Color, Images, and Cameras

Slides by Sarah Jobalia and Kevin Li, with modifications by Kate Baker

Housekeeping

- **HW1 GRADING TODAY**
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- **SUBMIT ON GRADESCOPE!!**

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- Check out Blender tutorials!

Revisiting Questions

- OpenGL
  - Skimmed last time, too much today to discuss the pipeline in full again
  - Have a look at the linked resources in Tuesday's lecture

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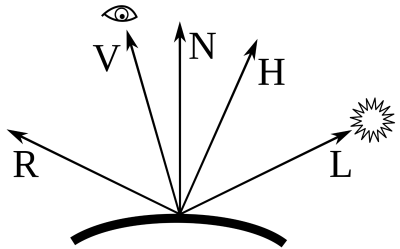
- Phong vs Gouraud shading
  - Gouraud shading can and typically uses the Phong reflection model for the colors at its vertices
  - Gouraud can miss highlight entirely inside a triangle, and smears highlights at vertices
  - Normals in Phong shading add more flexibility even if more expensive

Last time…

- Rasterization of triangles to pixels
  - For each pixel, if the center of the pixel is inside the triangle, consider it part of the triangle (and color it with the triangle's color)
- Shading: determining how light and energy bounces off objects

C = ambient + diffuse + specular



Lecture Outline

- In real life
  - The human eye (pupil, cornea, lens)
  - RGB color space
  - The pinhole camera
- In the rasterizer
  - Coordinate frames
  - Perspective & orthographic projection
  - Normalized coordinates & the z-buffer algorithm
- Lens-based cameras
- Beyond rasterization

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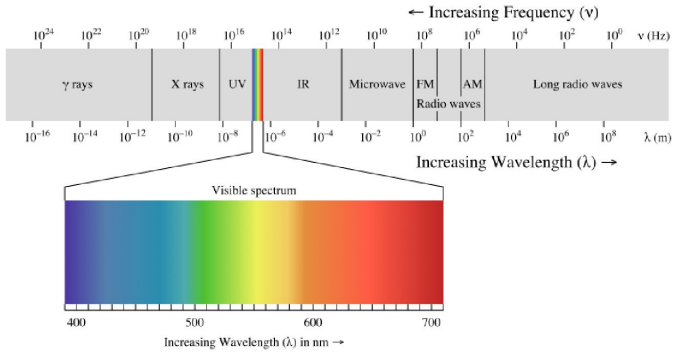

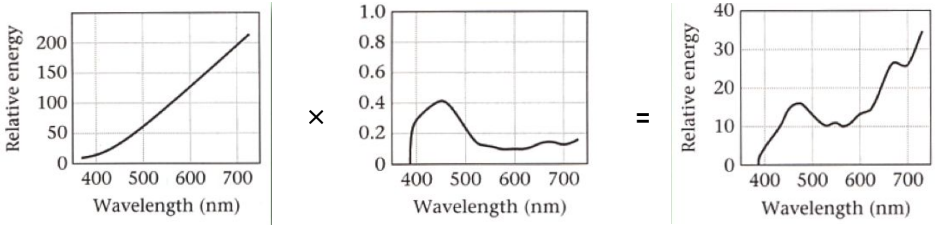

Incoming Energy × Material Reflectance = Reflected Energy

Light and the Human Eye

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  - **3** types of cone cells, **1** type of rod cell

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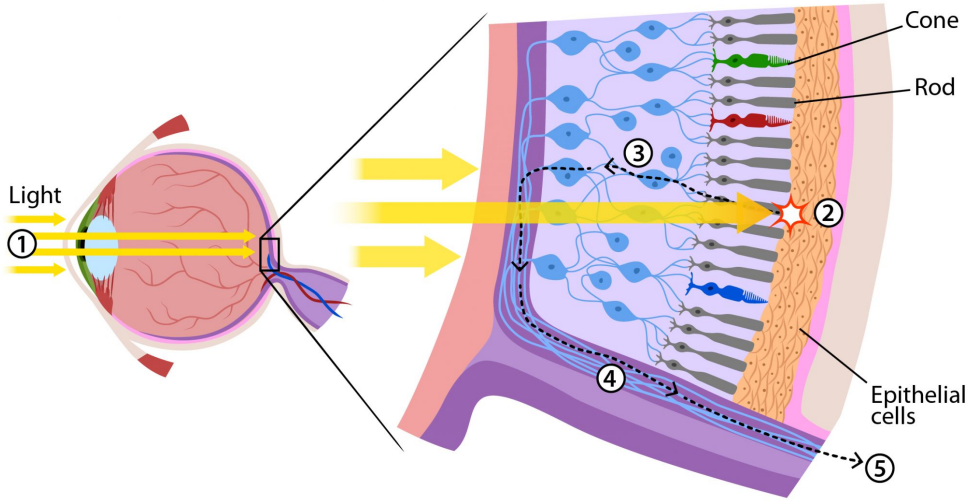
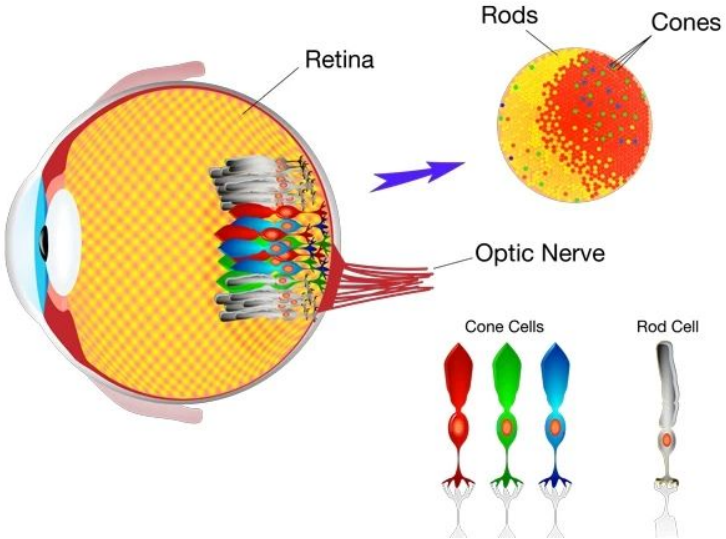
  - **3** types of cone cells, **1** type of rod cell
  - Each specialized receptor fires a single signal that can vary in strength
  - Each of the **4** cells are sensitive to different frequencies and intensities of light
- **Cone**: used when there's sufficient light and distinguishes color
- **Rod**: used in low light settings

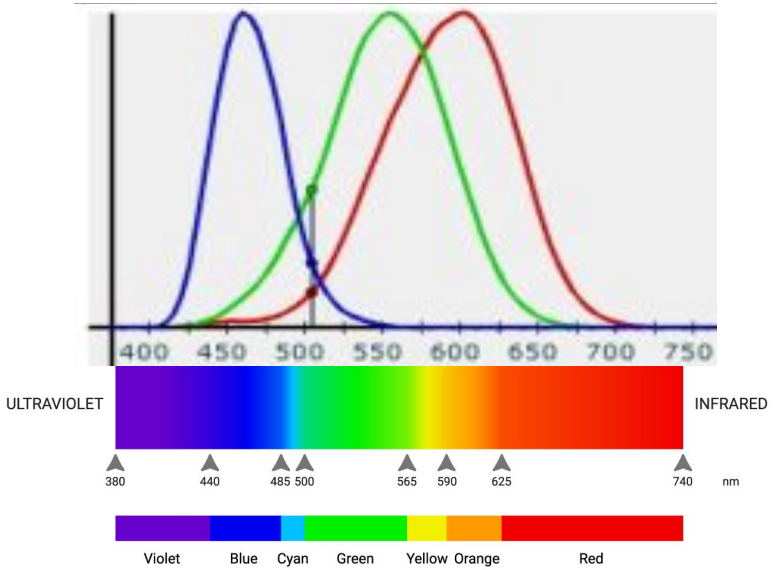
Light and the Human Eye





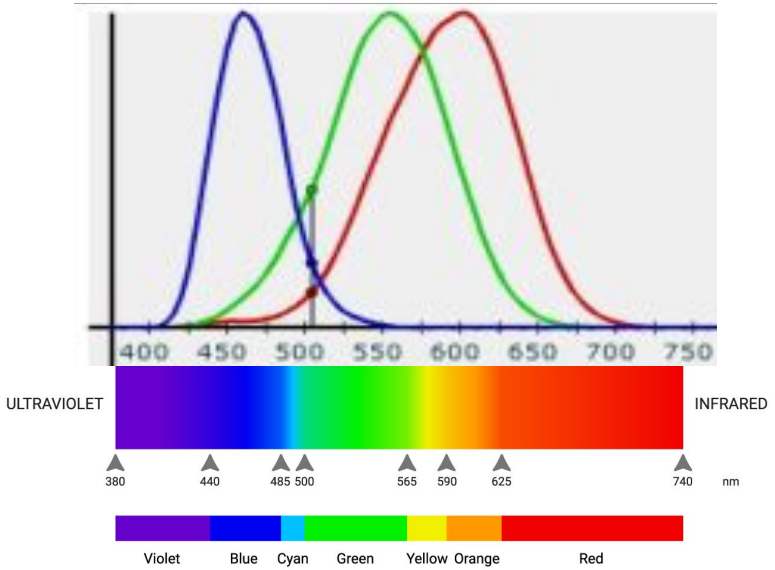
Light and the Human Eye

- Humans have **trichromatic vision**
- Our brains differentiate between colors via the three types of signals we get:
  - L-cones: longer wavelengths (red cones)
  - M-cones: medium wavelengths (green cones)
  - S-cones: shorter wavelengths (blue cones)



Light and the Human Eye

- Ex: a dandelion (570nm wavelength)



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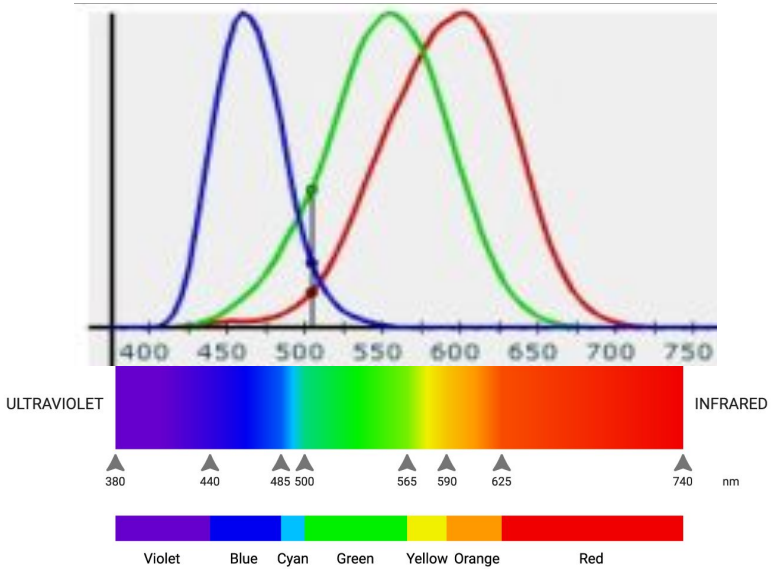

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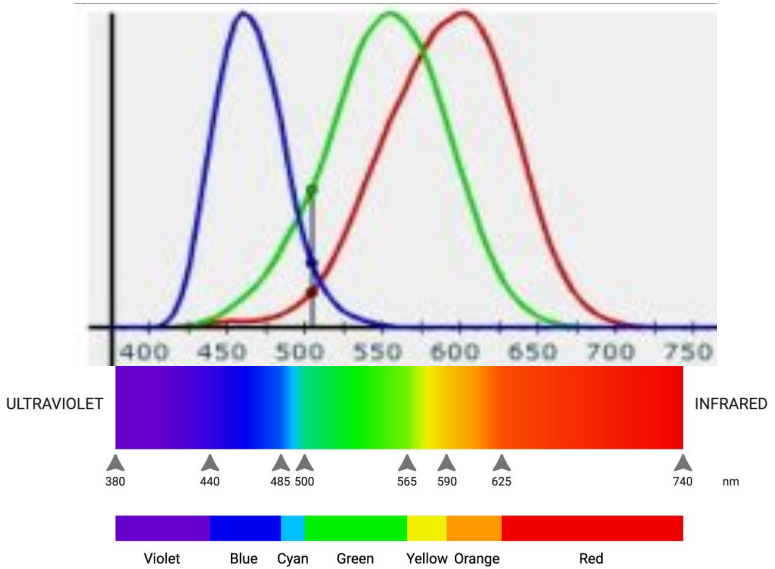

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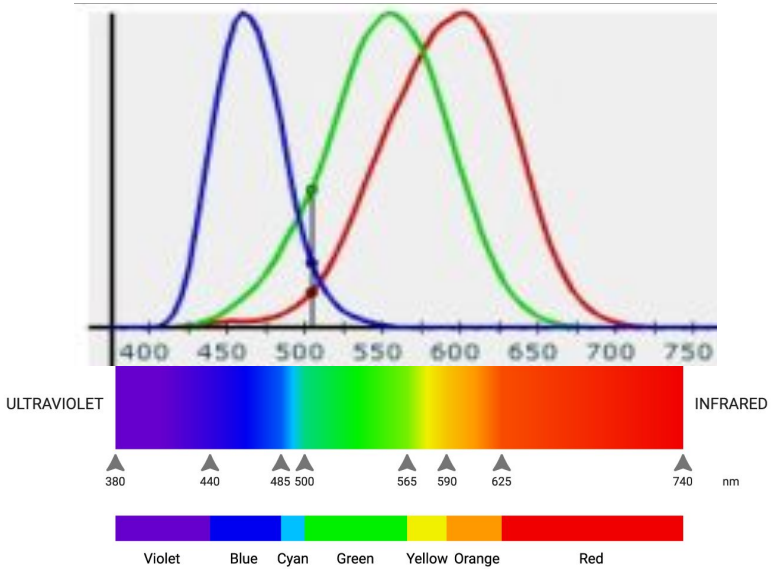

