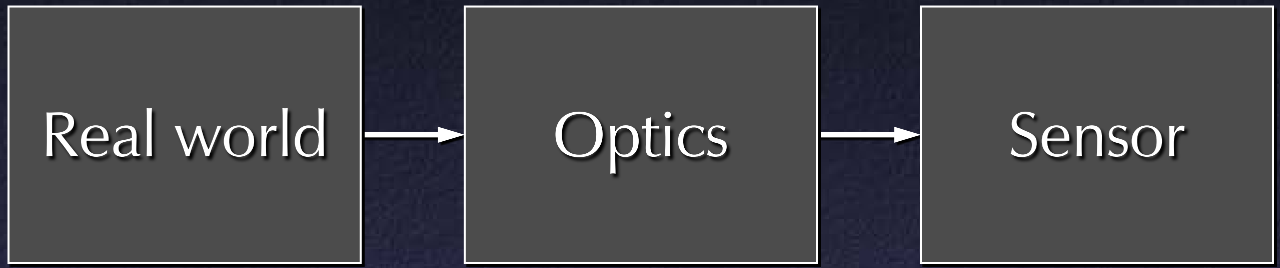
Image Formation and Capture

Acknowledgment: some figures by B. Curless, E. Hecht, W.J. Smith, B.K.P. Horn, and A. Theuwissen

