Image Formation and Capture

- Devices
- Sources of Error
Optics

- Pinhole camera
- Lenses
- Focus, aperture, distortion
Pinhole Camera

- **Camera obscura** (“dark room”) – known since antiquity
Pinhole Camera

- Each point on image plane illuminated by light from one direction

- Joseph Nicéphore Niépce: first recording onto pewter plate coated with bitumen
Perspective Projection Phenomena...
Straight Lines Remain Straight
Parallel Lines Converge at Vanishing Points
Parallel Lines Converge at Vanishing Points

Each family of parallel lines has its own vanishing point
Nearer Objects Appear Bigger

\[
\text{size in image } \sim \frac{1}{\text{distance}}
\]
Pinhole Camera Limitations

- Aperture too big: blurry image
- Aperture too small: requires long exposure or high intensity
- Aperture much too small: diffraction through pinhole $\rightarrow$ blurry image
Lenses

- Focus a bundle of rays from a scene point onto a single point on the imager
- **Result:** can make clear images with bigger aperture
  - But only one distance “in focus”
Ideal “Thin” Lens Law

- Relationship between focal distance and focal length of lens:

\[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \]
Camera Adjustments

- Focus?
  - Changes $d_i$

- Iris?

- Zoom?
Focus and Depth of Field

- For a given $d_i$, “perfect” focus at only one $d_o$
- In practice, OK for some range of depths
  - Circle of confusion smaller than a pixel

- Better depth of field with smaller apertures
  - Better approximation to pinhole camera
- Also better depth of field with wide-angle lenses
Camera Adjustments

• **Focus**?
  – Changes $d_i$

• **Iris**?
  – Changes aperture

• **Zoom**?
Aperture

- Controls amount of light
- Affects depth of field
- Affects distortion (since thin-lens approximation is better near center of lens – stay tuned)

f/1.4  f/5.6  f/16
Aperture

• Aperture typically given as “f-number”

• What is \( f/4 \)?
  
  – Aperture diameter is \( \frac{1}{4} \) the focal length

• One “f-stop” equals change of f-number by \( \sqrt{2} \)
  
  – Equals change in aperture area by factor of 2
  
  – Equals change in amount of light by factor of 2
  
  – Example: \( f/2 \rightarrow f/2.8 \rightarrow f/4 \) (each one doubles light)
Camera Adjustments

- **Focus?**
  - Changes $d_i$

- **Iris?**
  - Changes aperture

- **Zoom?**
  - Changes $f$ and sometimes $d_i$
Zoom Lenses – Varifocal
Zoom Lenses – Parfocal
Field of View

Q: What does field of view of camera depend on?
   – Focal length of lens
   – Size of imager
   – Object distance?
Computing Field of View

\[
\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}
\]

\[
\tan \frac{\theta}{2} = \frac{1}{2} \frac{x_o}{d_o}
\]

\[
x_o / d_o = x_i / d_i
\]

\[
\theta = 2 \tan^{-1} \frac{1}{2} \frac{x_i}{f} \left(1/f - 1/d_o\right)
\]

Since typically \( d_o \gg f \),

\[
\theta \approx 2 \tan^{-1} \frac{1}{2} \frac{x_i}{f}
\]

\[
\theta \approx \frac{x_i}{f}
\]
Photoreceptors

- Human retina
- Vidicon
- CCD and CMOS imagers
Photoreceptors in Human Retina

- Two types of receptors: rods and cones

Rods and cones

Cones in fovea (central part of retina)
Rods and Cones

• **Rods**
  - More sensitive in low light: “scotopic” vision
  - More dense near periphery

• **Cones**
  - Only function with higher light levels: “photopic” vision
  - Densely packed at center of eye: fovea
  - Different types of cones → color vision
Color Perception

Spectral-response functions of the three types of cones (including absorption due to cornea and lens)
Tristimulus Color

- Any distribution of light can be summarized by its effect on 3 types of cones
- Therefore, human perception of color is a 3-dimensional space
- **Metamerism**: different spectra, same response
- Color blindness: fewer than 3 types of cones
  - Most commonly L cone = M cone
Electronic Photoreceptors

- Analog technologies:
  - Coated plates
  - Film

- Digital technologies
  - Vidicon
  - CCD
  - CMOS imagers

- Produce regular grid of pixels
  - Measures light power integrated over some time period, over some area on image plane
Vidicon

- Best-known in family of “photoconductive video cameras”
- Basically television in reverse
MOS Capacitors

- MOS = Metal Oxide Semiconductor

![Diagram of MOS Capacitor]

- Gate (wire)
- SiO₂ (insulator)
- p-type silicon
MOS Capacitors

- Voltage applied to gate repels positive “holes” in the semiconductor
MOS Capacitors

- Photon striking the material creates electron-hole pair
Charge Transfer

- **CCDs** (Charge-Coupled Devices) move charge from one bucket to another by manipulating voltages.
CMOS Imagers

- Recently, can manufacture chips that combine photosensitive elements and processing elements
- Benefits:
  - Partial readout
  - Signal processing
  - Eliminate some supporting chips → low cost
Color Cameras

- CCD sensitivity does not match human eye

- Use band-pass color filters to adapt…
3-Chip Color Cameras

- Use prisms and filters to split image across 3 sensors
- Expensive, hard to align
1-Chip Color Cameras

Estimate missing components from neighboring values (demosaicing)

Why more green?