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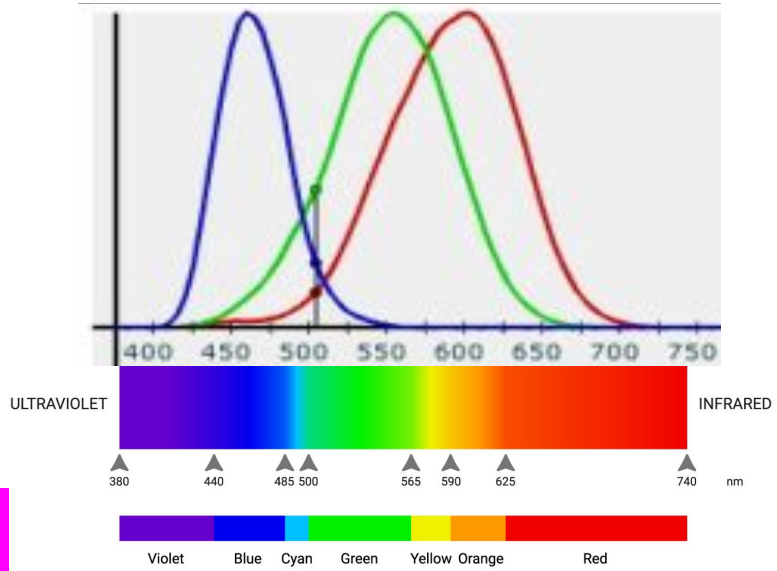
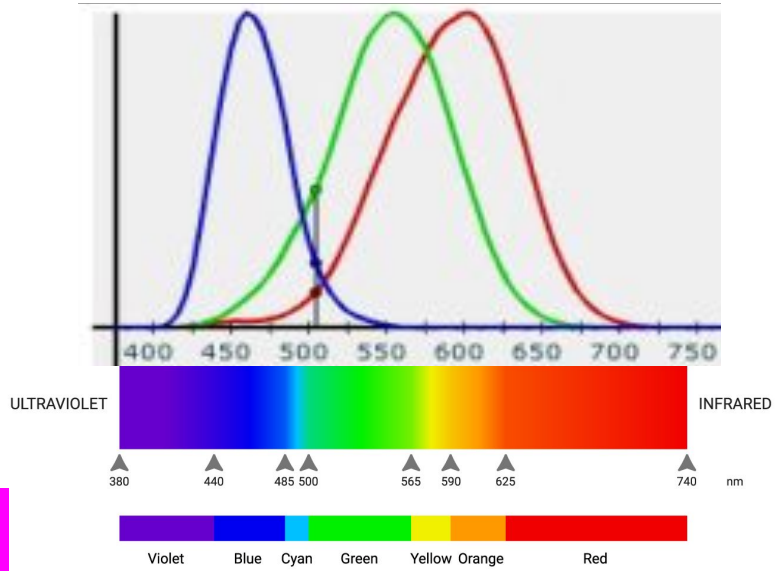
- Ex: magenta



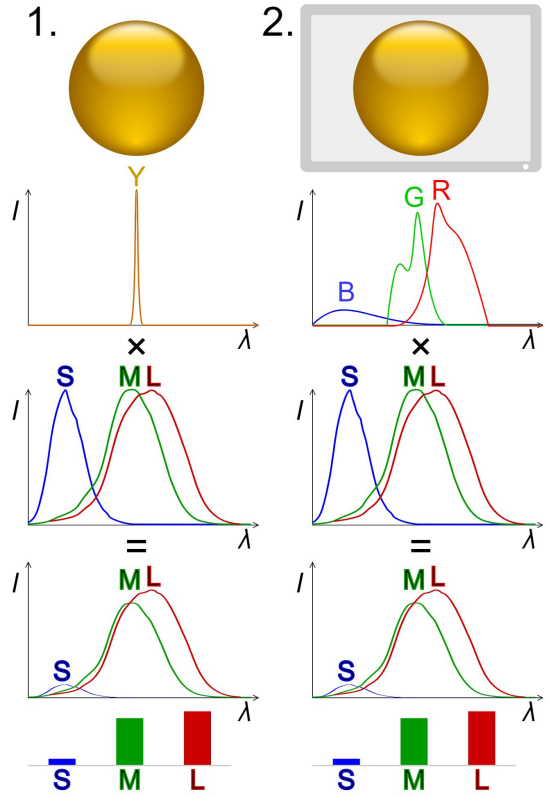
Light and the Human Eye

- Ex: a dandelion (570nm wavelength)
  - L/M cones would fire
- Ex: white light
  - All cones saturated
- Ex: magenta
  - Mix of blue and red light
  - Both blue and red tuned cones would spike



Mixed wavelengths vs single wavelengths

- Given any human perceived “color:”
- Can use **3 single wavelength** lasers to fool a human into mistakenly thinking that the laser combo matches that color
  - Aka turn into a single wavelength
  - Ex lasers: R = 700nm, G = 546nm, B = 435nm
- This is doable because each there are **three** different cones, and each can only send **one** signal



Mixed wavelengths vs single wavelengths

- Ex: magenta
  - Magenta objects reflect long/short wavelengths but absorb mid-length wavelengths
  - Cones don’t measure wavelength and rather how much they’re stimulated

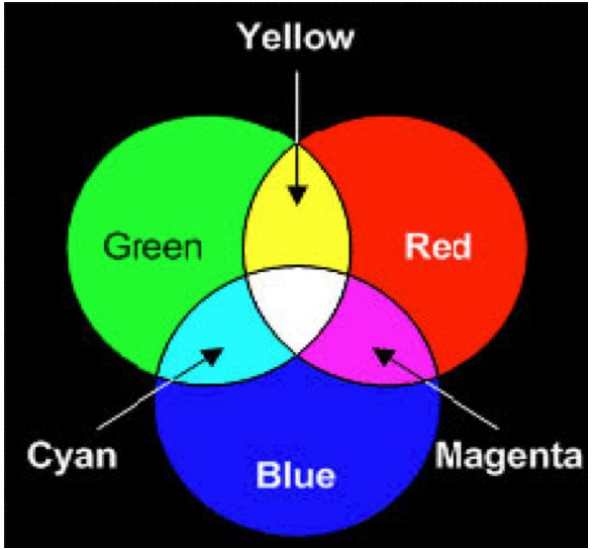


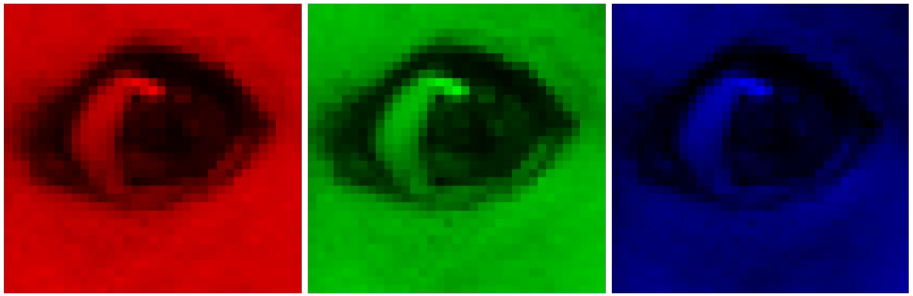
Image Representation

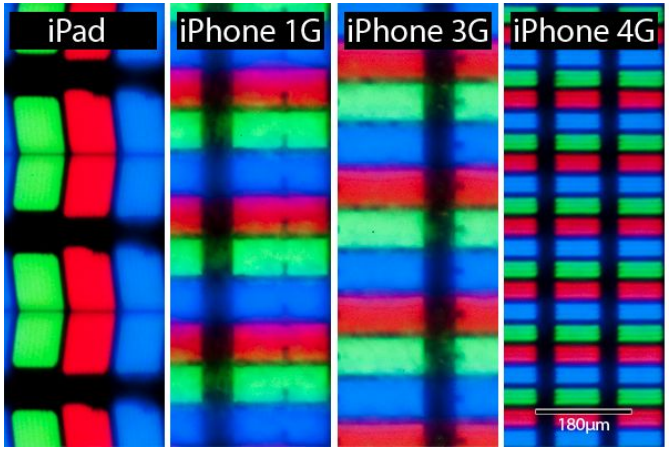
- Graphics: simulating the real world **as the human eye sees it!**

- Algorithms/hardware for displays, cameras, printing, etc. have been optimized for the human eye

Image Representation

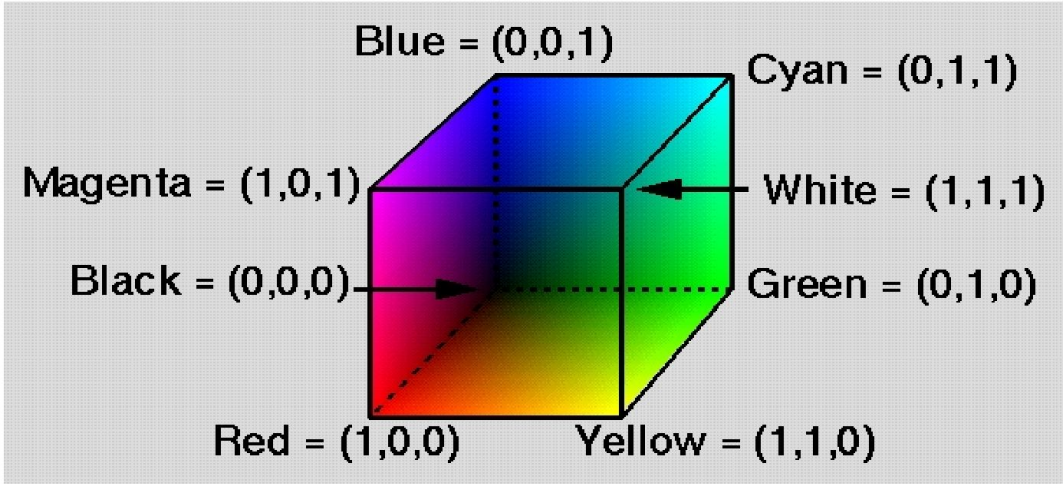
- Images = 2D grid of color (pixels), often in RGB
- Displays = grid of RGB LED lights
- Digital cameras = grid of RGB sensors
- Why?
  - The way our eyes process color!





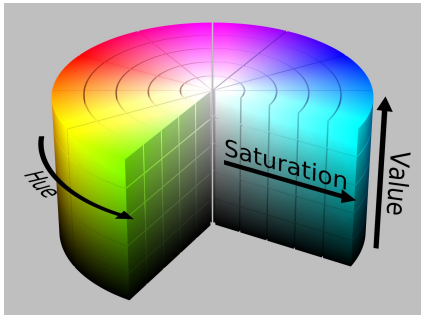
RGB Color Space

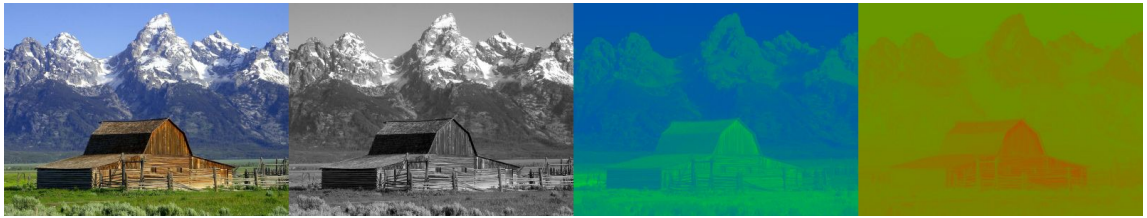
- Each image is a **2D spatial grid of colors** where (0,0,0) = black and (1,1,1) = white



Other Color Spaces

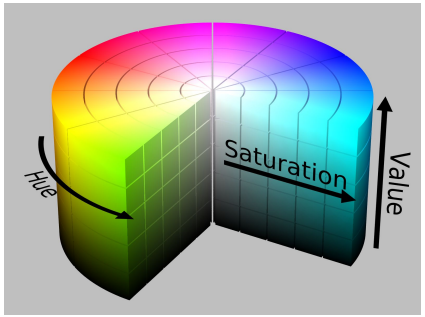
- **HSV** for user interfaces
  - Closer to how we reason about color (purity/intensity)

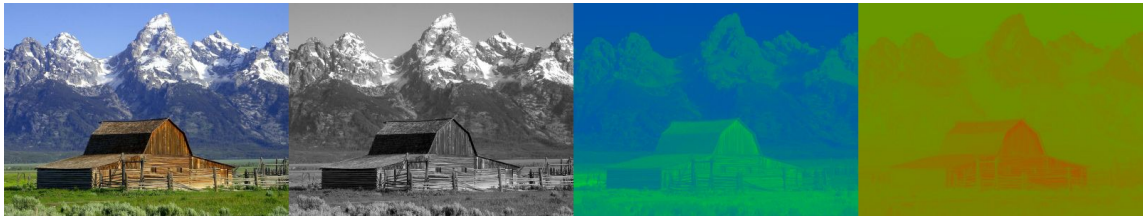




Other Color Spaces

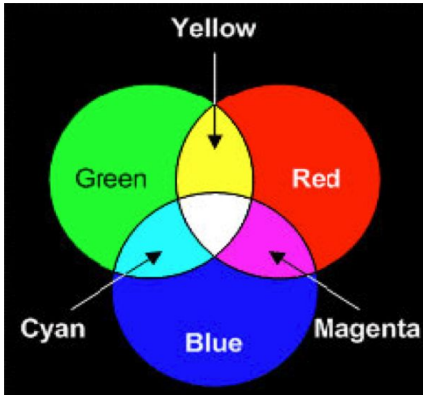
- **HSV** for user interfaces
  - Closer to how we reason about color (purity/intensity)
- **YUV** for video compression
  - Legacy model from black and white TV, but still used to store video
  - Human eyes are more spatially sensitive to intensity than color