Image Formation and Capture



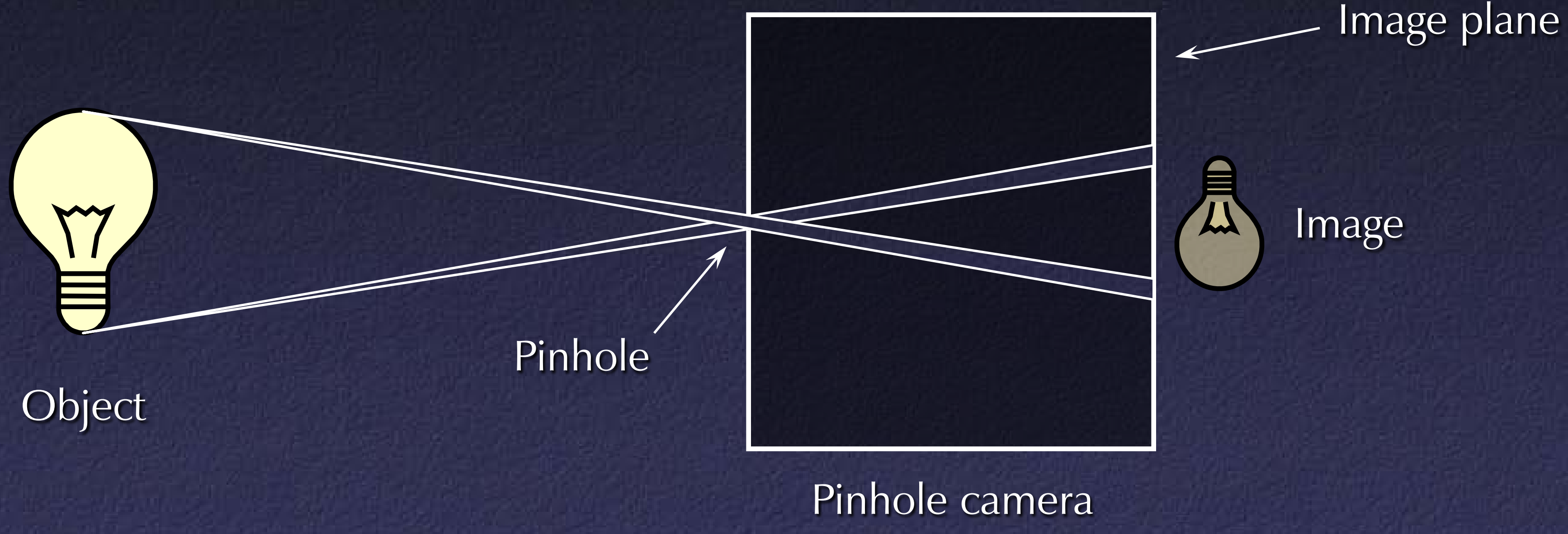
- Devices
- Sources of Error

Optics

- Pinhole camera
- Lenses
- Focus, aperture, distortion

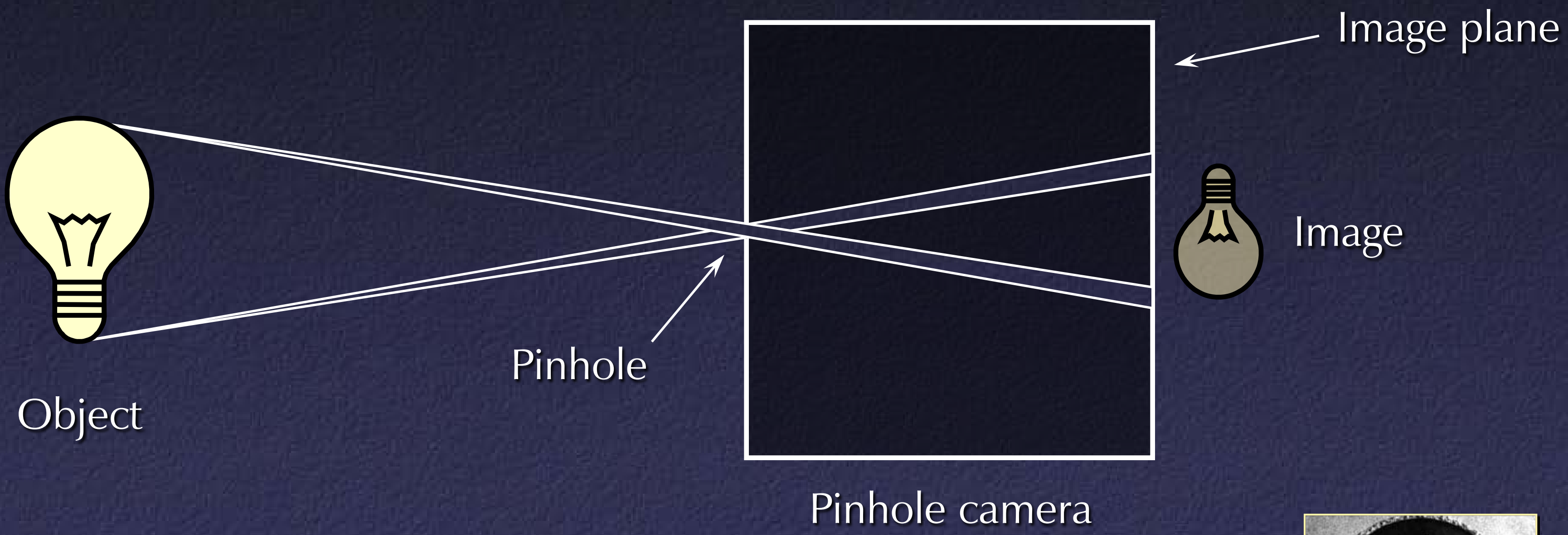
Pinhole Camera

- "Camera obscura" – known since antiquity



Pinhole Camera

- "Camera obscura" – known since antiquity



