The Camera
Image Formation

Digital Camera

The Eye
How do we see the world?

Let’s design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?
Pinhole camera

Add a barrier to block off most of the rays

- This reduces blurring
- The opening known as the **aperture**
- How does this transform the image?
Pinhole camera model

Pinhole model:

• Captures \textit{pencil of rays} – all rays through a single point
• The point is called \textit{Center of Projection (COP)}
• The image is formed on the \textit{Image Plane}
• \textbf{Effective focal length} $f$ is distance from COP to Image Plane
Dimensionality Reduction Machine (3D to 2D)

3D world

2D image

But there is a problem…
Emission Theory of Vision

“For every complex problem there is an answer that is clear, simple, and wrong.”

-- H. L. Mencken

Supported by:
• Empedocles
• Plato
• Euclid (kinda)
• Ptolemy
• …
• 50% of US college students*


Eyes send out “feeling rays” into the world
How we see the world

3D world

Point of observation

2D image

Figures © Stephen E. Palmer, 2002
How we see the world

3D world

2D image

Painted backdrop
Fooling the eye
Fooling the eye

Making of 3D sidewalk art: http://www.youtube.com/watch?v=3SNYtd0Ayt0
Why did evolution opt for such strange solution?

- Nice to have a passive, long-range sensor
- Can get 3D with stereo or by moving around, plus experience
Dimensionality Reduction Machine (3D to 2D)

3D world

2D image

What have we lost?

• Angles
• Distances (lengths)
Funny things happen…
Parallel lines aren’t…
Exciting New Study!

Study: People Far Away From You Not Actually Smaller

Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.
Lengths can’t be trusted...
…but humans adopt!

Müller-Lyer Illusion

We don’t make measurements in the image plane

http://www.michaelbach.de/ot/sze_muelue/index.html
Modeling projection

The coordinate system

- We will use the pin-hole model as an approximation
- Put the optical center (Center Of Projection) at the origin
- Put the image plane (Projection Plane) in front of the COP
  - Why?
- The camera looks down the negative z axis
  - we need this if we want right-handed-coordinates
Modeling projection

Projection equations

- Compute intersection with PP of ray from (x, y, z) to COP
- Derived using similar triangles (on board)

\[(x, y, z) \rightarrow \left( -d\frac{x}{z}, -d\frac{y}{z}, -d \right)\]

- We get the projection by throwing out the last coordinate:

\[(x, y, z) \rightarrow \left( -d\frac{x}{z}, -d\frac{y}{z} \right)\]
Orthographic Projection

Special case of perspective projection

- Distance from the COP to the PP is infinite

- Also called “parallel projection”
- $x' = x$
- $y' = y$
Scaled Orthographic or “Weak Perspective”

If $\Delta z \ll -\bar{z}$:

\[
\begin{align*}
x' &\approx -mx \\
y' &\approx -my
\end{align*}
\]

\[m = -\frac{f'}{\bar{z}}\]

Justified if scene depth is small relative to average distance from camera.
Scaled Orthographic or “Weak Perspective”
Spherical Projection

What if PP is spherical with center at COP?
In spherical coordinates, projection is trivial:

$$(\theta, \phi) = (\theta, \phi, d)$$

Note: doesn’t depend on focal length $f$!
Building a real camera
Camera Obscura: the pre-camera

- First Idea: Mo-Ti, China (470-390 BC)
- First build: Al Hacen, Iraq/Egypt (965-1039 AD)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
8-hour exposure (Abelardo Morell)

http://www.abelardomorell.net/books/books_m02.html
Pinhole cameras everywhere

Tree shadow during a solar eclipse
photo credit: Nils van der Burg
http://www.physicstogo.org/index.cfm
Accidental pinhole cameras

My hotel room, contrast enhanced.

The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

A. Torralba and W. Freeman, Accidental Pinhole and Pinspeck Cameras, CVPR 2012
Accidental pinhole camera
Window turned into a pinhole

View outside
Pinspeck Camera: the anti-pinhole
Project 2: a Shoe-box Camera Obscura
Another way to make pinhole camera

Why so blurry?

http://www.debevec.org/Pinhole/
Shrinking the aperture

Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…
Shrinking the aperture
The reason for lenses
Focus
A lens focuses light onto the film

- There is a specific distance at which objects are “in focus”
  - other points project to a “circle of confusion” in the image
- Changing the shape of the lens changes this distance
Thin lenses

Thin lens equation: \( \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \)

- Any object point satisfying this equation is in focus
- What is the shape of the focus region?
- Thin lens applet: [http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html](http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html) (by Fu-Kwun Hwang)
Varying Focus
Depth Of Field
Depth of Field

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm
Aperture controls Depth of Field

Changing the aperture size affects depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces amount of light – need to increase exposure
F-number: focal length / aperture diameter
Varying the aperture

Large aperture = small DOF

Small aperture = large DOF
Nice Depth of Field effect
Field of View (Zoom)
Field of View (Zoom)

From London and Upton
Field of View (Zoom) = Cropping

From London and Upton
FOV depends on Focal Length

Size of field of view governed by size of the camera retina:

\[ \varphi = \tan^{-1}\left(\frac{d}{2f}\right) \]

Smaller FOV = larger Focal Length
Expensive toys...

Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/

Field of View / Focal Length

Large FOV, small f
Camera close to car

Small FOV, large f
Camera far from the car
Fun with Focal Length (Jim Sherwood)

http://www.hash.com/users/jsherwood/tutes/focal/Zoomin.mov

Figure 5.1

Figure 5.2
Dolly Zoom ("Vertigo Shot")

http://filmmakermagazine.com/83872-hitchcock-to-scorcese-47-years-of-the-dolly-zoom/#.VBNtn_IdVac
Shutter Speed

http://en.wikipedia.org/wiki/Shutter_speed
Exposure: shutter speed vs. aperture

F5.6
1/30 sec.

= Same amount

F11
1/8 sec.
Fun with slow shutter speeds

Photos by Fredo Durand
More fun

http://vimeo.com/14958082
Lens Flaws
Lens Flaws: Chromatic Aberration

Dispersion: wavelength-dependent refractive index

- (enables prism to spread white light beam into rainbow)

Modifies ray-bending and lens focal length: $f(\lambda)$

color fringes near edges of image

Corrections: add ‘doublet’ lens of flint glass, etc.
Chromatic Aberration

Near Lens Center

Near Lens Outer Edge
Radial Distortion (e.g. ‘Barrel’ and ‘pin-cushion’)

straight lines curve around the image center
Radial Distortion

Radial distortion of the image

- Caused by imperfect lenses
- Deviations are most noticeable for rays that pass through the edge of the lens
Radial Distortion

(a) Orthoscopic

(b) Barrel

(c) Pin-cushion