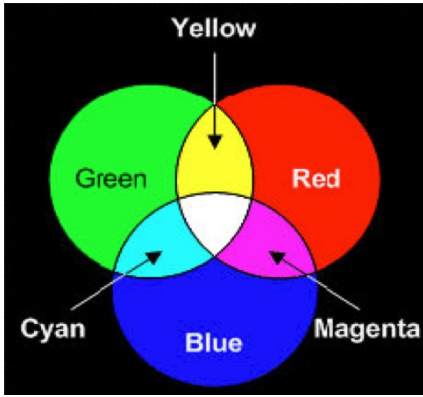
Additive Light vs Subtractive Materials

- Additive color
  - Start with black
  - Every light source you add contributes more weight



Additive Light vs Subtractive Materials

- Additive color
  - Start with black
  - Every light source you add contributes more weight
- Subtractive color
  - Start with white
  - Each ink layer removes certain wavelengths by absorbing them
  - Material colors = defined by what light they absorb
  - Ex: a cyan material absorbs red light

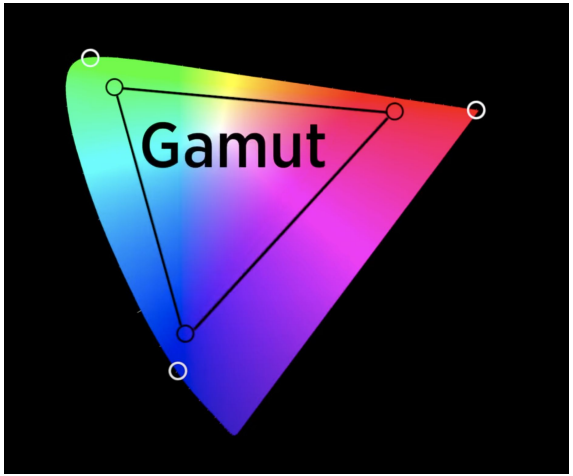


8 bit quantization: 0-255

- Quantization for efficient storage, but need to make it look smooth
- We typically use 256 levels for brightness
  - Store R,G,B each ranging from 0-255
- High Dynamic Range image formats use an even larger range

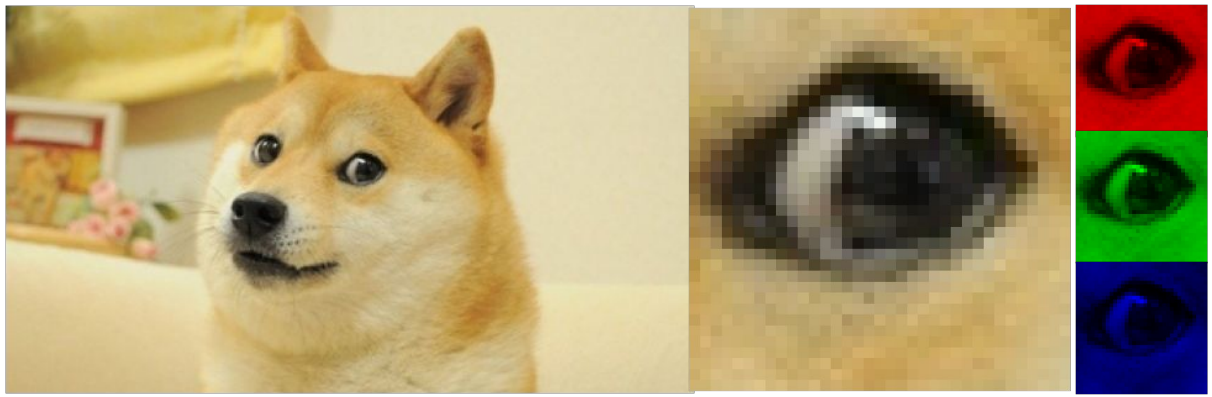
Color Gamut

- A way of converting between storage and display
- Even if a display is composed of three different types of RGB light, it doesn't mean it can represent all the possible colors a human can perceive
- Can lead to differences in color between displays:



Summary so far

- Understanding human perception allows for MANY optimizations in both software and hardware
  - RGB LED displays, camera sensors, video compression, …
- The images we create are not intended to duplicate reality, only to fool humans into believing such!



The human eye: part 2

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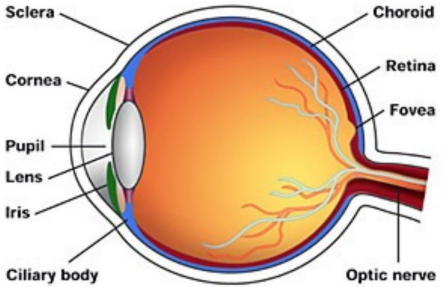
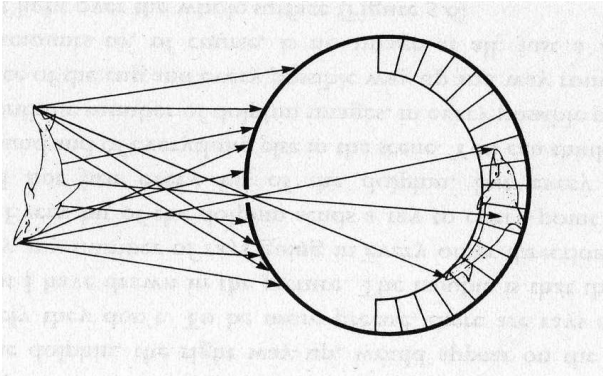
- The **pupil** restricts the entry of light so that each cone only receives light emanating from a small region on the object, giving spatial detail





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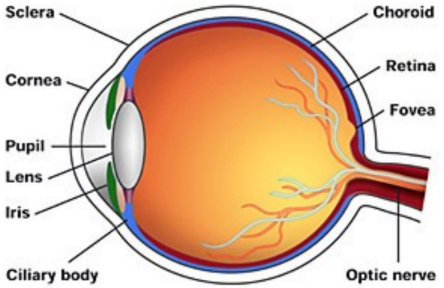
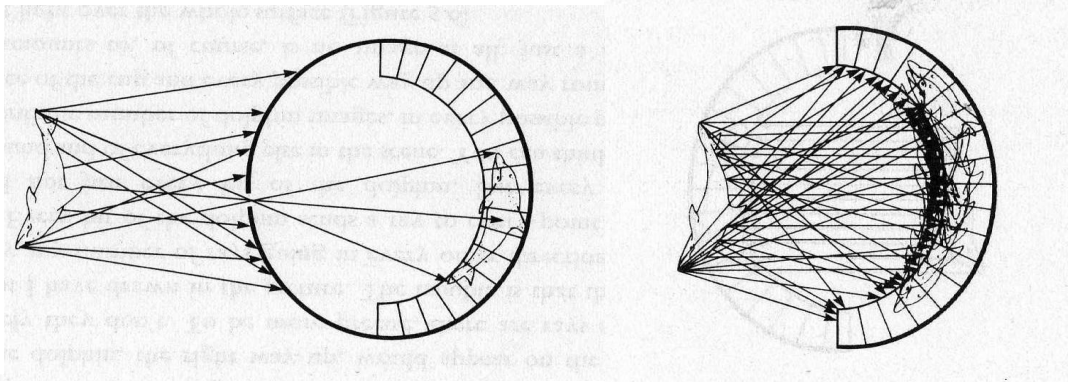
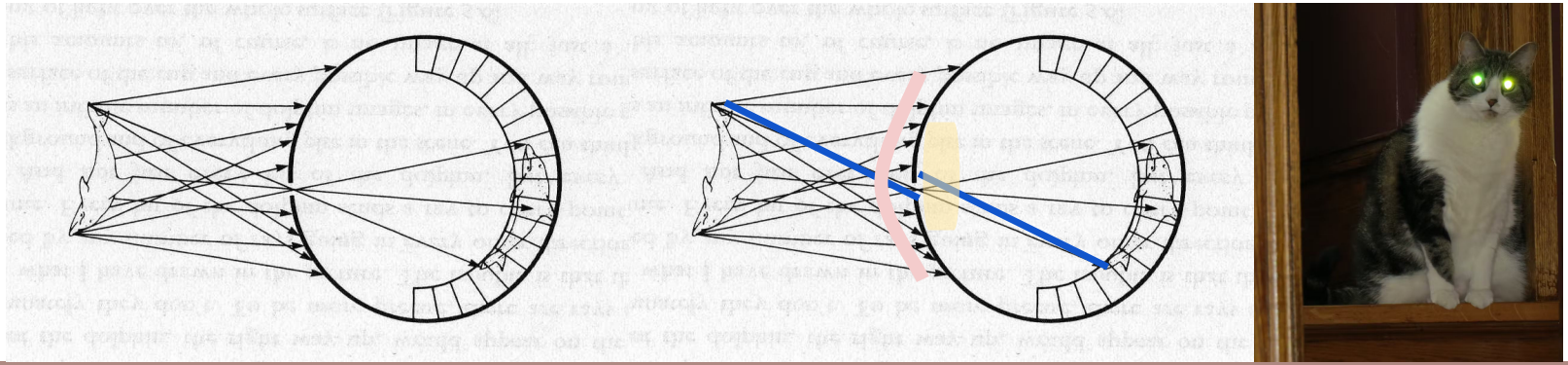
- The **pupil** restricts the entry of light so that each cone only receives light emanating from a small region on the object, giving spatial detail
- Without the pupil, light from every part of an object would hit the same cone on our eye, blurring the image





The human eye: part 2

- The pupil restricts the entry of light
  - In the dark, it dilates to allow for more light to enter
  - Cats have wide pupils to let more light in – lots of reflects from the back of their eyes at night!



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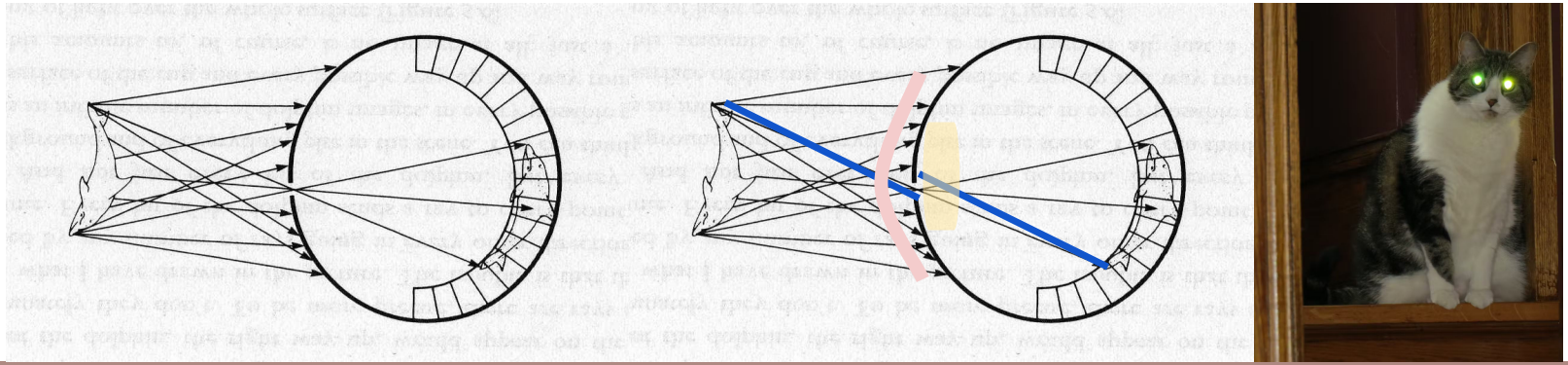
- We rely on our **cornea** and **lens** to bend light and make everything converge properly



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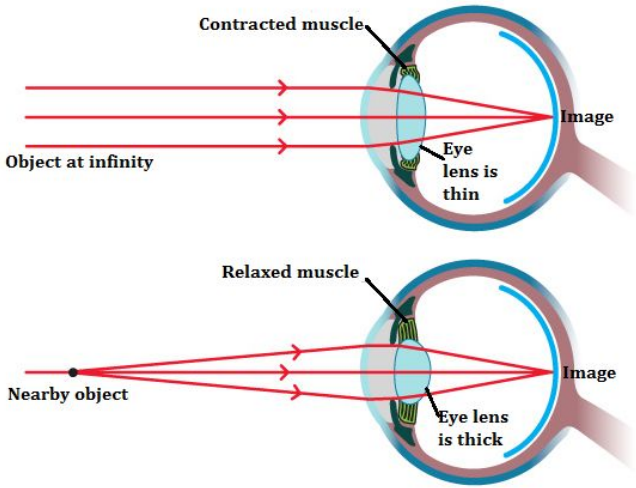
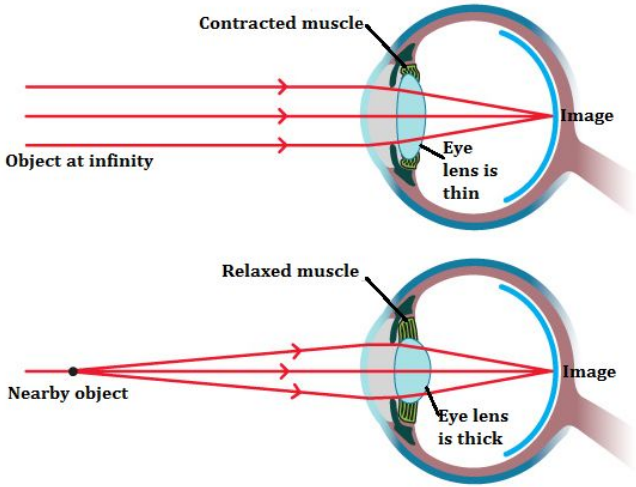
- We rely on our **cornea** and **lens** to bend light and make everything converge properly
- Light travels in straight lines and reflect/refract based on the material