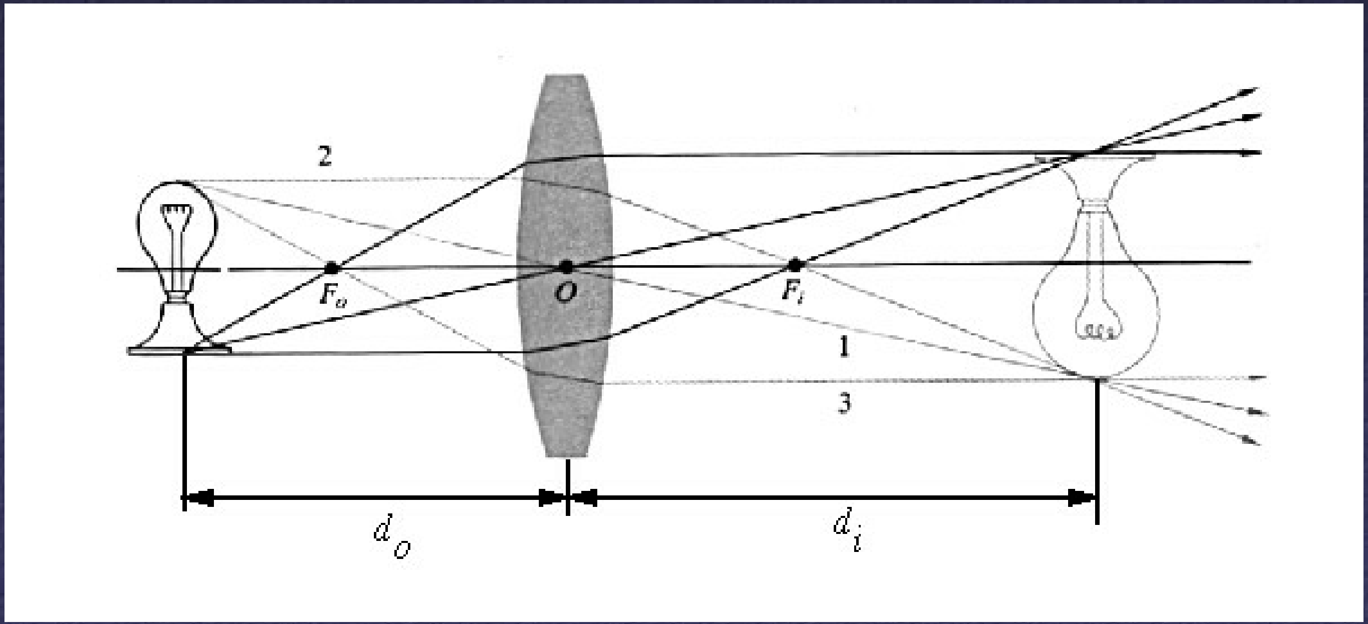
- Joseph Nicéphore Niépce: first recording onto pewter plate coated with bitumen

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

Lenses

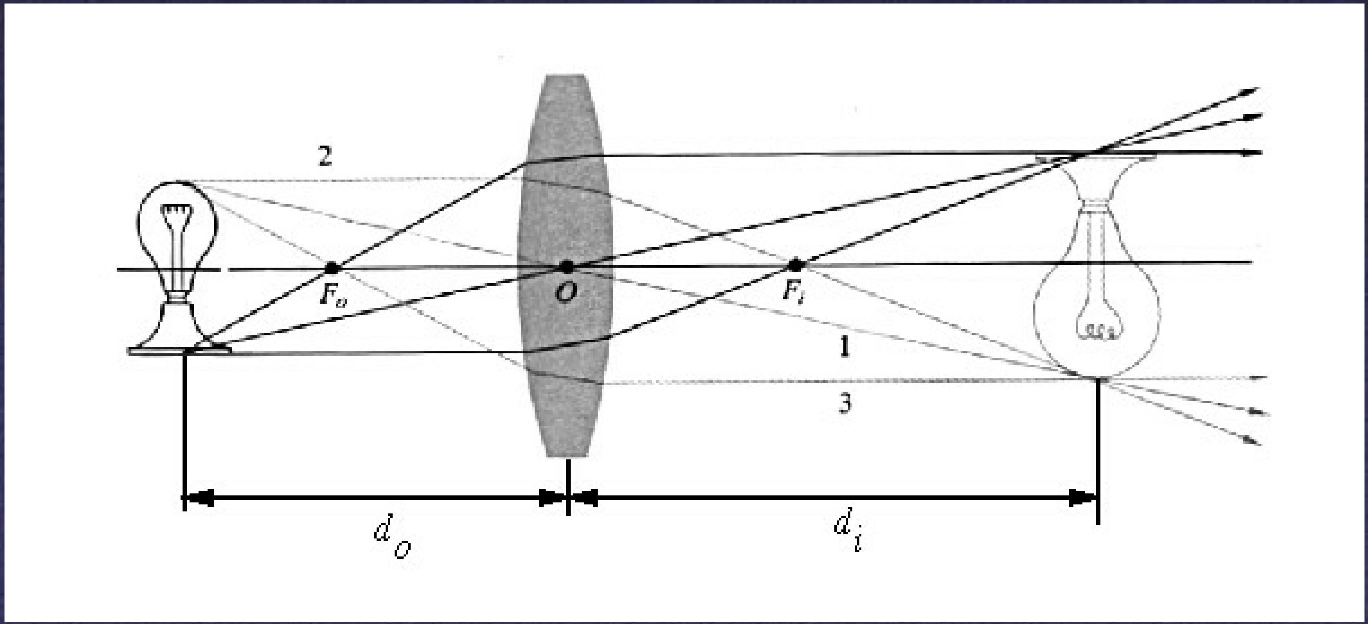
- Focus a bundle of rays from a scene point onto a single point on the imager
- Result: can make aperture bigger



