Image Formation and Optics
Image Formation + Capture

- Real world
- Optics
- Sensor

- Devices
- Sources of Error
Optics

• Lenses
• Focus, aperture, distortion
Pinhole Camera

- “Camera obscursa”

Object → Pinhole → Image plane → Image
Pinhole Camera

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

—Rule of thumb: aperture should be significantly larger than wavelength of light (400-700 nm)
Lenses

• Focus a bundle of rays from a scene point onto single point on the imager

• Result: can make aperture larger
Ideal “Thin” Lens Law

- Relationship between focal length and focal distance:

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

- Focus?
- Iris?
- Zoom?
Focus and Depth of Field

- For a given $d_i$, “perfect” focus at only one depth
- In practice, OK for some range of depths
  - Circle of confusion smaller than a pixel
- Better depth of field with smaller aperture, but requires more light intensity (closer to pinhole camera)
Field of View

Q: What does field of view of camera depend on?
- Focal length of lens
- Size of imager
- Object distance?

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

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

- Controls amount of light
- Affects depth of field
- Affects distortion (thin-lens approximation is better near center of lens)
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 → f/2.8 → f/4
Charge Coupled Devices

Acknowledgment: Michael Richmond
CCD Read-Out

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CCD Noise

• Thermal ("dark current") noise:
  • Thermal energy generates electrons in silicon chip (indistinguishable from electrons generated by photons)

• Read-out noise:
  • Noise in digitization process
Capturing Color
Capturing Color
Errors in Digital Images
Sources of Error

• Geometric (focus, distortion)
• Color (spectral aliasing, chromatic abberation)
• Radiometric (vignetting)
• Bright areas (flare, bloom, clamping)
• Signal processing (gamma, compression)
• Noise
Monochromatic Aberrations

- Real lenses do not follow ideal thin lens approximation
- Only valid if \( \sin (\theta) \sim \theta \)
Spherical Aberration

- Results in blurring of image, focus shifts when aperture is adjusted
- Exact distortion depends on orientation of lens
Radial Distortion

- Varies with placement of aperture
Radial Distortion
Chromatic Aberration

- Due to dispersion in glass (focal length varies with wavelength of light)
- Result: color fringes
- Worst at edges of image
- Correct with lens system with multiple types of glass
Correcting for Aberrations

- Compound lenses use multiple lens elements to “cancel out” distortion and aberration
Vignetting

- Darkening of image toward edges
- Optical: less power per unit area transferred for light at an oblique angle
- Mechanical: due to apertures
Lens Flare

- Light reflecting from glass-air interfaces
- Results in ghost images or haziness
- Worse in multi-lens systems
- Ameliorated by optical coatings
Bloom

- Overflow charge in pixel "buckets"
- Spills into neighboring areas
- Streaks (usually vertical) next to bright areas
Dynamic Range

- Most consumer digital cameras have 8-bit (per color channel) dynamic range
- Can be non-linear: more than 255:1 intensity range
- Too bright: clamp to 255
- Too dim: clamp to 0
# Dynamic Range

<table>
<thead>
<tr>
<th></th>
<th>Dynamic Range</th>
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<tbody>
<tr>
<td><strong>Human Eye (Instantaneous)</strong></td>
<td>1,000:1</td>
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<tr>
<td><strong>Human Eye (Overall)</strong></td>
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<tr>
<td><strong>Canon G1</strong></td>
<td>495:1*</td>
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<tr>
<td><strong>Nikon Coolpix 990</strong></td>
<td>446:1*</td>
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<td><strong>Canon EOS-D30</strong></td>
<td>488:1*</td>
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<td><strong>Nikon D1</strong></td>
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<td><strong>Conventional CRT</strong></td>
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* [www.dpreview.com](http://www.dpreview.com)
× Gabriel Torres (hardwaresecrets.com)
Noise
Noise
Filtering Noise

- Low-pass filter (e.g. Gaussian)
- Edge-preserving adaptive filters (e.g. bilateral filter)
- “Despeckling” uses a median filter to remove dead pixels