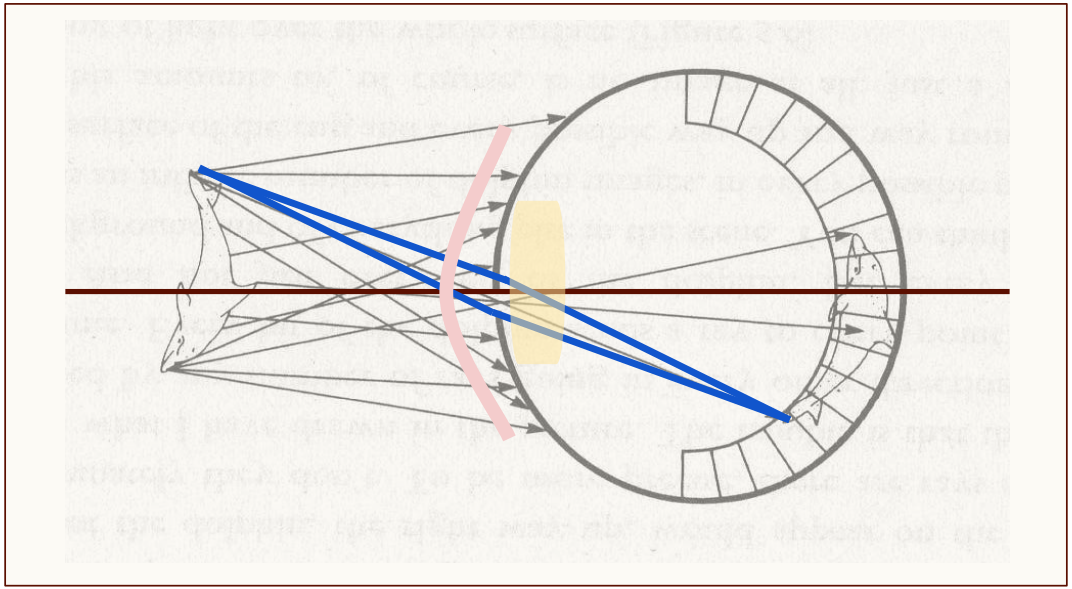
The human eye: part 2

- We rely on our **cornea** and **lens** to bend light and make everything converge properly
- Light travels in straight lines and reflect/refract based on the material
- The **lens** changes its shape so that objects at different depths are in focus
  - Ex: Hold your palm out and stare at it. The projector/laptop screen becomes out of focus



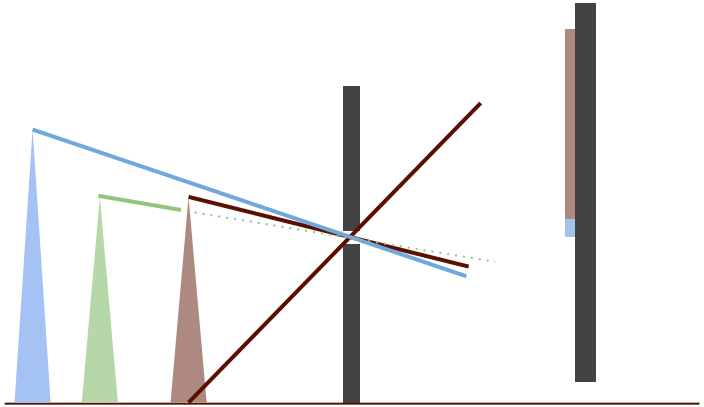
The human eye: part 2

- Note: images as assembled on our retina are “flipped,” so our brains flip them back!



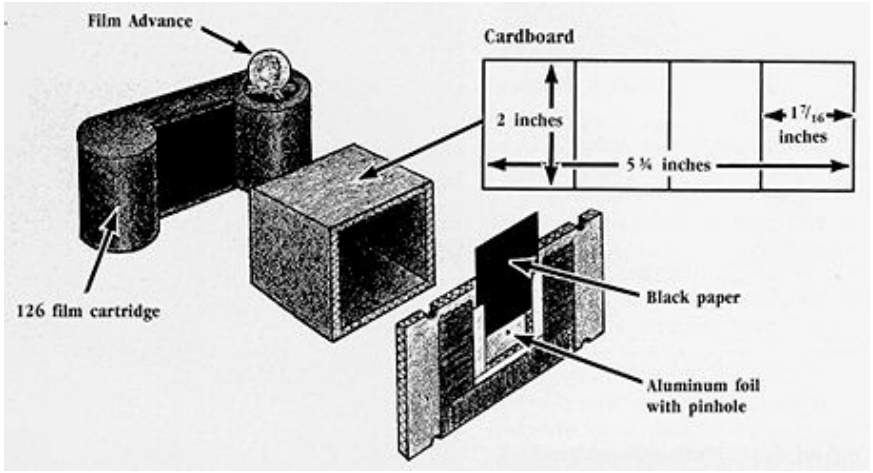
Pinhole Camera

- The first camera (camera obscura effect)!
  - Been around for thousands of years
  - Now used to safely observe solar eclipses
- Make a really small hole on the wall of a very dark room when it's bright out



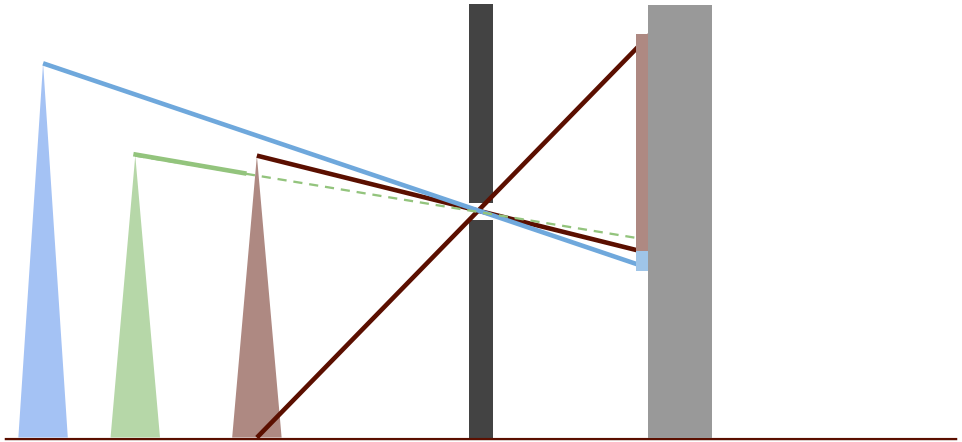
Pinhole Camera

- Can make a simple camera this way!
  - Place film that reacts to light in a dark chamber
  - Cover up the hole once sufficient light has entered and accumulated chemical reactions on the film



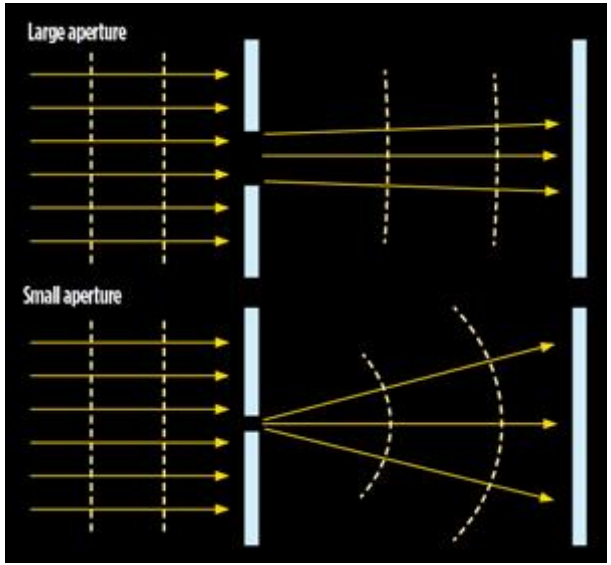
Pinhole Camera

- The pinhole model is a simplification of human perception but…
- It demonstrates why objects get occluded in our vision and why objects that are farther away appear smaller



Pinhole Camera

- Disadvantages
  - Very little light comes in, so you need to **expose** for a long time to allow enough light to enter



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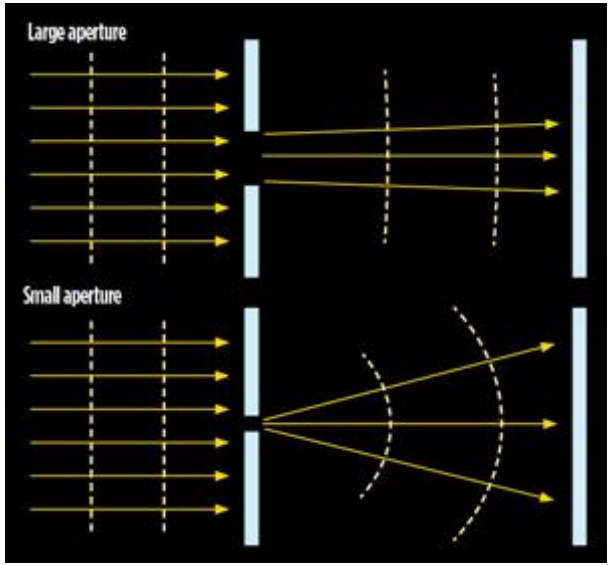
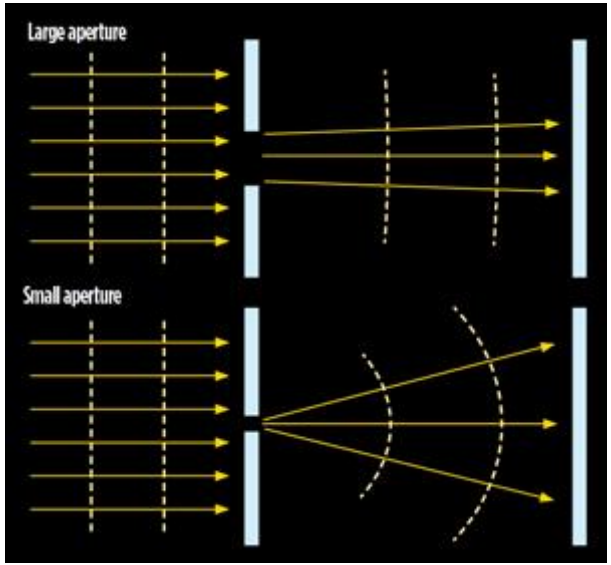
  - Physical limits to pupil size. Diffraction means we can’t go too small



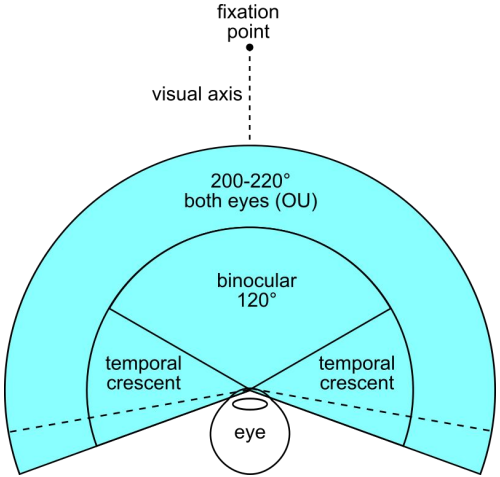
Pinhole Camera

- Disadvantages
  - Very little light comes in, so you need to **expose** for a long time to allow enough light to enter
  - Physical limits to pupil size. Diffraction means we can't go too small
- But we don't have this problem with virtual cameras!



Field of View

- Determines is visible/capturable on the film (retina)
- For pinhole camera: depends mostly on **size of film**
- For eyes / lens-based cameras: depends on the **lens**
  - We will return to lens-based cameras later



Lecture Outline

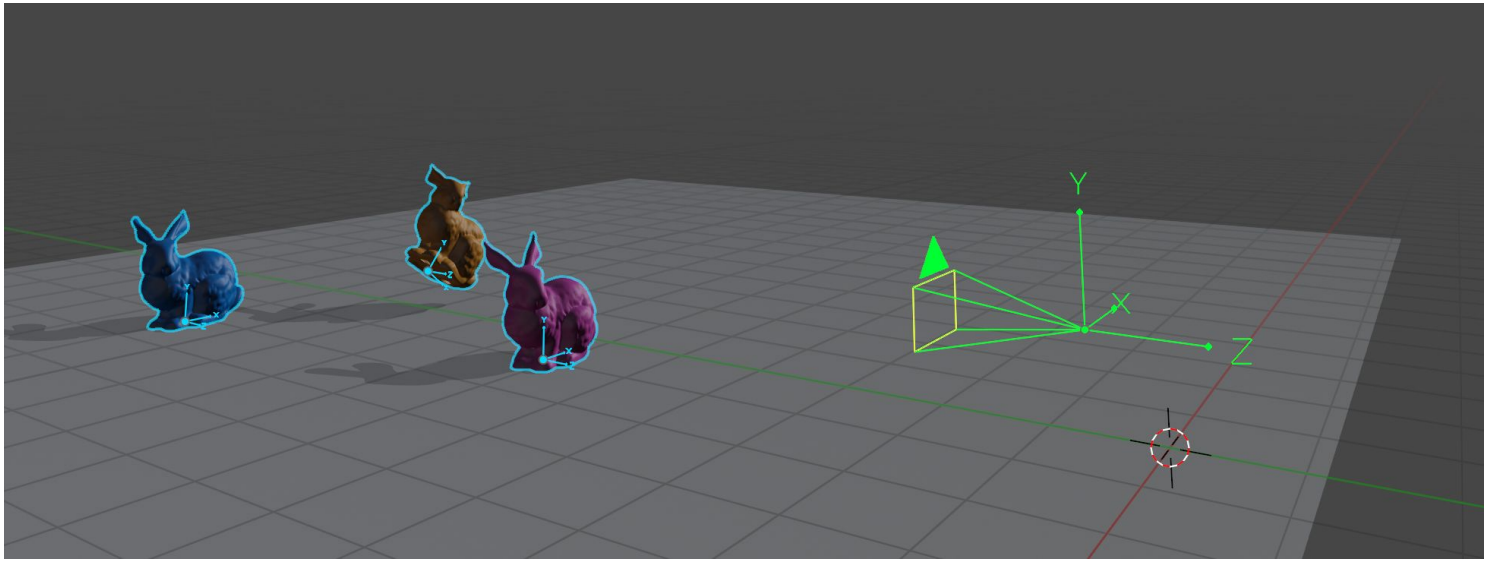
- In real life
  - The human eye (pupil, cornea, lens)
  - RGB color space
  - The pinhole camera
- In the rasterizer
  - Coordinate frames
  - Perspective & orthographic projection
  - Normalized coordinates & the z-buffer algorithm
- Lens-based cameras
- Beyond rasterization

