What is a Camera?
Last Time

• What is computer vision?
• Input: digital images
• Output: information about the world
What is a Camera?
Outline for Today

• What is a digital image?
• What is a pin-hole camera?
• Lens & optics
• Geometric transformation
• Accidental camera
Outline for Today

• What is a digital image?
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What is a Digital Image?
What is a Digital Image?

http://en.wikipedia.org/wiki/Lenna
From Lawrence G. Roberts’s master's thesis at MIT 1961
What is a Digital Image?

- An image is a 2D rectilinear array of pixels

Continuous image

Digital image
What is a Pixel?
What is a Pixel?

• Sample of a continuous (color) function at a position

  e.g., Color at (x,y)
What is a Pixel?

• Sample of a continuous (color) function at a position

  e.g., Intensity at \((x,y)\)

  Larger value = brighter
  Smaller value = darker

  Brightest White = 1.0
  Darkest Black = 0.0

Digital image
Outline for Today

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Image formation

3D world

2D image

Point of observation
What Is a Photographic Image?

• What does each pixel represent?
What Is a Photographic Image?

Conceptually, each pixel is a sample of radiance arriving at a camera viewpoint from a direction
The plenoptic function $L(x,y,z, \theta, \phi, t, \lambda)$ describes the radiance arriving ...

- at any point $(x,y,z)$,
- in any direction $(\theta, \phi)$,
- at any time $(t)$,
- at any frequency $(\lambda)$
Photographic Image

Conceptually, a photographic image is a slice of the plenoptic function representing radiance arriving ...

– at a particular camera viewpoint,
– in the camera’s field of view,
– at a certain time,
– at certain frequencies
Lightfield Camera

https://pictures.lytro.com
Pinhole Camera

- “Camera obscura” – idea known since antiquity
Pinhole Camera

- Joseph Nicéphore Niépce: first recorded image

- Pewter plate coated with bitumen

- Real World
Digital Camera

- Today: photon sensors are CCD, CMOS, etc.
Focal length

The magical $f$
Why do we need a pinhole?
Why is there no image on a white piece of paper?
The structure of ambient light
The structure of ambient light
Measuring the Plenoptic function

Why is there no picture appearing on the paper?
Light rays from many different parts of the scene strike the same point on the paper.
Measuring the Plenoptic function

The camera obscura
The pinhole camera
The pinhole camera only allows rays from one point in the scene to strike each point of the paper.

Light rays from many different parts of the scene strike the same point on the paper.

Forsyth & Ponce
Why not use sensors without optics?

- It receives light from all directions
- It gets all possible images from all possible viewpoints
- We need to be more selective
Pinhole camera

Photograph by Abelardo Morell, 1991
Pinhole camera

Photograph by Abelardo Morell, 1991
Pinhole camera

Photograph by Abelardo Morell, 1991
Pinhole camera

Photograph by Abelardo Morell, 1991
Problem Set 1

http://www.foundphotography.com/PhotoThoughts/archives/2005/04/pinhole_camera_2.html
Problem Set 1
Cool demo

- [Link](http://www.youtube.com/watch?v=gvzpu0Q9RTU)
Box? Room? Egg!

Pinhole Camera is Awesome

But there are some parameters to tune!

A Grad-student

WT*
Pinhole Camera

Only one parameter!
Effect of pinhole size

(A) Source

(B) Source

Wandell, Foundations of Vision, Sinauer, 1995
Define: aperture

• In optics, an aperture is a hole or an opening through which light travels.

• More specifically, the aperture of an optical system is the opening that determines the cone angle of a bundle of rays that come to a focus in the image plane.
Pinhole Camera

• What if **aperture** (pinhole size) is very small?
  – long exposure time (static scene)
  – high intensity

*Photograph made with small pinhole*
Pinhole Camera

• What if aperture (pinhole size) is too big?
  – blurry image
Pinhole Camera

• No aperture is good!
  – If large, blurry
  – If small, not enough light
• There is no in-between
Pinhole Camera

• What if aperture (pinhole size) is extremely small?
  – diffraction through pinhole $\Rightarrow$ blurry image

2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.
Diffraction

- Wave nature of light
- Smaller aperture means more diffraction

diffraction of water waves
Youtube demos

- [http://www.youtube.com/watch?v=kH57Di7Sj0c](http://www.youtube.com/watch?v=kH57Di7Sj0c)
- [http://www.youtube.com/watch?v=lIn-BLJNXpY](http://www.youtube.com/watch?v=lIn-BLJNXpY)
- [http://www.youtube.com/watch?v=KSIg_EaIFrw](http://www.youtube.com/watch?v=KSIg_EaIFrw)
- [http://www.youtube.com/watch?v=sjmBcm84iA4](http://www.youtube.com/watch?v=sjmBcm84iA4)
**Bottom line**

- The smaller the hole, the more diffraction

[http://www.mashpedia.com/Ripple_tank](http://www.mashpedia.com/Ripple_tank)
Recap: Problem with pinhole?