Human Luminance Sensitivity Function
Errors in Digital Images

- What are some sources of error in this image?
Sources of Error

- Geometric (focus, distortion)
- Color (1-chip artifacts, chromatic aberration)
- Radiometric (cosine falloff, vignetting)
- Bright areas (flare, bloom, clamping)
- Signal processing (gamma, compression)
- Noise
Monochromatic Aberrations

- Real lenses do not follow thin lens approximation because surfaces are spherical (manufacturing constraints)
- Result: thin-lens approximation only valid iff
  \[ \sin \varphi \approx \varphi \]
Spherical Aberration

- Results in blurring of image, focus shifts when aperture is stopped down
- Can vary with the way lenses are oriented
Distortion

- Pincushion or barrel **radial distortion**
  - Straight lines in the world no longer straight in image
Distortion

- Varies with placement of aperture
Distortion

- Varies with placement of aperture
Distortion

- Varies with placement of aperture
First-Order Radial Distortion

- Goal: mathematical formula for distortion
- If small, can be approximated by “first-order” formula (like Taylor series expansion):
  \[
  r' = r \left(1 + \kappa r^2\right)
  \]
  \[
  r = \text{ideal distance to center of image}
  \]
  \[
  r' = \text{distorted distance to center of image}
  \]
- Higher-order models are possible
Chromatic Aberration

- Due to dispersion in glass (focal length varies with the wavelength of light)
- Result: color fringes
- Worst at edges of image

- Correct by building lens systems with multiple kinds of glass
Correcting for Aberrations

• High-quality compound lenses use multiple lens elements to cancel out distortion and aberration

• Often 5-10 elements, more for zooms
Other Limitations of Lenses

- **Optical vignetting:** less power per unit area for light at an oblique angle
  - Approximate falloff $\sim \cos^4 \phi$
  - Result: darkening of edges
  - Also mechanical vignetting due to multiple apertures
Other Limitations of Lenses

- **Flare**: light reflecting (often multiple times) from glass-air interface
  - Results in ghost images or haziness
  - Worse in multi-lens systems
  - Ameliorated by optical coatings (thin-film interference)

- **Bloom**: overflow of charge in CCD buckets
  - Spills to adjacent buckets
  - Streaks (usually vertical) next to bright areas
  - Some cameras have “anti-bloom” circuitry
Flare and Bloom
Dynamic Range

- Most common cameras have 8-bit (per color channel) dynamic range
  - Can be nonlinear: more than 255:1 intensity range
- Too bright: clamp to maximum
- Too dim: clamp to 0
- Specialty cameras with higher dynamic range (usually 10-, 12-, and 16-bit)
High Dynamic Range (HDR) from Ordinary Cameras

- Take pictures of same scene with different shutter speeds
- Identify regions clamped to 0 or 255
- Average other pixels, scaled by $1 / \text{shutter speed}$
- Can extend dynamic range, but limitations of optics and imager (noise, flare, bloom) still apply
Gamma

- Vidicon tube naturally has signal that varies with light intensity according to a power law:
  \[ \text{Signal} = E^\gamma, \quad \gamma \approx \frac{1}{2.5} \]
- CRT (televisions) naturally obey a power law with gamma \( \approx 2.3–2.5 \)
- Result: video signal standard has gamma of 1/2.5
- CCDs and CMOS linear, but gamma \( \approx 2.2 \) almost always applied
Consequences for Vision

• Output of most camera systems is not linear
• Know what it is! (Sometimes system automagically applies “gamma correction”)
• Necessary to correct raw pixel values for:
  – Reflectance measurements
  – Shape from shading
  – Photometric stereo
  – Recognition under variable lighting
Consequences for Vision

- What about e.g. edge detection?
  - Often want “perceptually significant” edges
  - Standard nonlinear signal close to (inverse of) human response
  - Using nonlinear signal often the “right thing”
Noise

- **Thermal noise: in all electronics**
  - Noise at all frequencies
  - Proportional to temperature
  - Special cooled cameras available for low noise

- **Shot noise: discrete photons / electrons**
  - Shows up at extremely low intensities
  - CCDs / CMOS can have high efficiency – approaching 1 electron per photon
Noise

• $1/f$ noise – inversely proportional to frequency
  – Amount depends on quality, manufacturing techniques
  – Can be dominant source of noise

• All of the above apply for imager and amplifier
Filtering Noise

• Most common method – simple blur
  – e.g., convolution with Gaussian

• Adaptive filters to prevent bleed across intensity edges

• Other filters for specialized situations
  – e.g., “despeckling” (median filters) for dead pixels

• Next time!
David Macaulay
Great Moments in Architecture
Plate XV: Locating the Vanishing Point (June 8, 1874)