Ideal "Thin" Lens Law

- Relationship between focal distance and focal length of lens:

$$1/d_o + 1/d_i = 1/f$$

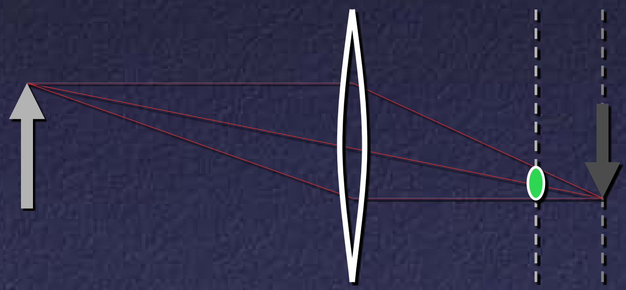


Camera Adjustments

- 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)

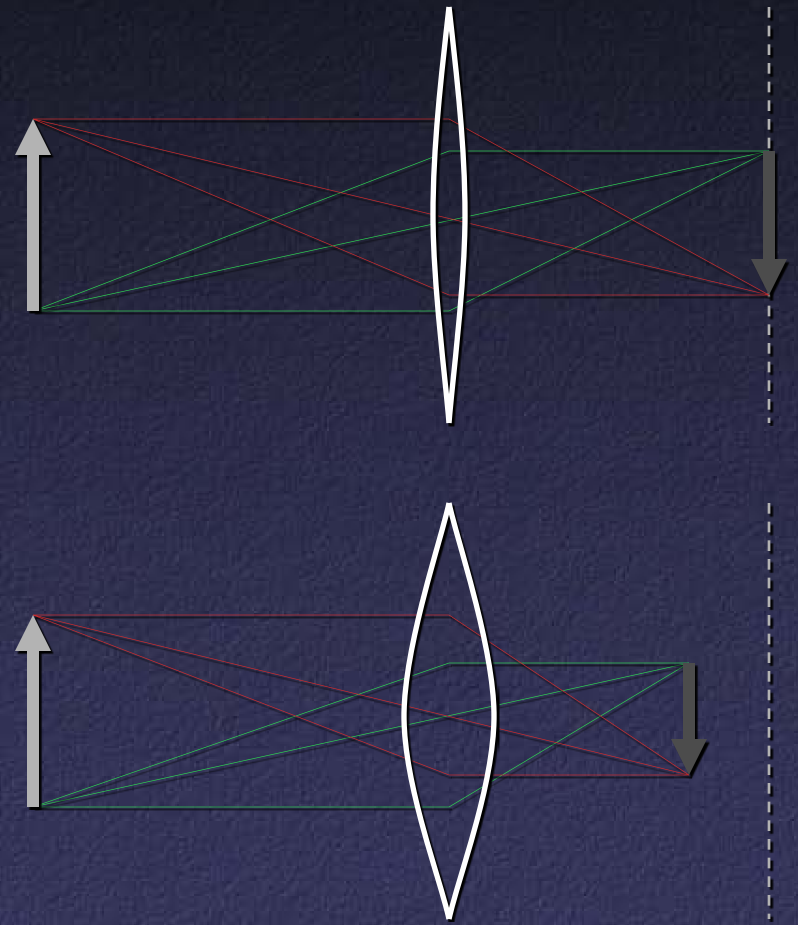
Aperture

- Aperture typically given as "*f*-number"
- What is $f/4$?
  - Aperture *diameter* is ¼ 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