- Not enough light!
- Diffraction limits sharpness
Solution?
Solution: refraction!

From Photography, London et al.
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Lenses

- Gather more light!
- But need to be focused

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.

This time, using a simple convex lens with an f/16 aperture, the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.

The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.
Lenses

- Essentially add multiple pinhole images
- ~ shift them to align (refraction)
- Alignment works only for one distance

From Photography, London et al.
Thin Lens Optics

Rays emanating from one point on focus plane converge at one point on image plane
Thin Lens Optics

• All parallel rays converge to one point on a plane located at the focal length $f$

• All rays going through the center are not deviated
  – Hence same perspective as pinhole
Thin Lens Optics

• Tracing rays through lens
  – Start by rays through the center
Thin Lens Optics

• Tracing rays through lens
  – Start by rays through the center
  – Choose focal length, trace parallels
Thin Lens Optics

• All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens
Thin Lens Optics

\[
\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}
\]

Image plane

Focus plane
Camera Terminology

• Lens parameters:
  – Focal length

• Camera parameters:
  – Aperture

• Camera properties:
  – Depth of field
  – Field of view
Focus Depth (D)

Can control $D$ by changing $D'$

$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$
Focus Depth ($D$)

Can control $D$ by changing $D'$

$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$

Image plane    Focus plane
Depth of Field

Only objects on focus plane are in “perfect” focus

$D'$  $D$

$f$

Image plane  Focus plane
Depth of Field

Objects closer to focus plane are in better focus

Image plane

Focus plane

Circle of Confusion

Object Depth

$D'$

$D$

$f$
Depth of Field

Objects closer to focus plane are in better focus

$D'$

$D$

$f$

Circle of Confusion

Object Depth

Image plane

Focus plane
Depth of Field

Objects closer to focus plane are in better focus
Aperture

Controls radius of hole through which light can pass

F-number is diameter of aperture relative to focal length
Aperture

Smaller apertures ...

– Let in less light
– Have larger depth of field
Fig. 1.6 A patch of light sensitive epithelium can be gradually turned into a perfectly focussed camera-type eye if there is a continuous selection for improved spatial vision. A theoretical model based on conservative assumptions about selection pressure and the amount of variation in natural populations suggest that the whole sequence can be accomplished amazingly fast, in less than 400 000 generations. The number of generations is also given between each of the consecutive intermediates that are drawn in the figure. The starting point is a flat piece of epithelium with an outer protective layer, an intermediate layer of receptor cells, and a bottom layer of pigment cells. The first half of the sequence is the formation of a pigment cup eye. When this principle cannot be improved any further, a lens gradually evolves. Modified from Nilsson and Pelger (1994).
Camera

The film in a film camera records the image transmitted by the lens.

The lens elements move forward and back to bring objects at different distances into sharp focus.

The aperture adjusts the amount of light reaching the film or sensor. A large opening allows the most light to pass through the lens. The smallest opening lets in the least amount of light.

The shutter opens and closes to control the length of time that light strikes the light-sensitive surface.

The memory card in a digital camera stores electronic images until they can, for example, be printed or transferred to a computer or other storage device. Images can be deleted at any time.

The sensor in a digital camera converts the light from the lens into electrical signals that are sent to the memory card.

The viewfinder shows the picture that the lens focuses on the sensor or film.

Source: S. Lazebnik, N. Saveley
Camera Anatomy

- **Lens Elements**: Move forward and backward to bring objects at different distances into sharp focus.
- **The Filtration**: Records the image transmitted by the lens.
- **The Sensor**: Converts the light from the lens into electrical signals that are sent to the memory card.
- **The Memory Card**: Stores electronic images until they can, for example, be printed or transferred to a computer or other storage device. Images can be deleted at any time.
- **The Aperture**: Adjusts the amount of light reaching the film or sensor. A large opening allows the most light to pass through the lens. The smallest opening lets in the least amount of light.
- **The Shutter**: Opens and closes to control the length of time that light strikes the light-sensitive surface.
- **Prisma**: Diverts light to the viewfinder.
Sensing Parameters

Quiz: how to make an image brighter in a dark room?

Sensor ISO:
How sensitive it is.

