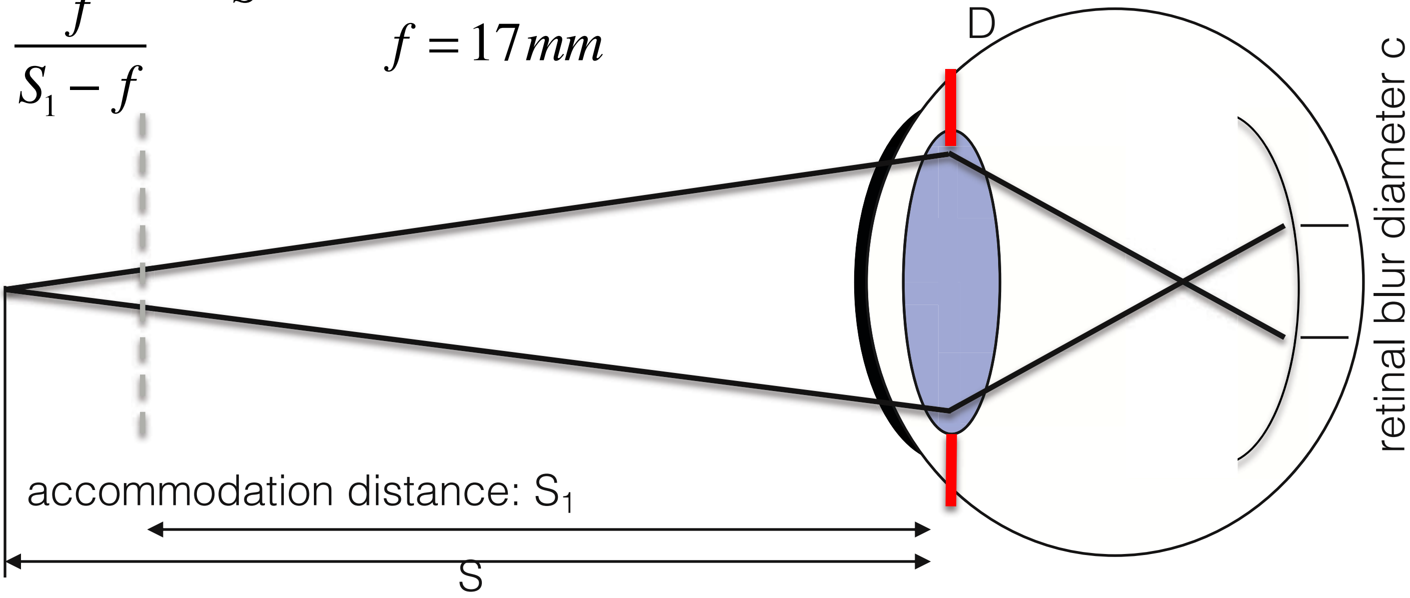


Retinal Blur / Depth of Field Rendering

$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

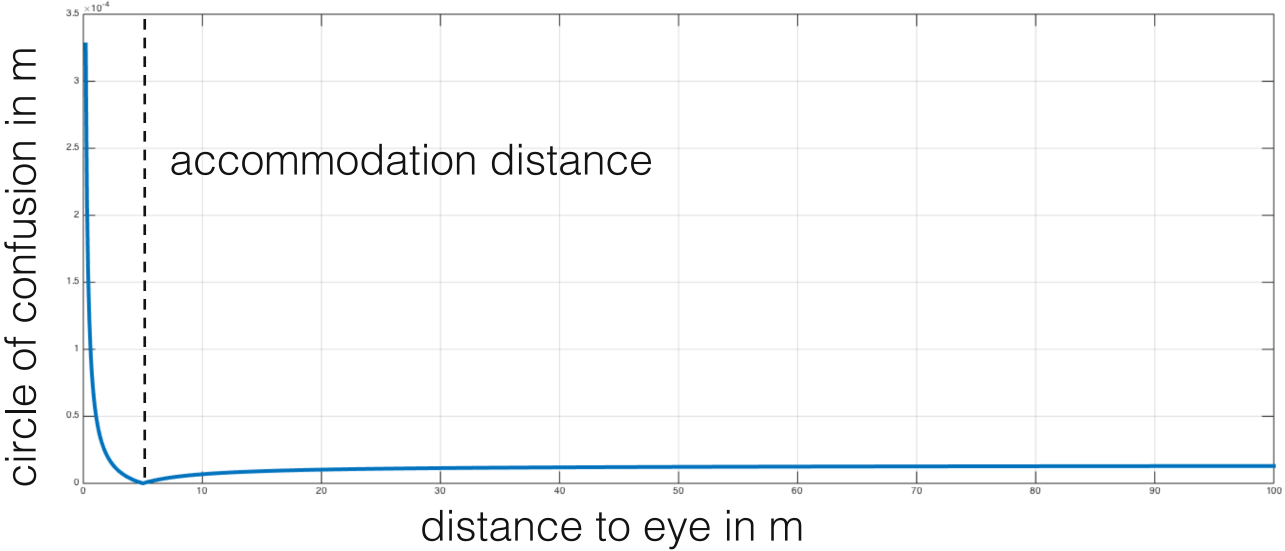
$$M = \frac{f}{S_1 - f}$$

$$f = 17mm$$



Retinal Blur Diameter / Circle of Confusion

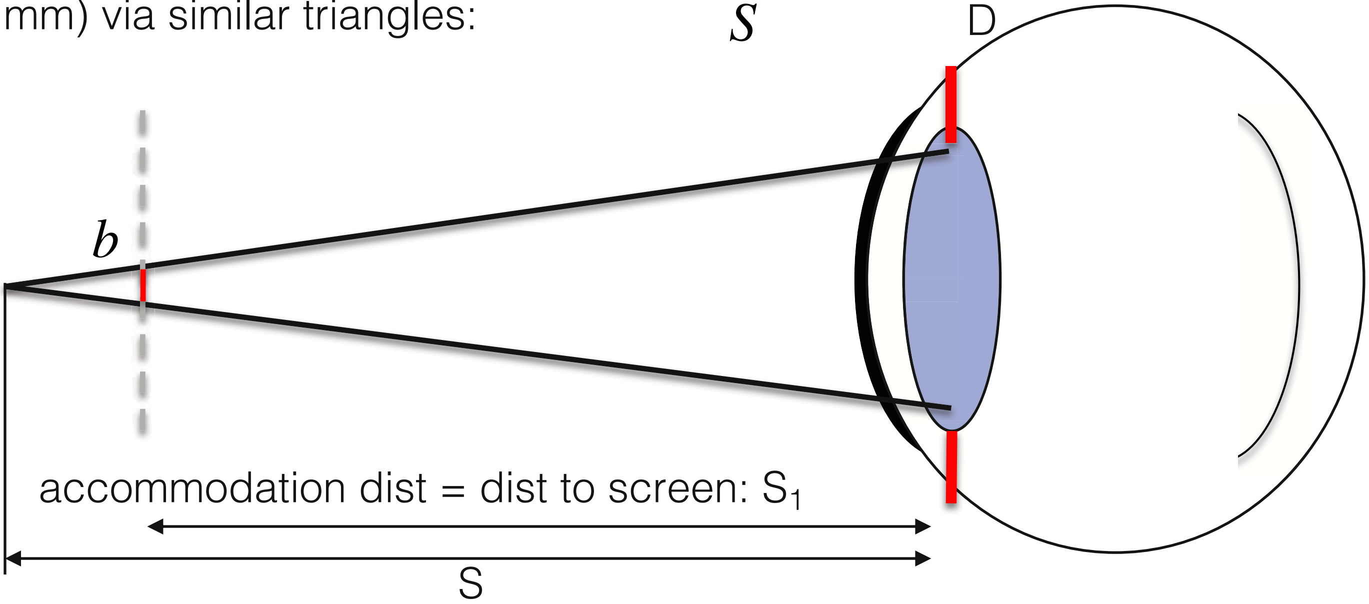
$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$



Retinal Blur / Depth of Field Rendering

depth of field blur on screen (in mm) via similar triangles:

$$b = \frac{|S - S_1| D}{S}$$



Depth of Field with OpenGL/GLSL

- two rendering passes:
    1. render image and depth map into FBO
    2. render quad textured with image + depth
        - vertex shader is pass-through (just transforms, pass on texture coordinates, no lighting)
        - in fragment shader:
            - calculate depth for each fragment in mm (given in clip coords)
            - calculate retinal blur size in pixels given depth & pupil diameter
            - apply blur via convolution with double for loop over neighboring color values in the texture

Depth of Field with OpenGL/GLSL

- how to get metric depth of a fragment?