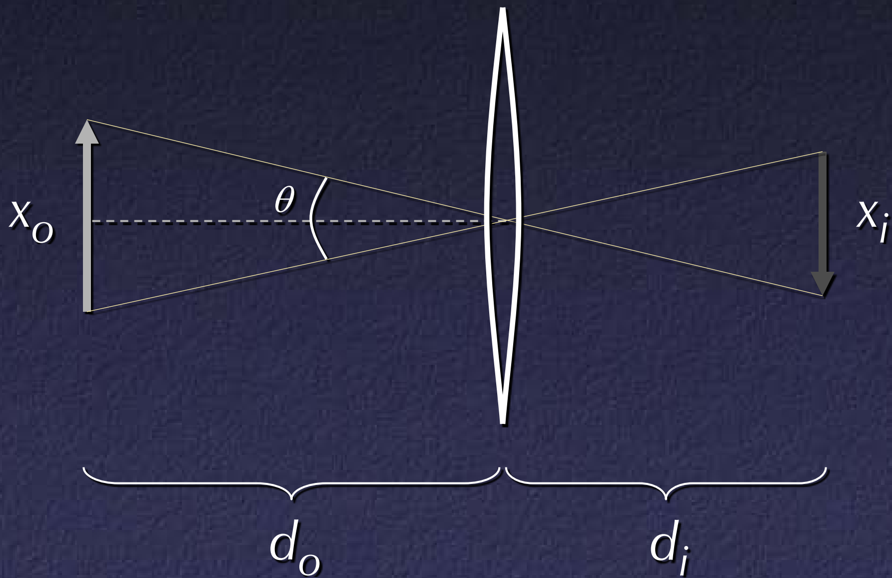


Zoom Lenses – Parfocal

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



$$1/d_o + 1/d_i = 1/f$$

$$\tan\ \theta/2 = \tfrac{1}{2}\, x_o / d_o$$

$$x_o\ /\ d_o = x_i\ /\ d_i$$

$$\theta\ = 2\ \tan^{-1}\ \tfrac{1}{2}\ x_i\,(1/f - 1/d_o)$$

Since typically $d_o >> f$,

$$\theta\ \approx 2\ \tan^{-1}\ \tfrac{1}{2}\ x_i / f$$

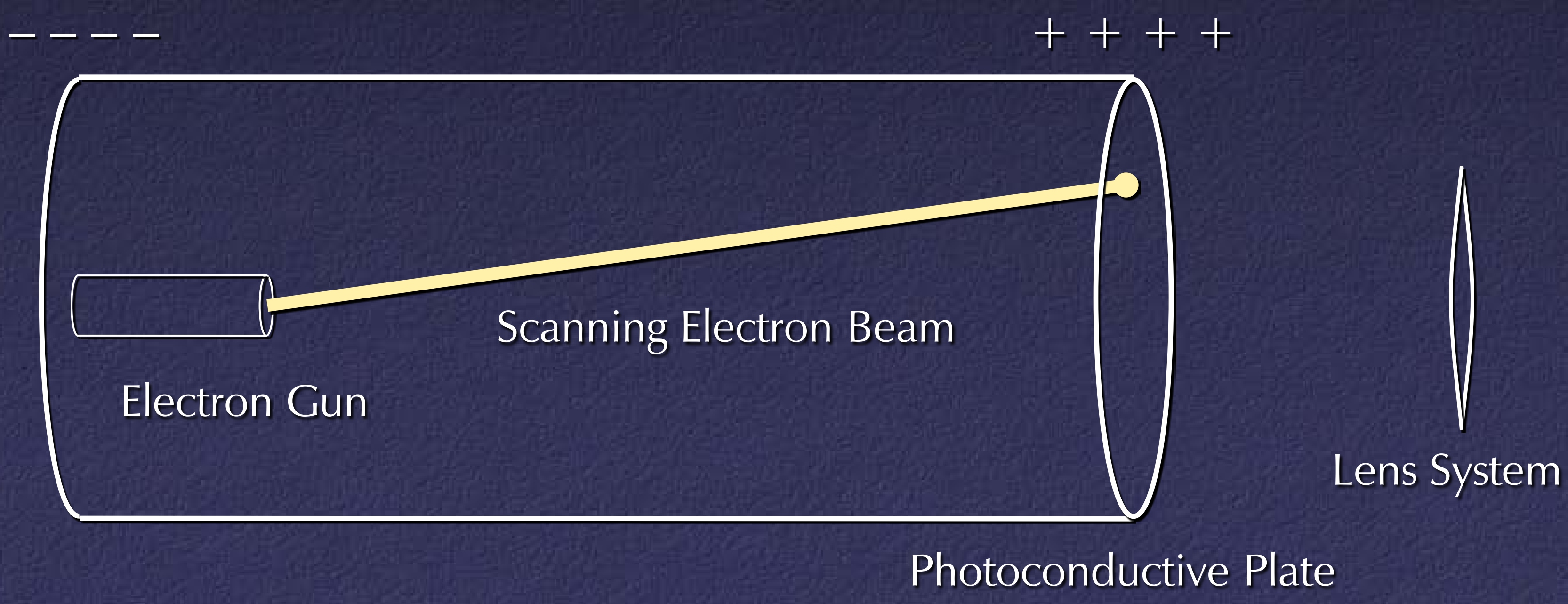
$$\theta\ \approx x_i / f$$

Development of Sensors

- Coated plates
- Film
- Vidicon
- CCD
- CMOS

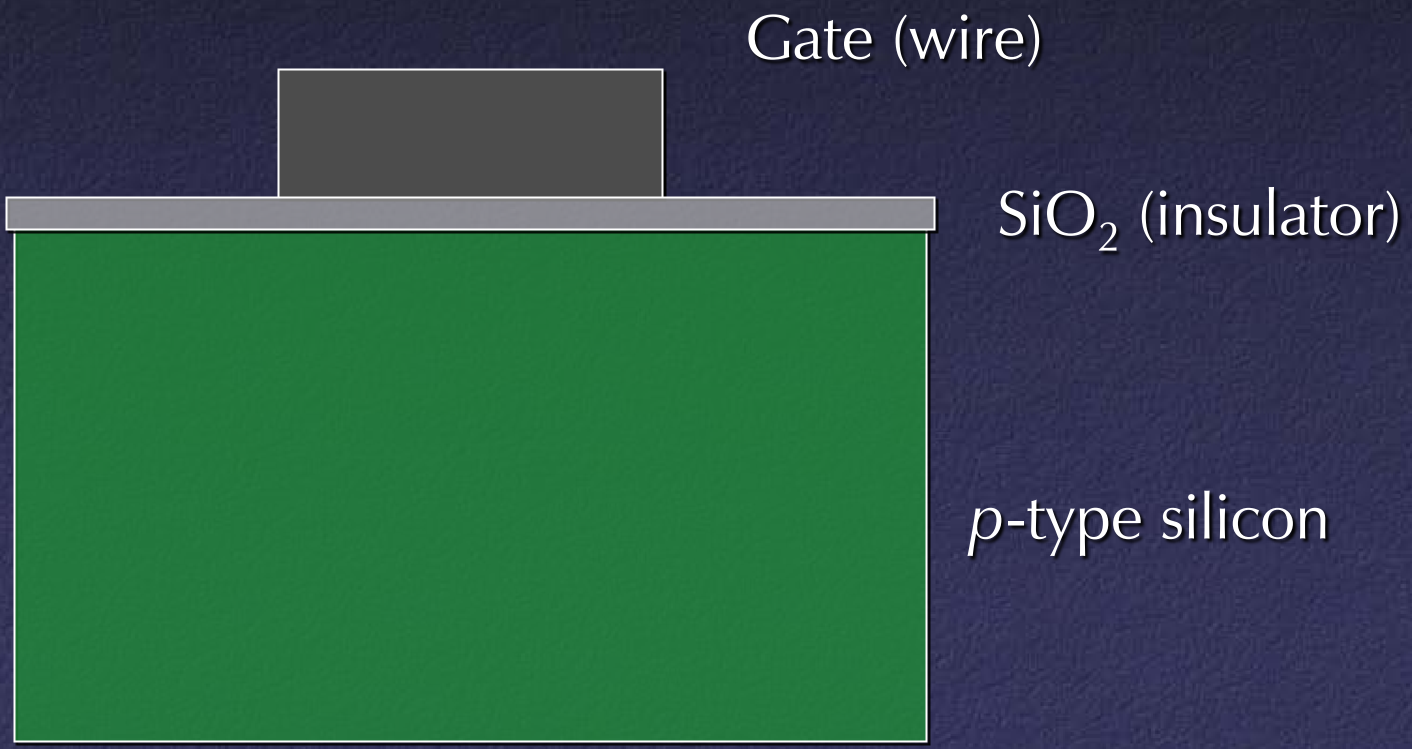
Vidicon

- Best-known in family of "photoconductive video cameras"
- Basically television in reverse