Shutter speed:
time that the sensor receive light

Aperture: size of the hole
Pin-hole Camera

• Physics of real cameras are all different (too tedious to model all of them).
• But they all try their best to approximate pin-hole camera.
• So in most of computer vision subjects, we model all cameras mathematically as a pin-hole camera.
• With some extra parameters that is too much to ignore (e.g. radial distortion).
Measuring distance

- Object size decreases with distance to the pinhole
- There, given a single projection, if we know the size of the object we can know how far it is.
- But for objects of unknown size, the 3D information seems to be lost.
Playing with pinholes
Two pinholes
Two pinholes

What is the minimal distance between the two projected images?
Anaglyph pinhole camera
Anaglyph pinhole camera
Anaglyph pinhole camera
Synthesis of new views

Anaglyph
Problem Set 1

• Build the device
• Take some pictures and put them in the report
• Correct the perspective to a rectangular picture
• Bonus: Take anaglyph images
• Bonus: Work out the geometry
• Bonus: Recover depth for some points in the image
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2D Geometric Transformations
What is the geometric relationship between these two images?
Image Transformation

• image filtering: change *range* of image
  
  • $g(x) = h(f(x))$

• image warping: change *domain* of image

  • $g(x) = f(h(x))$
Image Transformation

- image filtering: change range of image
  - \( g(x) = h(f(x)) \)

- image warping: change domain of image
  - \( g(x) = f(h(x)) \)
Other Image Transformation
Parametric (global) warping

• Examples of parametric warps:

  - translation
  - rotation
  - aspect
Parametric (global) warping

- Transformation $T$ is a coordinate-changing machine:
  \[ p' = T(p) \]

- What does it mean that $T$ is global?
  - Is the same for any point $p$
  - Can be described by just a few numbers (parameters)

- Let’s consider linear xforms (can be represented by a 2D matrix):
  \[ p' = Tp \]
  \[
  \begin{bmatrix}
  x' \\
  y'
  \end{bmatrix}
  =
  T
  \begin{bmatrix}
  x \\
  y
  \end{bmatrix}
  \]
Common linear transformations

• Uniform scaling by $s$:

$$S = \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix}$$

What is the inverse?
Common linear transformations

- Rotation by angle $\theta$ (about the origin)

$$R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$$

What is the inverse?

For rotations:

$$R^{-1} = R^T$$
2x2 Matrices

• What types of transformations can be represented with a 2x2 matrix?

2D mirror about Y axis?

\[
x' = -x \\
y' = y
\]

\[
T = \begin{bmatrix}
-1 & 0 \\
0 & 1
\end{bmatrix}
\]

2D mirror across line y = x?

\[
x' = y \\
y' = x
\]

\[
T = \begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\]
2x2 Matrices

• What types of transformations can be represented with a 2x2 matrix?

2D Translation?

\[
\begin{align*}
x' &= x + t_x \\
y' &= y + t_y
\end{align*}
\]

NO!

Translation is not a linear operation on 2D coordinates
All 2D Linear Transformations

- Linear transformations are combinations of ...
  - Scale,
  - Rotation,
  - Shear, and
  - Mirror

- Properties of linear transformations:
  - Origin maps to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition

\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix} = \begin{bmatrix}
  a & b \\
  c & d
\end{bmatrix} \begin{bmatrix}
  x \\
  y
\end{bmatrix}
\]

\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix} = \begin{bmatrix}
  a & b & e & f & i & j \\
  c & d & g & h & k & l
\end{bmatrix} \begin{bmatrix}
  x \\
  y
\end{bmatrix}
\]
**Homogeneous coordinates**

Trick: add one more coordinate:

\[
(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}
\]

homogeneous image coordinates

Converting *from* homogeneous coordinates

\[
\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)
\]
Translation

• Solution: homogeneous coordinates to the rescue

\[
T = \begin{bmatrix}
1 & 0 & t_x \\
0 & 1 & t_y \\
0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 0 & t_x \\
0 & 1 & t_y \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
1
\end{bmatrix} = \begin{bmatrix}
x + t_x \\
y + t_y \\
1
\end{bmatrix}
\]
Affine transformations

\[ T = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \]

any transformation with last row \([ 0 \ 0 \ 1 ]\) we call an affine transformation

\[ \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \]
Basic affine transformations

$$
\begin{bmatrix}
  x' \\
  y' \\
  1
\end{bmatrix}
= \begin{bmatrix}
  1 & 0 & t_x \\
  0 & 1 & t_y \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
$$

Translate

$$
\begin{bmatrix}
  x' \\
  y' \\
  1
\end{bmatrix}
= \begin{bmatrix}
  \cos \theta & -\sin \theta & 0 \\
  \sin \theta & \cos \theta & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
$$