3D → 2D

- There are **objects** in the **world**. We point a **camera** at them and an image appears on **film**
- To model a pinhole camera:
  - Where the camera is and where it's pointing (camera coordinate system)
- To model image creation:
  - Field of view, image resolution (film size)

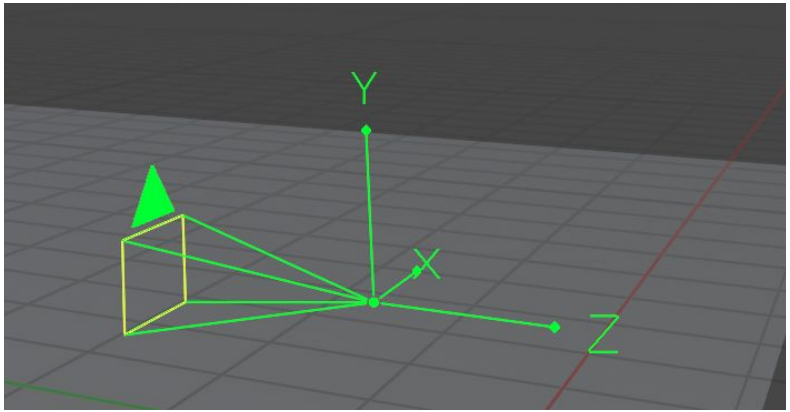
Coordinate Frames

- Object space, world space, **camera space**



Standard Camera Frame

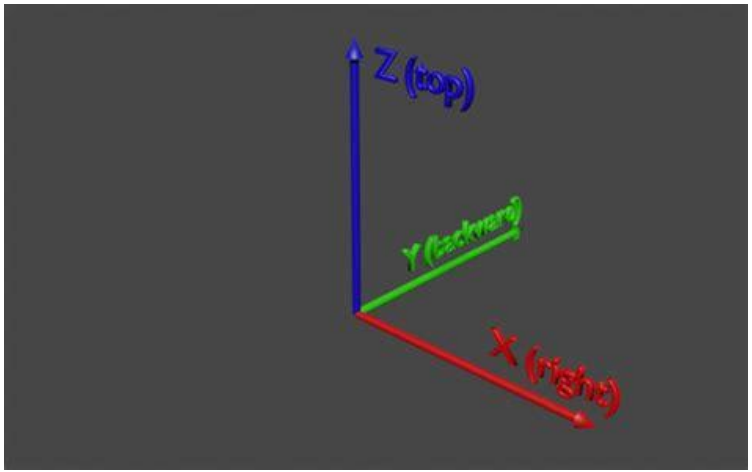
- For rendering: X-right, Y-up, **Z-out**
- In rendering/graphics, we prefer this "Z-out" coordinate
  - This way, x&y correspond to pixel location



Standard Camera Frame

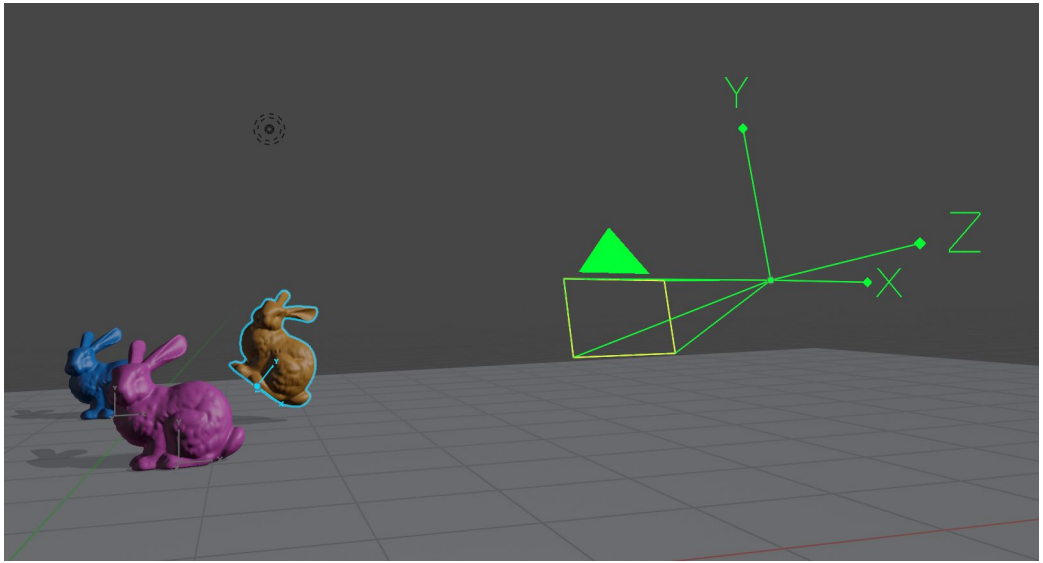
- For rendering: X-right, Y-up, **Z-out**
- In rendering/graphics, we prefer this "Z-out" coordinate
  - This way, x&y correspond to pixel location

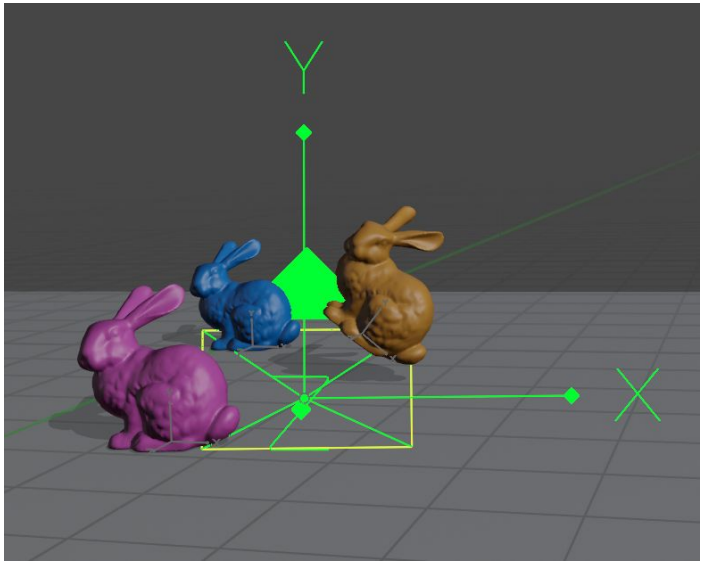
- For modeling: X-right, Y-out, **Z-up**
- In modeling software, they often use "Z-up"
  - This way, x&y is the "flat" ground plane



Camera to Film

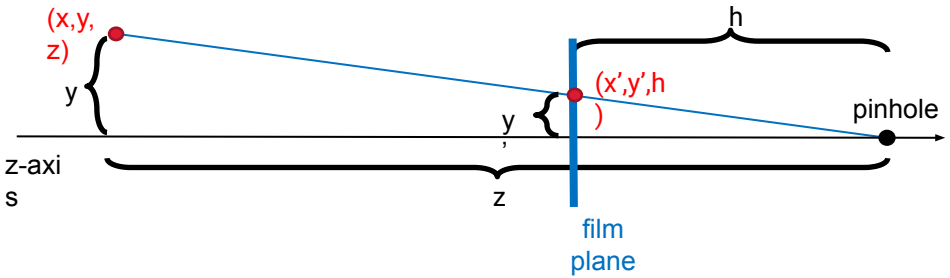
- Once we're in camera space coordinates what do we do?
  - Reminder: origin at (0,0,0), x right, y up

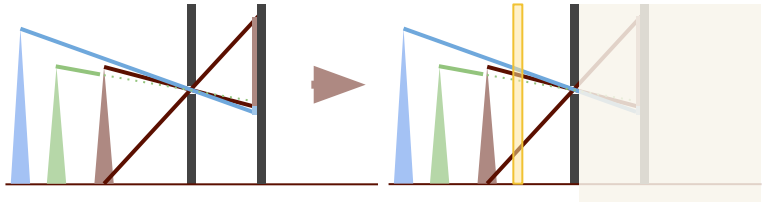




Camera to Film: Modeling Pinhole Camera

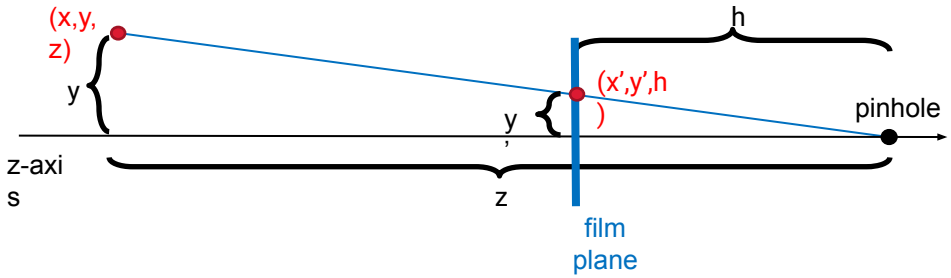
- Move the film **out in front** of the pinhole, so that the image is **not** upside down
- With the pinhole at the origin (0,0,0), points at (x,y,z) get projected to (x',y',h) where h is the distance between the film and the pinhole





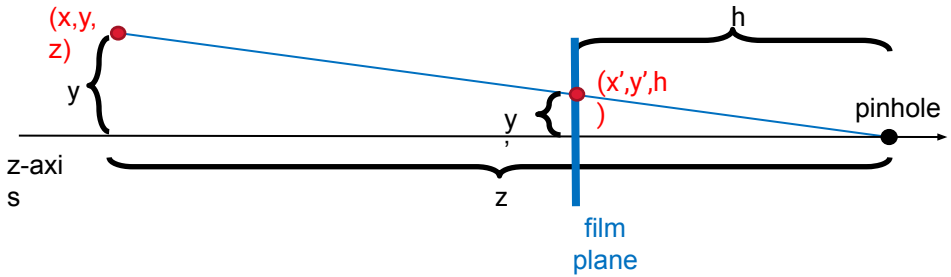
Camera to Film: Modeling Pinhole Camera

- Because the pinhole is at the origin, we can use ratios:
  - The point is at distance **z** from the pinhole
  - The film is at distance **h** from the pinhole



Camera to Film: Modeling Pinhole Camera

- Because the pinhole is at the origin, we can use ratios:
  - The point is at distance **z** from the pinhole
  - The film is at distance **h** from the pinhole
  - So… the projection coordinates scale by **h/z:**
  - **Projection function:** $P(x, y, z) = \left(\frac{h}{z}x,\ \frac{h}{z}y,\ \frac{h}{z}z\right) = \left(\frac{h}{z}x,\ \frac{h}{z}y,\ h\right)$



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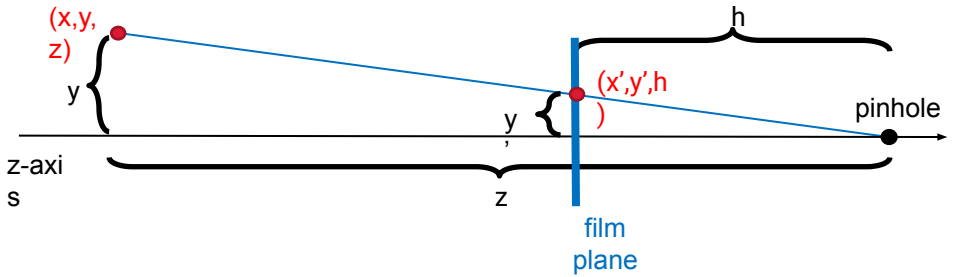
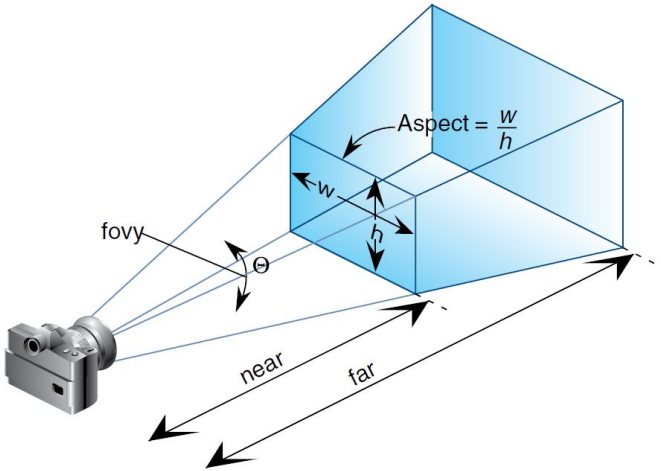


- **Normalized pixel coordinates:** $\left(\frac{hx}{z}, \frac{hy}{z}\right)$ Is the normalized pixel coordinate for film at depth h
- This is perspective projection!