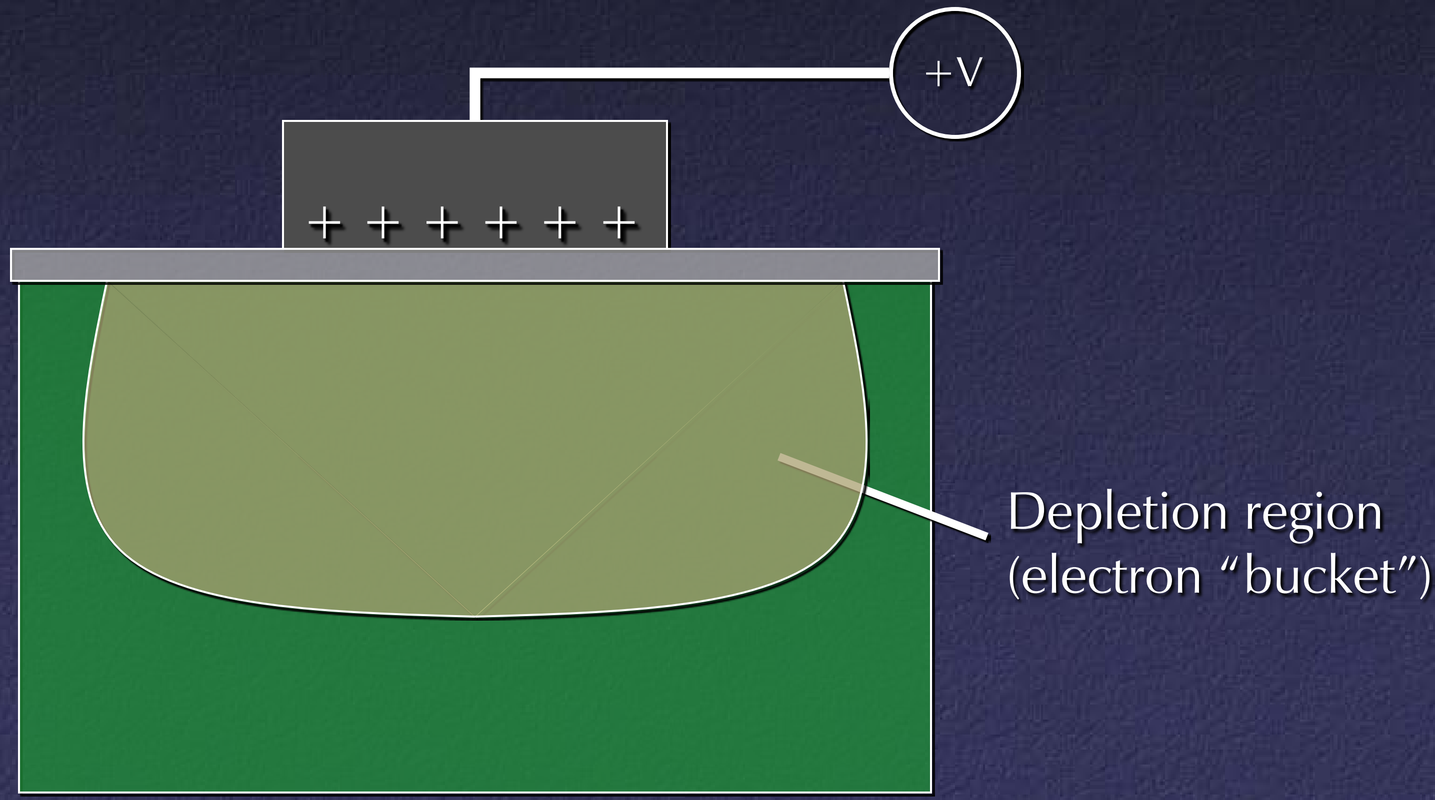
MOS Capacitors

- MOS = Metal Oxide Semiconductor



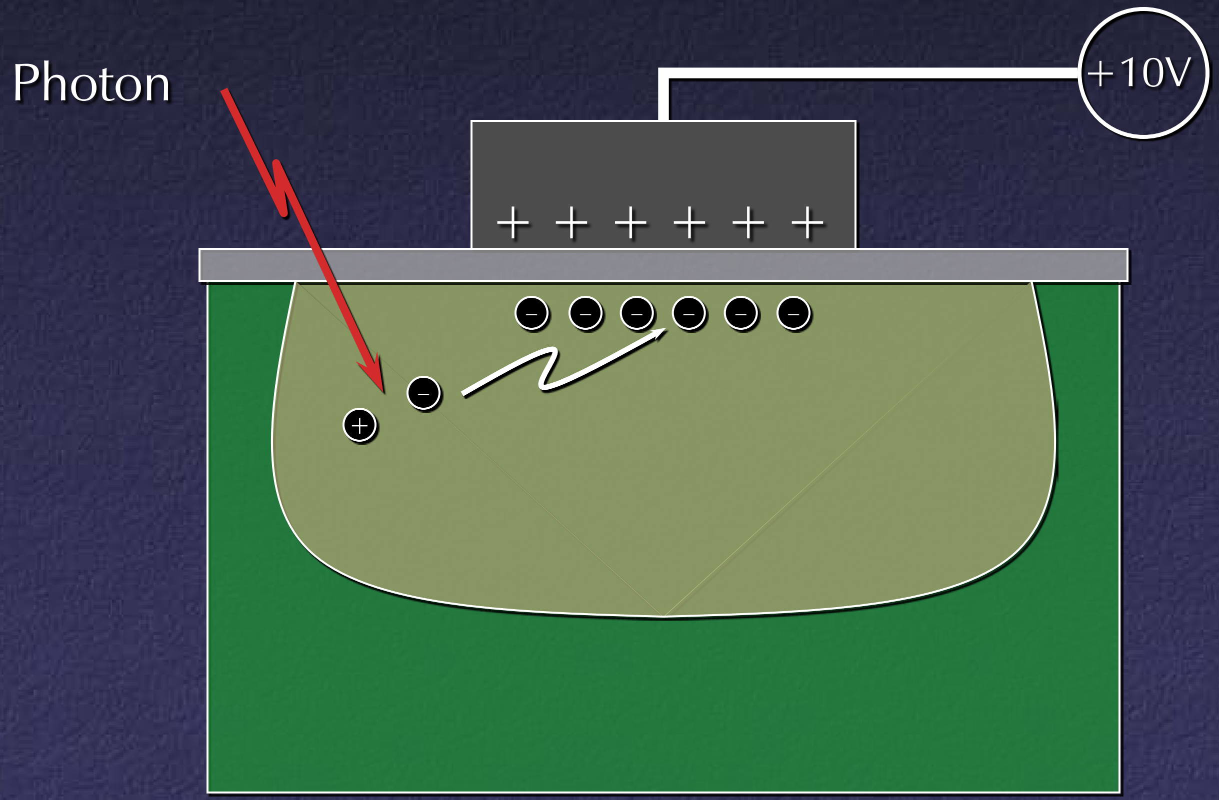
MOS Capacitors

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



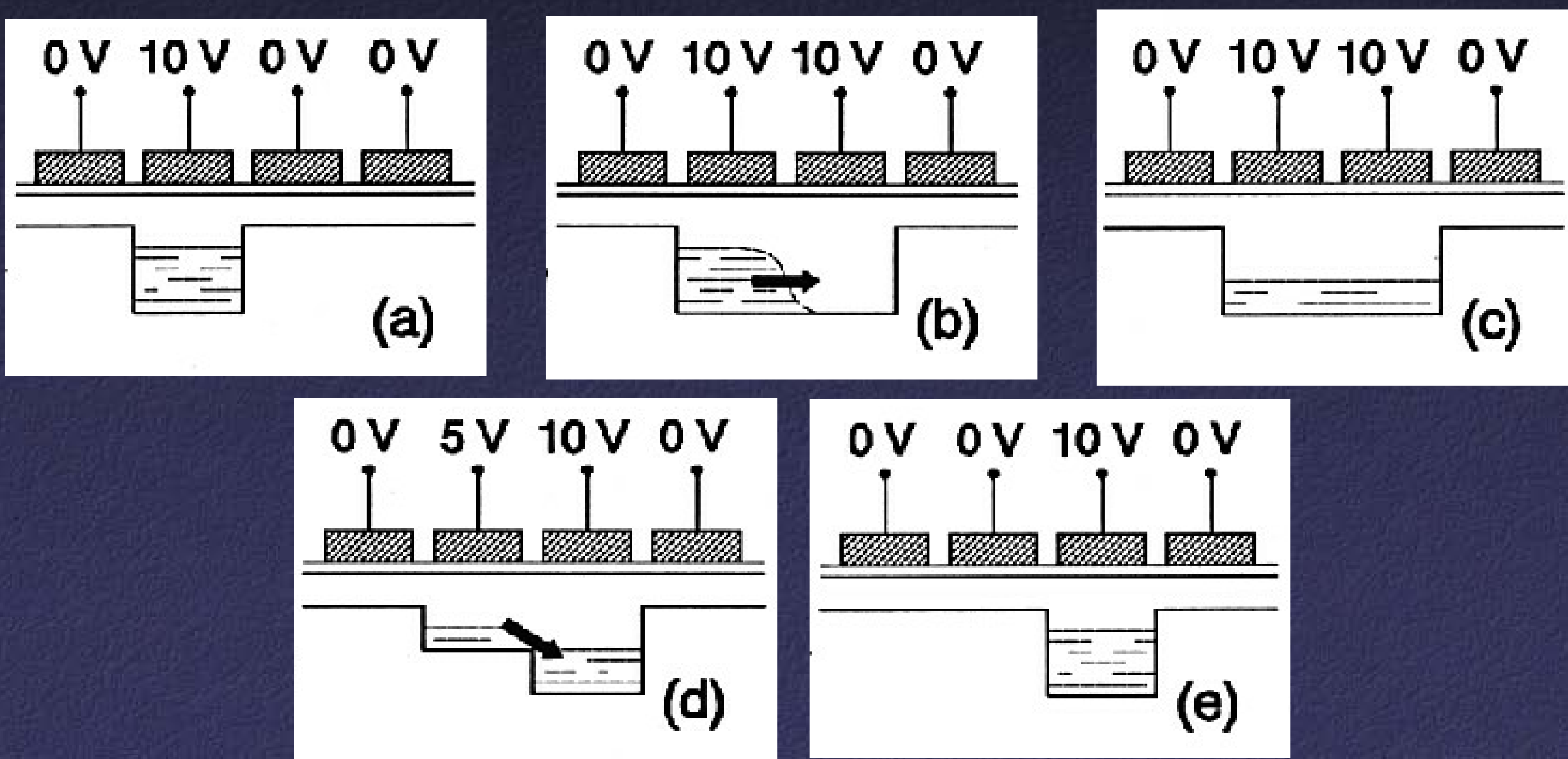
MOS Capacitors

- Photon striking the material creates electron-hole pair



Charge Transfer