- in fragment shader we provide depth map `z` as uniform texture in window coordinates (range [0,1]) along with x,y fragment position in window coordinates

- need to convert x,y,z_{window} to view/camera coordinates x,y,z_{view} and then calculate distance as $dist = \sqrt{x_{view}^2 + y_{view}^2 + z_{view}^2}$

How to get Metric Depth of Fragment

1. convert window coordinates to clip coordinates (see course notes on graphics pipeline for derivation)

$$M_{proj} = \begin{pmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & \frac{-2\cdot f\cdot n}{f-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

$$\begin{aligned} z_{clip} &= -\frac{f+n}{f-n} z_{view} - \frac{2fn}{f-n} \\ w_{clip} &= -z_{view} \end{aligned}$$

$$z_{view} = \frac{2fn}{f-n} \cdot \frac{1}{z_{NDC} - \frac{f+n}{f-n}}$$

$$\underbrace{\begin{pmatrix} x_{NDC} \\ y_{NDC} \\ z_{NDC} \\ 1 \end{pmatrix}}_{v_{NDC}} = \begin{pmatrix} x_{clip}/w_{clip} \\ y_{clip}/w_{clip} \\ z_{clip}/w_{clip} \\ 1 \end{pmatrix}$$

$$\underbrace{\begin{pmatrix} x_{clip} \\ y_{clip} \\ z_{clip} \\ w_{clip} \end{pmatrix}}_{v_{clip}} = M_{proj} \cdot M_{view} \cdot M_{model} \cdot \underbrace{\begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}}_{v} = M_{proj} \cdot \underbrace{\begin{pmatrix} x_{view} \\ y_{view} \\ z_{view} \\ 1 \end{pmatrix}}_{v_{view}}$$

How to get Metric Depth of Fragment

1. convert window coordinates to clip coordinates (see course notes on graphics pipeline for derivation)

$$M_{proj} = \begin{pmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & -\frac{f+n}{f-n} & \frac{-2\cdot f\cdot n}{f-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

⇨

$$x_{clip} = \frac{2n}{r-l} x_{view} + \frac{r+l}{r-l} z_{view}$$

$$y_{clip} = \frac{2n}{t-b} y_{view} + \frac{t+b}{t-b} z_{view}$$

⇩

$$x_{view} = \frac{x_{clip} - \frac{r+l}{r-l} z_{view}}{\frac{2n}{r-l}}, \qquad y_{view} = \frac{y_{clip} - \frac{t+b}{t-b} z_{view}}{\frac{2n}{t-b}}$$

How to get Metric Depth of Fragment

2. now compute distance (see course notes on graphics pipeline for derivation)

$$dist = \sqrt{x_{view}^2 + y_{view}^2 + z_{view}^2}$$

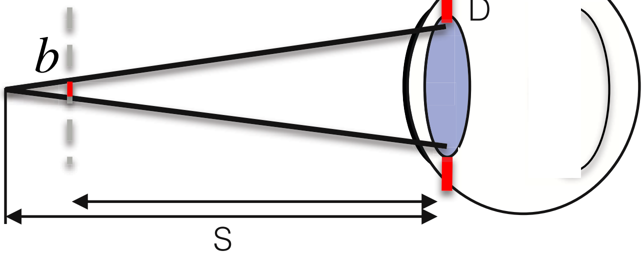
Depth of Field with OpenGL/GLSL

- how to compute retinal blur size and convert to pixels ?

$$pixel\_size_{x/y} = \frac{screen\_size_{x/y}}{screen\_resolution_{x/y}}$$

$$blur\_diameter\_px = \frac{b}{pixel\_size}$$

$$b = \frac{|S - S_1| D}{S}$$



$screen\_size$	is *either* screen width *or* height (same units as other distances)
$screen\_resolution$	is *either* number of horizontal pixels *or* vertical pixels of the screen