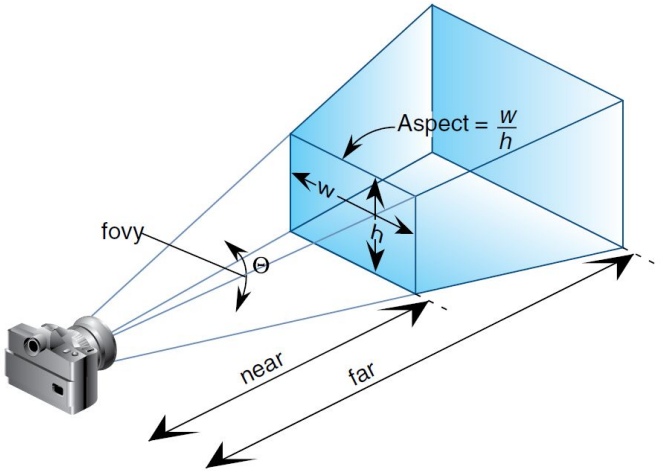
Viewing Frustum

- Only render objects that project to **within the boundaries** of the film



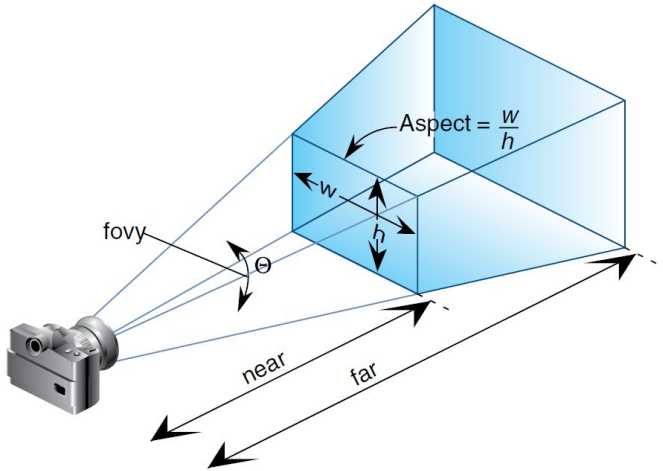
Viewing Frustum

- Only render objects that project to **within the boundaries** of the film
- Only render objects **further away from the camera** than the film



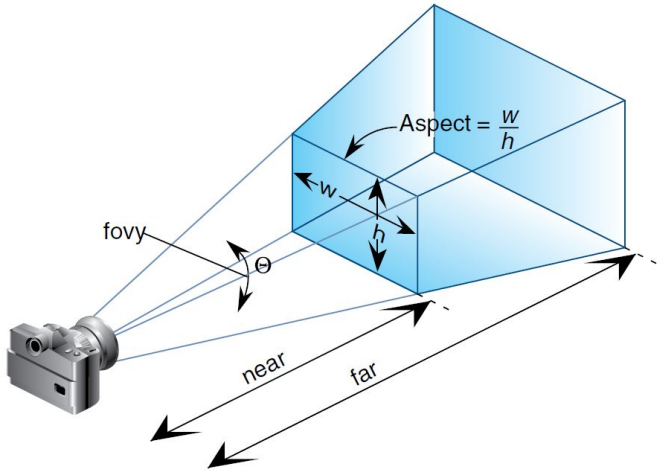
Viewing Frustum

- Only render objects that project to **within the boundaries** of the film
- Only render objects **further away from the camera** than the film
- Film is the **front clipping plane** and you can also add a **back clipping plane** for efficiency
- Volume between **front** and **back** clipping plane is the **<u>viewing frustum</u>** (shown in blue)



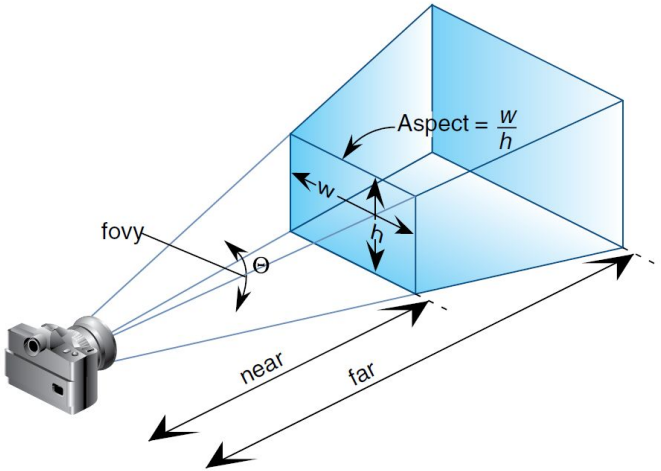
Viewing Frustum

- Only render objects that project to **within the boundaries** of the film
- Only render objects **further away from the camera** than the film
- Film is the **front clipping plane** and you can also add a **back clipping plane** for efficiency
- Volume between **front** and **back** clipping plane is the **<u>viewing frustum</u>** (shown in blue)
- We have a lot of control over the virtual camera!



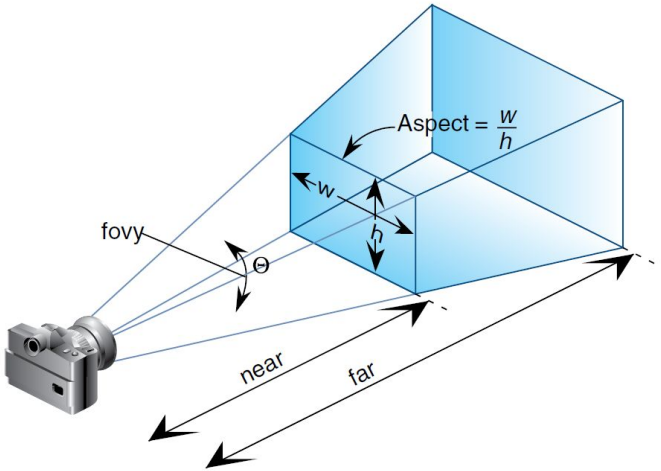
Viewing Frustum

- Ensure near/far clipping planes have enough space between them to contain the scene



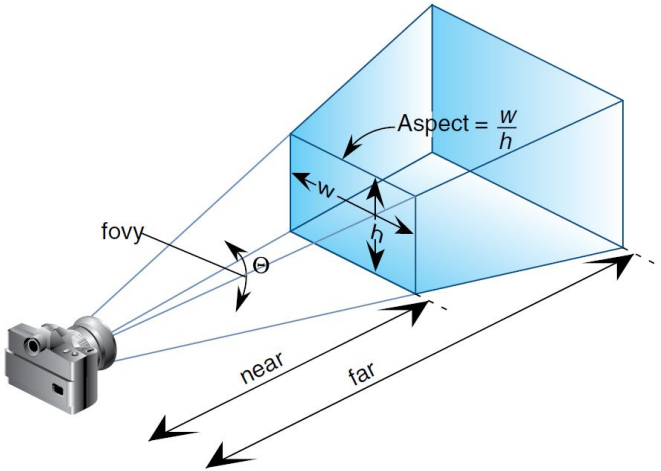
Viewing Frustum

- Ensure near/far clipping planes have enough space between them to contain the scene
- Make sure objects of interest are inside the viewing frustum



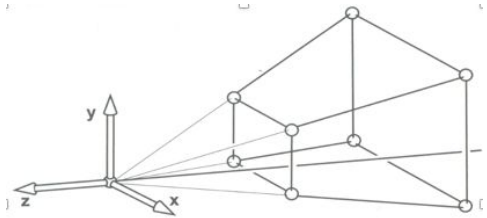
Viewing Frustum

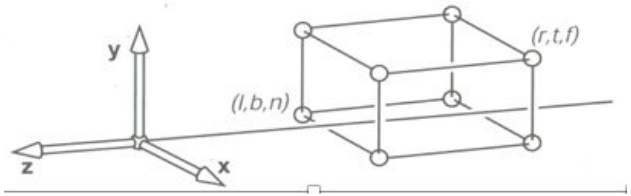
- Ensure near/far clipping planes have enough space between them to contain the scene
- Make sure objects of interest are inside the viewing frustum
- In general, don’t set the near clipping plane at the camera aperture
  - This can cause extreme distortion

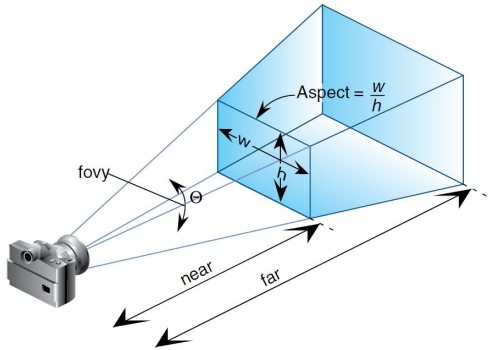


Viewing Frustum

- Bounds on x and y: field of view
- Bounds on z: between the front and back clipping planes

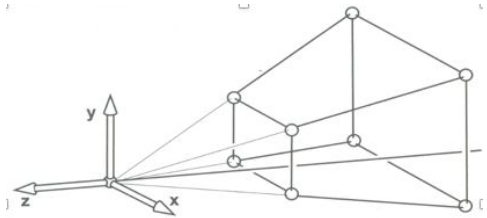


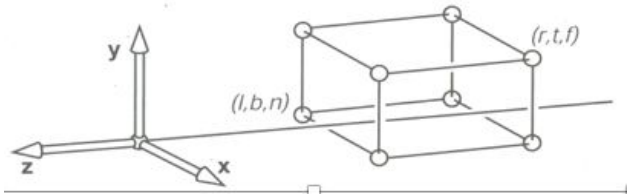


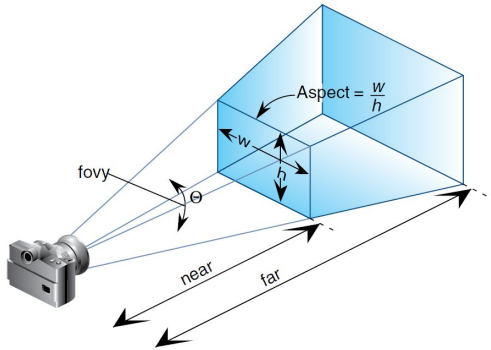


Viewing Frustum

- Bounds on x and y: field of view
- Bounds on z: between the front and back clipping planes
- How do we efficiently convert the frustum into a bounding box?

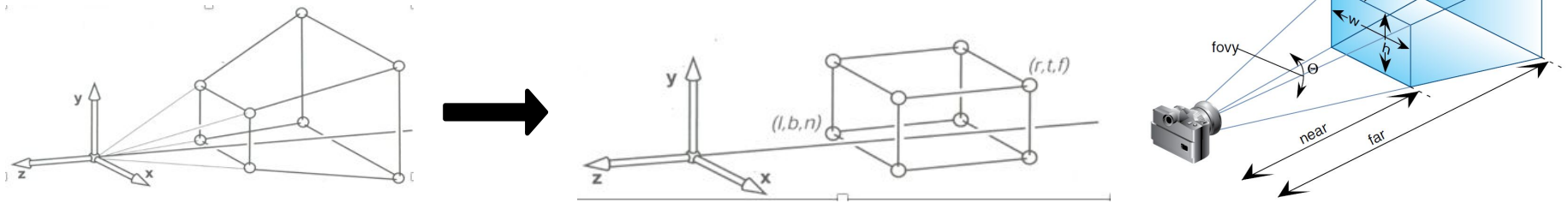






Viewing Frustum

- Bounds on x and y: field of view
- Bounds on z: between the front and back clipping planes
- How do we efficiently convert the frustum into a bounding box?
  - Yay homogeneous matrices again!



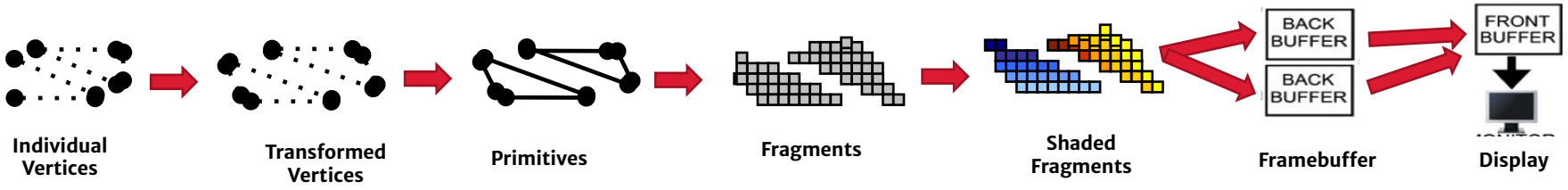
Projection, Field of View, Clipping Plane

- Transform viewing frustum to an orthographic bounding box (1x1x1 cube)
- Instead of projecting everything to the plane at a fixed depth, project to a cube first
- Then clip anything that's not within -1~1
- Note: rx,ry correspond to film boundaries, d0/d1 are clipping planes

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \rightarrow \begin{pmatrix} \frac{1}{r_x} & 0 & 0 & 0 \\ 0 & \frac{1}{r_y} & 0 & 0 \\ 0 & 0 & \frac{d0+d1}{d0-d1} & 2\frac{d0d1}{d0-d1} \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

With the Rasterizer…

1. Vertex shader outputs vertex attributes and orthogonal clipping space positions
2. Vertex data assembled into triangles, **data outside the viewing frustum is discarded**



With the Rasterizer…

1. Vertex shader outputs vertex attributes and orthogonal clipping space positions
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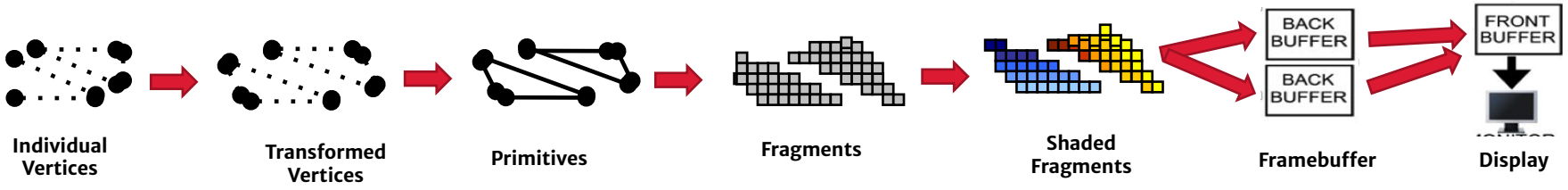
3. For each triangle, rasterize vertex attributes (barycentric interpolation)
4. Fragment shader takes interpolated attributes and computes color