- CCDs move charge from one bucket to another by manipulating voltages

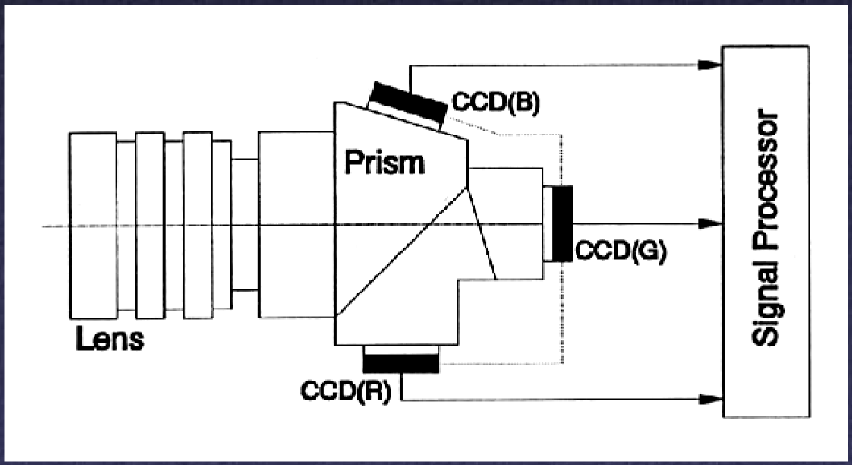


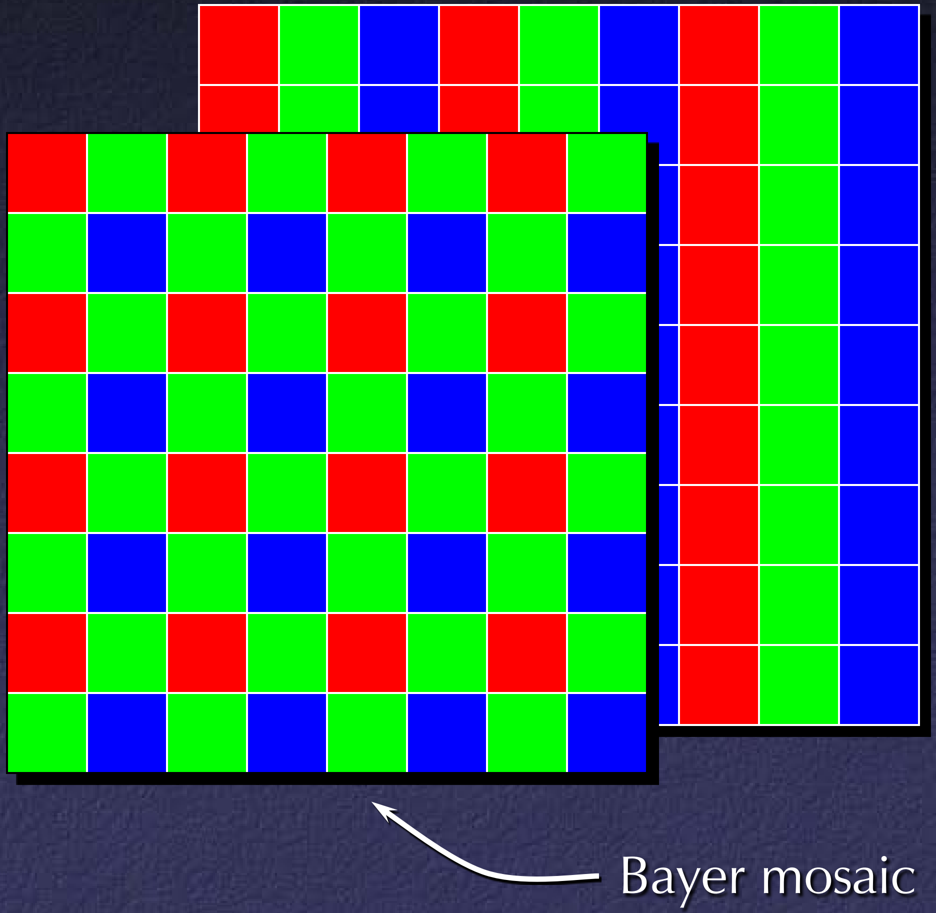
CMOS Imagers

- Recently, can manufacture chips that combine photosensitive elements and processing elements
- Benefits:
  - Partial readout
  - Signal processing
  - Eliminate some supporting chips $\Rightarrow$ low cost