2D in-plane rotation

$$
\begin{bmatrix}
  x' \\
  y' \\
  1
\end{bmatrix}
= \begin{bmatrix}
  s_x & 0 & 0 \\
  0 & s_y & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
$$

Scale

$$
\begin{bmatrix}
  x' \\
  y' \\
  1
\end{bmatrix}
= \begin{bmatrix}
  1 & sh_x & 0 \\
  sh_y & 1 & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
$$

Shear
Affine Transformations

- Affine transformations are combinations of ...
  - Linear transformations, and
  - Translations

\[
\begin{bmatrix}
  x' \\
  y' \\
  w
\end{bmatrix} = \begin{bmatrix}
  a & b & c \\
  d & e & f \\
  0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
  x \\
  y \\
  w
\end{bmatrix}
\]

- Properties of affine transformations:
  - Origin does not necessarily map to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition
Where do we go from here?

\[
\begin{bmatrix}
  a & b & c \\
  d & e & f \\
  0 & 0 & 1 \\
\end{bmatrix}
\]

affine transformation

what happens when we mess with this row?
Projective Transformations aka Homographies aka Planar Perspective Maps

\[
H = \begin{bmatrix}
a & b & c \\
d & e & f \\
g & h & 1 \\
\end{bmatrix}
\]

Called a homography (or planar perspective map)
Image warping with homographies

image plane in front

black area where no pixel maps to
Projective Transformations

• Projective transformations ...
  – Affine transformations, and
  – Projective warps

\[
\begin{bmatrix}
x' \\
y' \\
w'
\end{bmatrix} = \begin{bmatrix}
a & b & c \\
d & e & f \\
g & h & i
\end{bmatrix} \begin{bmatrix}
x \\
y \\
w
\end{bmatrix}
\]

• Properties of projective transformations:
  – Origin does not necessarily map to origin
  – Lines map to lines
  – Parallel lines do not necessarily remain parallel
  – Ratios are not preserved
  – Closed under composition
These transformations are a nested set of groups
• Closed under composition and inverse is a member
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Accidental Camera

http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0083325
The Great Torralba

Shadows?
Accidental pinhole camera
Window turned into a pinhole  

View outside
"a camera obscura has been used ... to bring images from the outside into a darkened room"
Making a pinhole with home materials
Making a pinhole with home materials
An hotel room, contrast enhanced.

The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows.
Another hotel room
Accidental pinholes in outdoor scenes

Pierre Moreels father (source: facebook)
Accidental pinhole camera

Anti-pinhole or Pinspeck cameras
Anti-pinhole or Pinspeck cameras

Adam L. Cohen, 1982

OPTICA ACTA, 1982, VOL. 29, No. 1, 63–67

Anti-pinhole imaging

ADAM LLOYD COHEN
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Chicago, Illinois 60626, U.S.A.

(Received 16 April 1981; revision received 8 July 1981)

Abstract. By complementing a pinhole to produce an isolated opaque spot, the
light ordinarily blocked from the pinhole image is transmitted, and the light
ordinarily transmitted is blocked. A negative geometrical image is formed,
distinct from the familiar ‘bright-spot’ diffraction image. Anti-pinhole, or
‘pinspeck’ images are visible during a solar eclipse, when the shadows of objects
appear crescent-shaped. Pinspecks demonstrate unlimited depth of field, freedom
from distortion and large angular field. Images of different magnification
may be formed simultaneously. Contrast is poor, but is improvable by averaging
to remove noise and subtraction of a d.c. bias. Pinspecks may have application in
X-ray space optics, and might be employed in the eyes of simple organisms.
Pinhole and Anti-pinhole cameras

Adam L. Cohen, 1982
Natural eyes

Lenses

Pinholes

Nautilus

Anti-pinholes

Euglena?
Mixed accidental pinhole and anti-pinhole cameras
Mixed accidental pinhole and anti-pinhole cameras
Mixed accidental pinhole and anti-pinhole cameras
Mixed accidental pinhole and anti-pinhole cameras

Room with a window  
Person in front of the window  
Difference image

-  
-  
=  ?
Mixed accidental pinhole and anti-pinhole cameras
Mixed accidental pinhole and anti-pinhole cameras

Body as the occluder

View outside the window
Looking for a small accidental occluder.
Looking for a small accidental occluder

Body as the occluder

Hand as the occluder

View outside the window
Accidental cameras reveal parts of the scene not directly visible

Mirrors

Pinholes

Lenses

Anti-pinholes

Gravitational lensing

Nishino and Nayar, IJCV 2006
Applications

• Computer graphics for better light models
• Image forensics (J. O’Brian & H. Farid, 2012)
Did man actually land on the moon?
Did man actually land on the moon?