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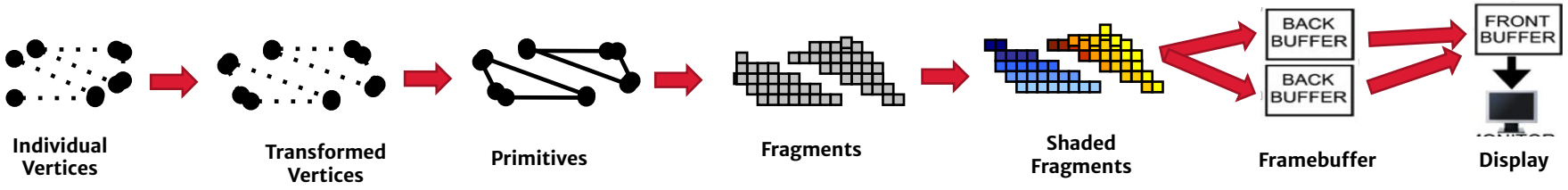
2. Vertex data assembled into triangles, **data outside the viewing frustum is discarded**
3. For each triangle, rasterize vertex attributes (barycentric interpolation)
4. Fragment shader takes interpolated attributes and computes color
5. Before we get to the final image:
   still need to **determine which triangles occlude other triangles!**



Z-Buffer Algorithm

- We used x&y for image space positions, now use z to determine depth

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Create color buffer C(x,y) to store color and z-buffer Z(x,y) to store depth
Set Z(x,y)= - infinity for all x,y

Z-Buffer Algorithm

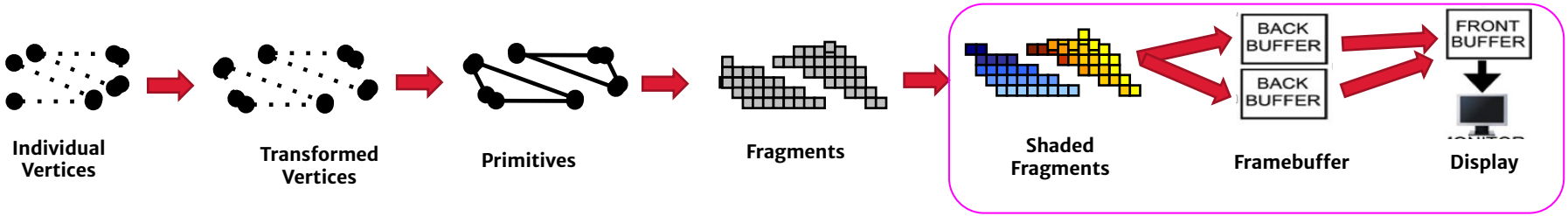
- We used x&y for image space positions, now use z to determine depth

```
Create color buffer C(x,y) to store color and z-buffer Z(x,y) to store depth
Set Z(x,y)= - infinity for all x,y
For each fragment:
    For each coordinate (x,y,z) in the fragment and its corresponding
    color c:
        If Z(x,y) < z:
            C(x,y)=c
            Z(x,y)=z
```

We've Completed the Rasterization Pipeline!

- Vertex shader outputs vertex attributes and orthogonal clipping space positions
- Vertex data assembled into triangles, data outside the viewing frustum is discarded
- For each triangle, rasterize vertex attributes (barycentric interpolation)
- Fragment shader takes interpolated attributes and computes color
- Use the **z-buffer** to help assemble pixel colors into the full image

- (There's more functionality to OpenGL, but we've walked through one instance of the entire pipeline!)



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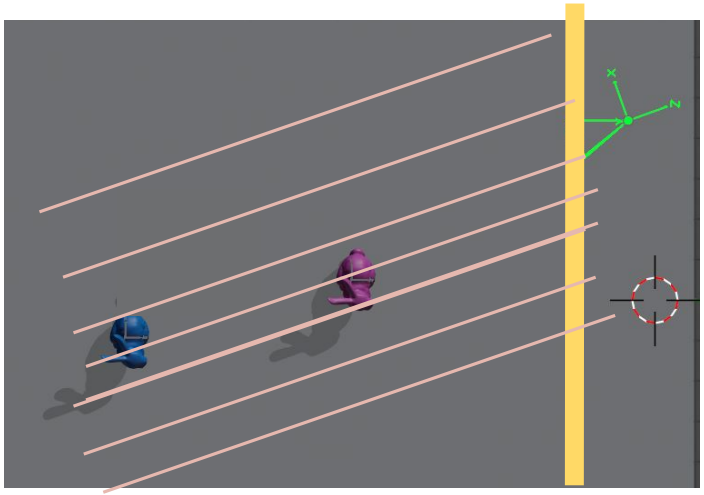
Perspective vs Orthographic Projection

- Orthographic projection = using a 4x4 identity matrix for camera projection
  - Aka all projection lines are orthogonal to the film plane



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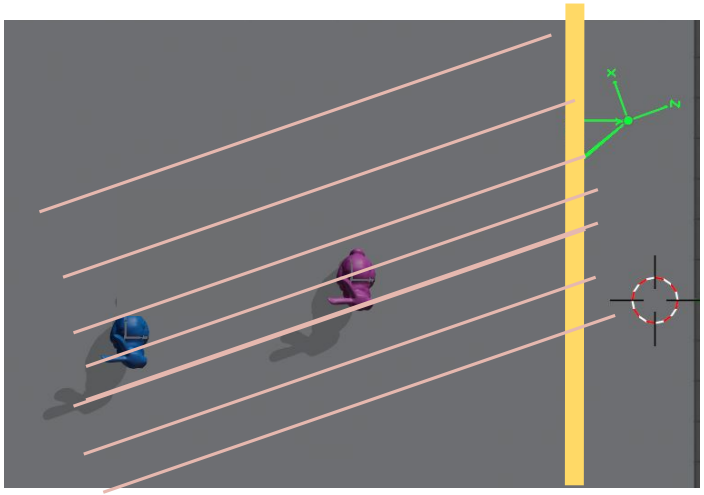
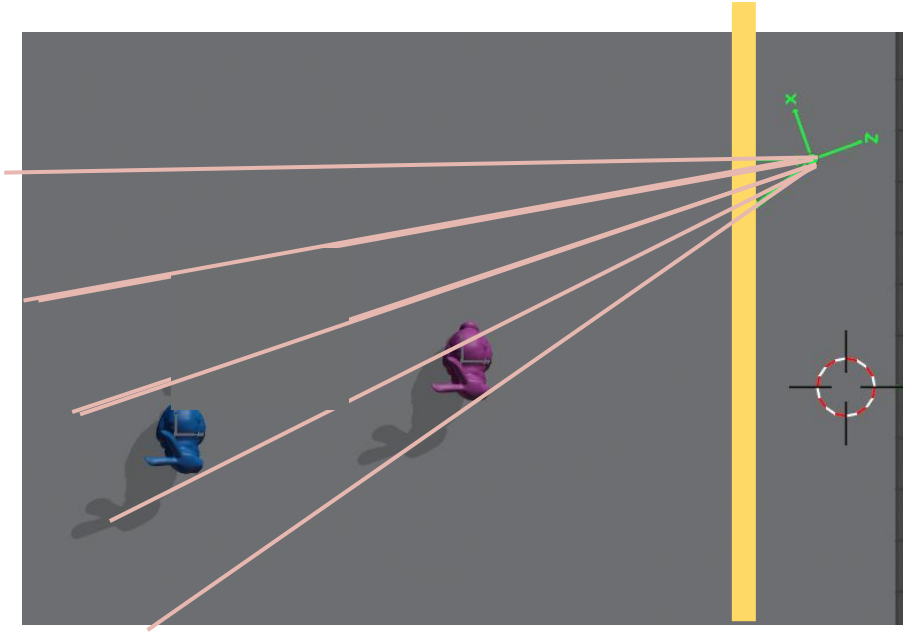


Perspective vs Orthographic Projection

- Versus perspective projection…



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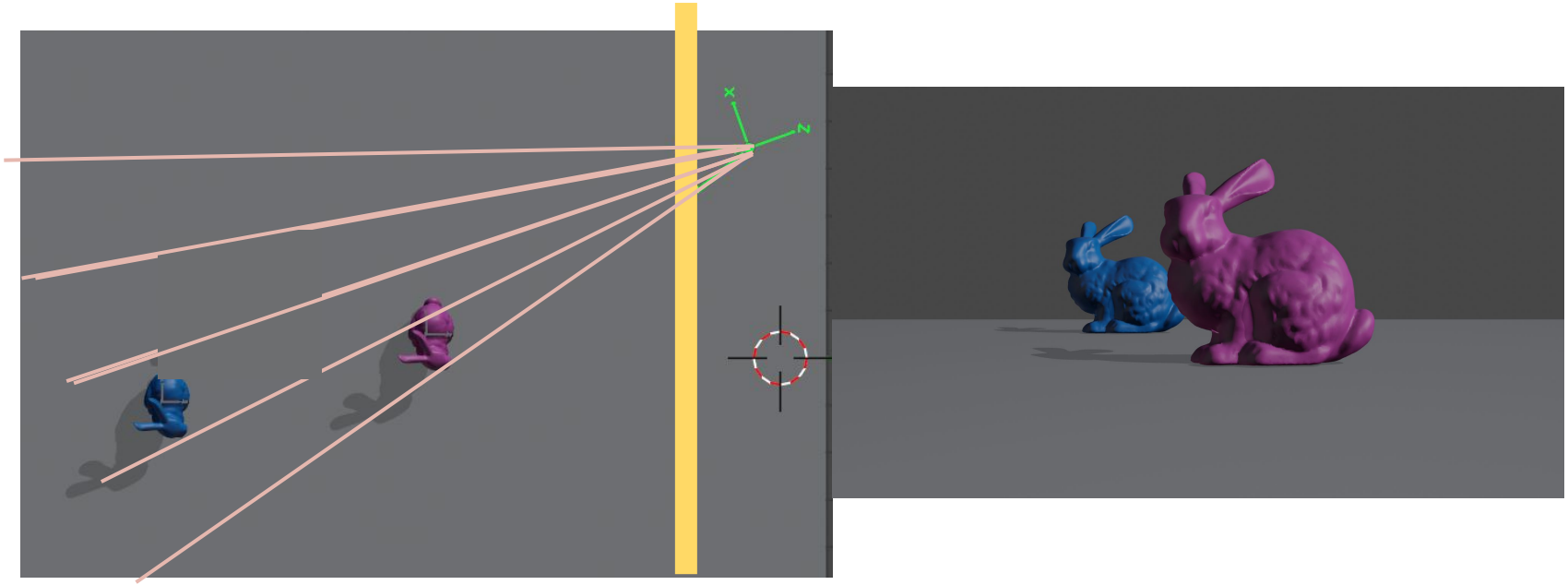
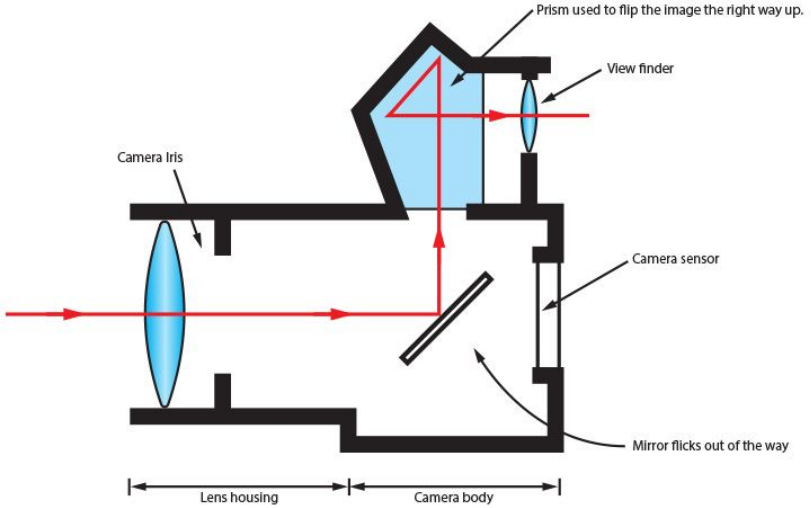


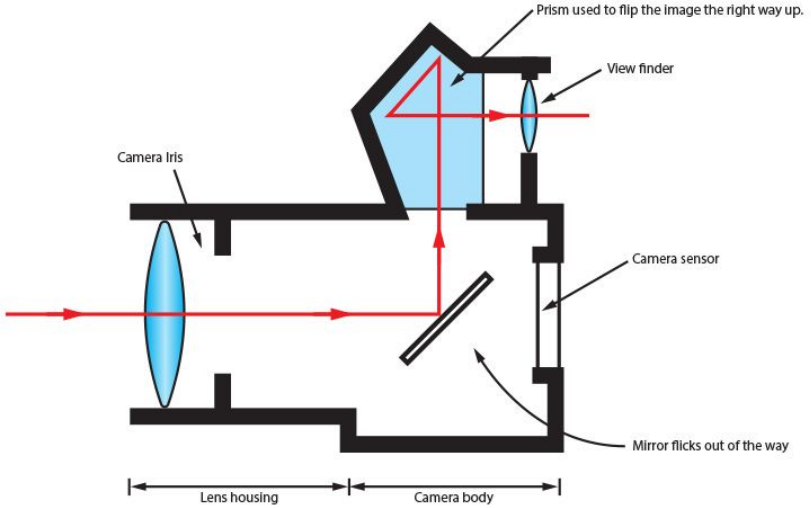
Lens-Based Cameras

- Problem with pinhole camera: long exposure time



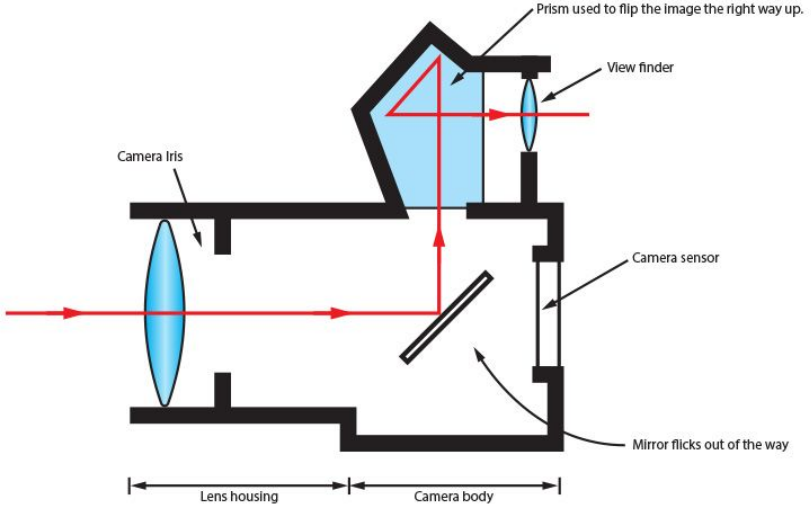
Lens-Based Cameras

- Problem with pinhole camera: long exposure time
- In contrast, lens-based can provide shorter exposure time and objects in focus