Depth of Field with OpenGL/GLSL

1. activate FBO
2. set modelview & projection matrix
3. render 3D scene
4. deactivate FBO
5. render rectangle, pass FBO with image & depth map into fragment shader as textures
6. execute depth of field fragment shader

render pass 1 (steps 1–4)

render pass 2 (steps 5–6)

Depth of Field with OpenGL/GLSL

- <u>putting it all together</u> – this is just a general overview, do not use this exact code

```
uniform sampler2D image;    // RGB image was written in the first rendering pass
uniform sampler2D depthMap; // depth map was written in the first rendering pass
uniform float     znear;
uniform float     zfar;
uniform float     pupilDiameter;
varying vec2      textureCoords;

void main () // fragment shader
{
  // get fragment z in NDC
  float zNDC = 2*texture2D( depthMap, textureCoords ).r - 1;

  // get z in view coordinates (metric depth of current fragment)
  float distanceToFragement = …

  // compute retinal blur radius in pixels
  float blurRadius = …
  int blurRadiusInt = round(blurRadius);

  // set output color by averaging neighboring pixels in the color image (i.e., convolution)
  gl_FragColor.rgb = 0;
  for (int i=-blurRadiusInt; i<blurRadiusInt; i++)
    for (int j=-blurRadiusInt; j<blurRadiusInt; j++)
      if (float(i*i+j*j) <= blurRadius*blurRadius)
        gl_FragColor.rgb += … texture lookup in neighboring pixels

  // normalize color
  …
}
```

Summary

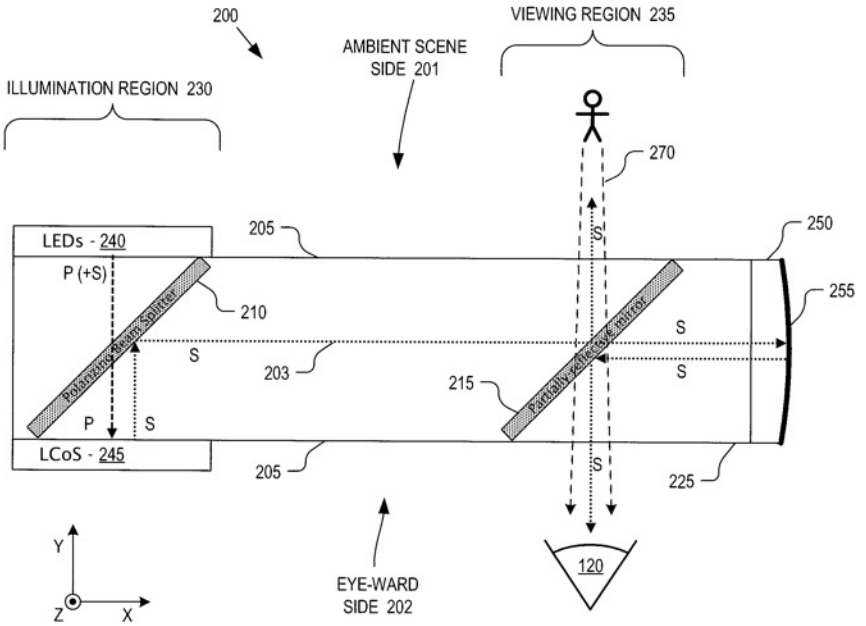
- many different technologies for glasses-based stereo
- we’ll work with anaglyph for this lab + homework
- color management is important for anaglyph
- getting the view and projection matrices right is important (otherwise headaches)

- may need multiple render passes (all wrapped in the starter code)

- depth of field rendering may add more realism

Next Lecture: HMD Optics and Microdisplays

- magnifiers
- VR & AR optics
- microdisplays
- stereo rendering for HMDs
- lens distortion / undistortion



drawing from Google Glass patent

Further Reading

- http://paulbourke.net/stereographics/stereorender/
- Eric Dubois, “A Projection Method to Generate Anaglyph Stereo Images”, ICASSP 2001
- Library of Congress, Stereoscopic Cards:

  http://www.loc.gov/pictures/search/?st=grid&co=stereo