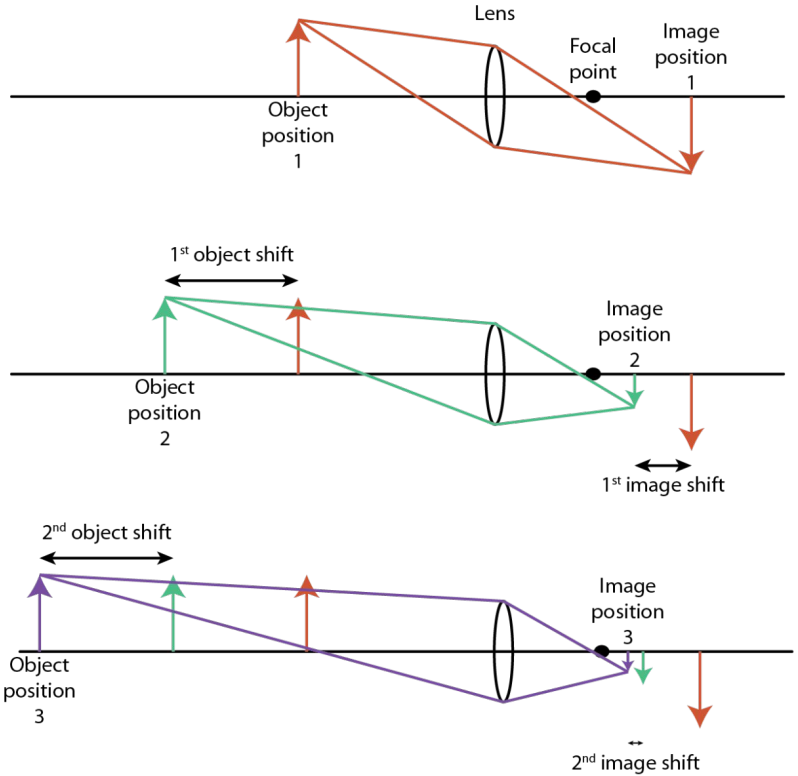
Lens-Based Cameras

- Problem with pinhole camera: long exposure time
- In contrast, lens-based can provide shorter exposure time and objects in focus
- Convex lens
  - Bends incoming light raws so that parallel rays converge at a single point (more light faster)
- Aperture / depth of field trade off



Focus Distance

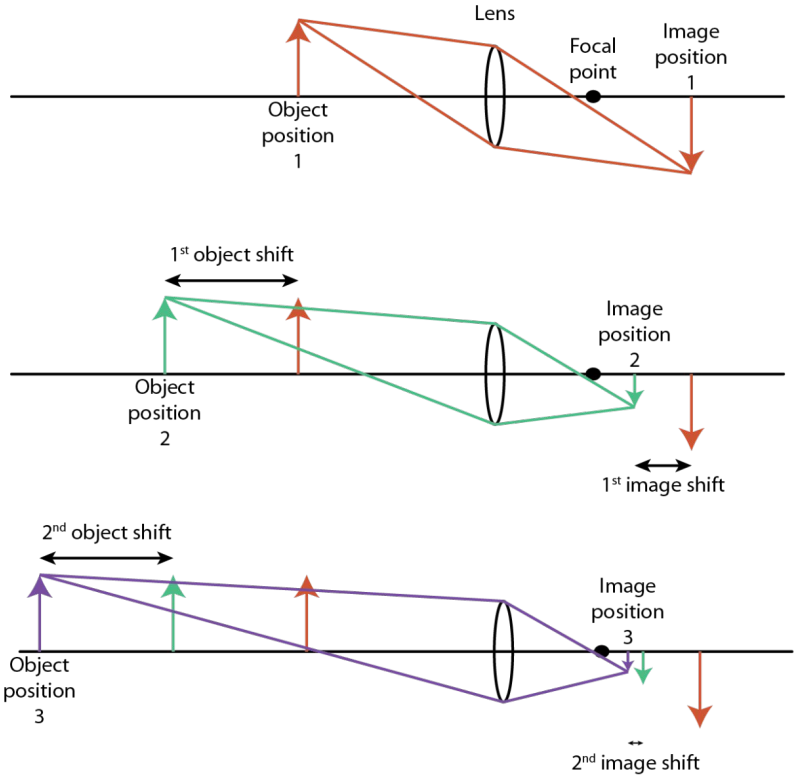
- How far away the object has to be in order to be in focus
- Determined by **focal length** and **distance of the lens to the sensor**
- Adjust focus distance by moving the lens.



https://physicssoup.wordpress.com/2015/04/26/how-do-object-distance-and-focal-length-affect-depth-of-field/

Focal Length

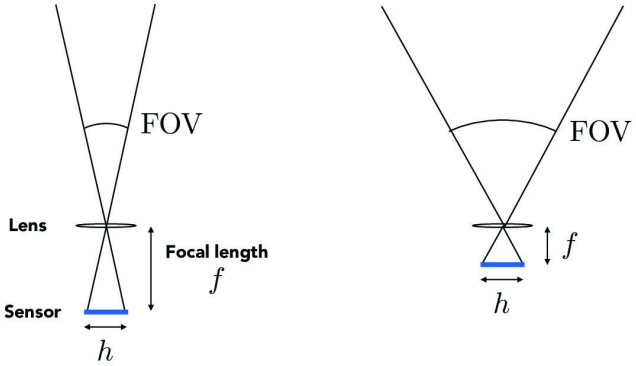
- The distance from the lens where parallel light beams converge
- Depends on the design of the lens
- Weaker lens have longer focal length
- **Field of view, focus distance, depth of field**
- Note: there are fixed lenses and zoom lenses



https://physicssoup.wordpress.com/2015/04/26/how-do-object-distance-and-focal-length-affect-depth-of-field/

Field of View

- Field of view depends on sensor size and focal length
- Wide angle lens have a wider field of view
  - Corresponds to a shorter focal length



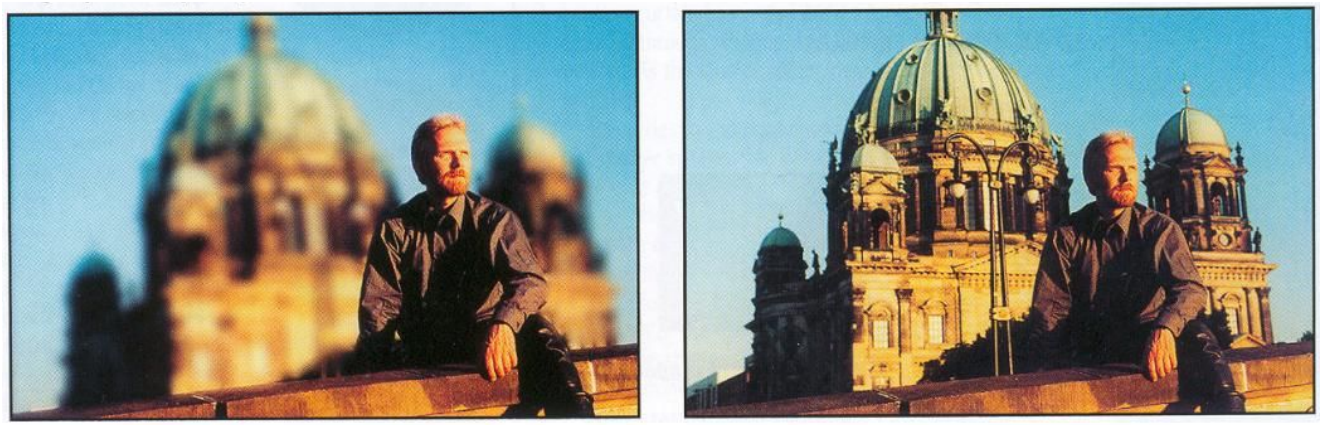
For a fixed sensor size, decreasing the focal length increases the field of view.

$$\text{FOV} = 2 \arctan\left(\frac{h}{2f}\right)$$

Berkeley CS 184

Depth of Field

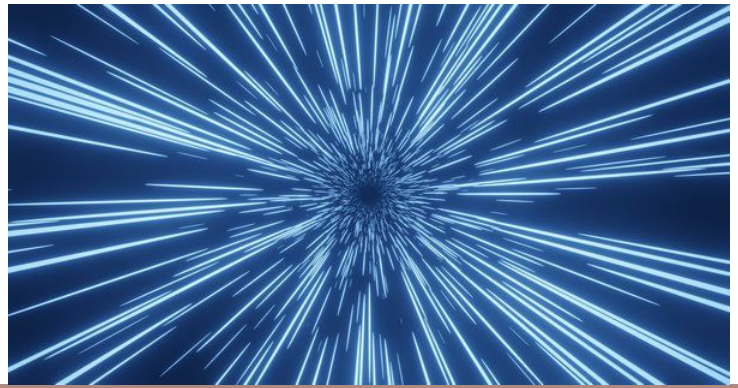
- Blurring of objects not in focus
- Depends on the focus distance and aperture size
- Larger aperture gives you **less** depth of field



From Photography, London et al.

Exposure Time

- Instead of 20 mins (pinhole camera), we can work with fractions of a second
- We can play with the exposure time on this level by controlling how long the mirror in the camera stays up (in DSLR and Film cameras)
  - Or by how long the sensor record data
- For graphics: motion blur!



Imperfections

- Oftentimes, we want to make things imperfect!
  - E.g. motion blur, depth of field, lens flare
  - Where we intentionally make things out of focus/blurry
- Overly sharp details can make things look fake

Lecture Outline

- In real life
  - The human eye (pupil, cornea, lens)
  - RGB color space
  - The pinhole camera
- In the rasterizer
  - Coordinate frames
  - Perspective & orthographic projection
  - Normalized coordinates & the z-buffer algorithm
- Lens-based cameras
- Beyond rasterization

Limitations of Rasterization

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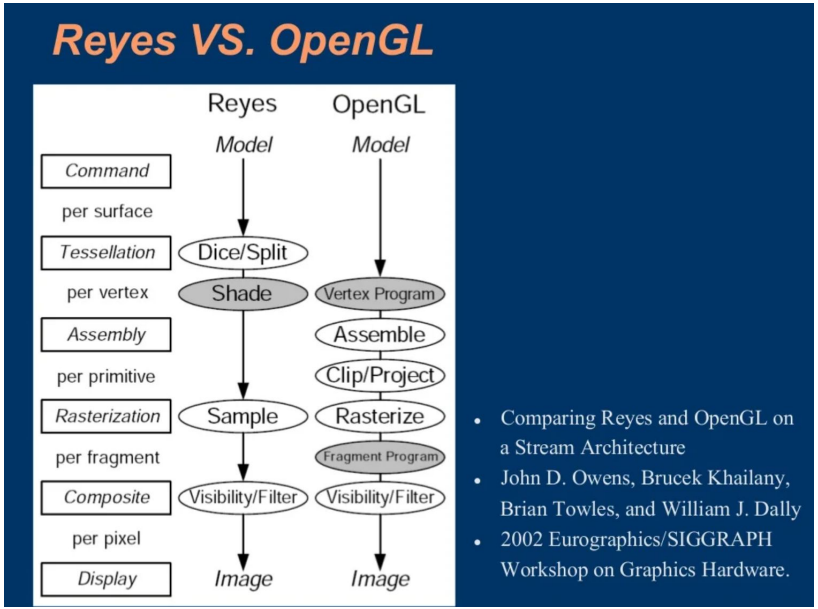
- If compute time and compute resources are not issues, we generally prefer more physically based image generation techniques over rasterization

Rasterization Still Used!

- REYES (Star Trek II, Toy Story…)
- Different type of rasterization pipeline
- But still rasterization!
- (Works on quads, not triangles)



Beyond Rasterization…

- **Rasterization**:
  - for every triangle in the environment:
    compute color **c** based on the lighting and material models.
  - for every projected point **(x,y,z)** and corresponding color **c**:
    set film position (x,y) to **c** (subject to depth test on z)

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- **Raytracing**:
  - for every point **(x,y)** on the camera film:
    backwards trace out possible trajectories of light rays hitting **(x,y)**, and check what the color of that light ray might be based on the objects and lights in the environment

Additional Resources + Exploring!

- Pixar's REYES rendering architecture
- List of color spaces and their uses
- Muybridge's *The Horse in Motion*
  - Great Stanford history here!
- Camera Obscura (Pinhole Camera)
- Lens flares: from accidental to artistic

- Fundamentals of Computer Graphics, Steve Marschner and Peter Shirley
  - Preview, Book