Color

- 3-chip vs. 1-chip: quality vs. cost





Errors in Digital Images

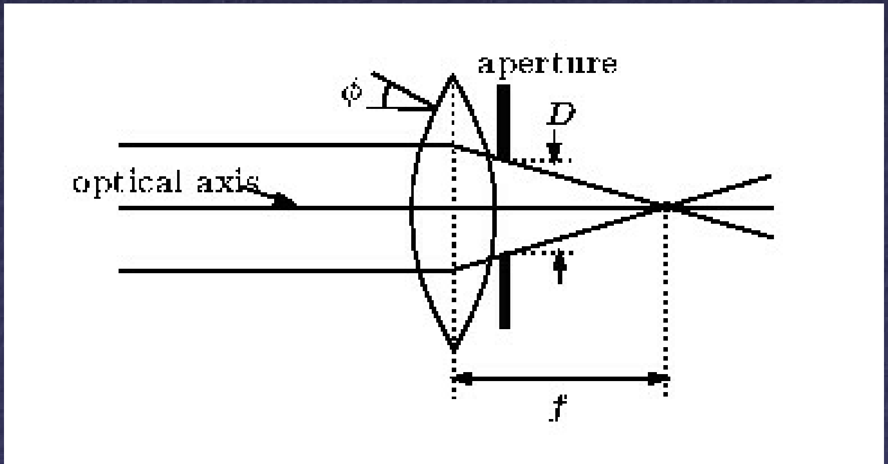
- What are some sources of error in this image?

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

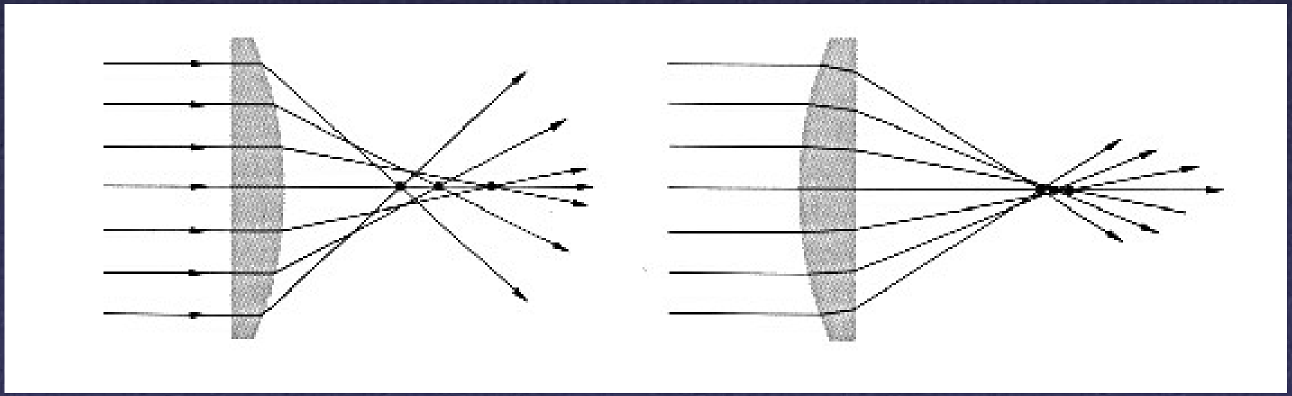
Monochromatic Aberrations

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



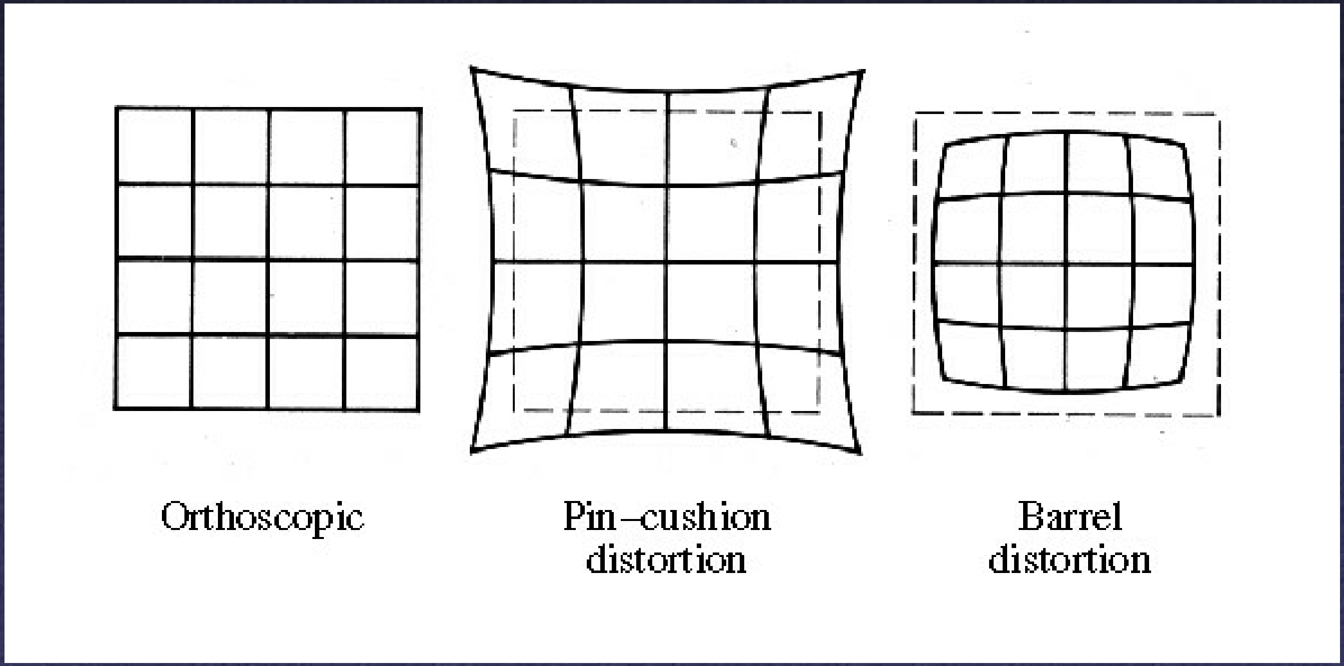
Spherical Aberration

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



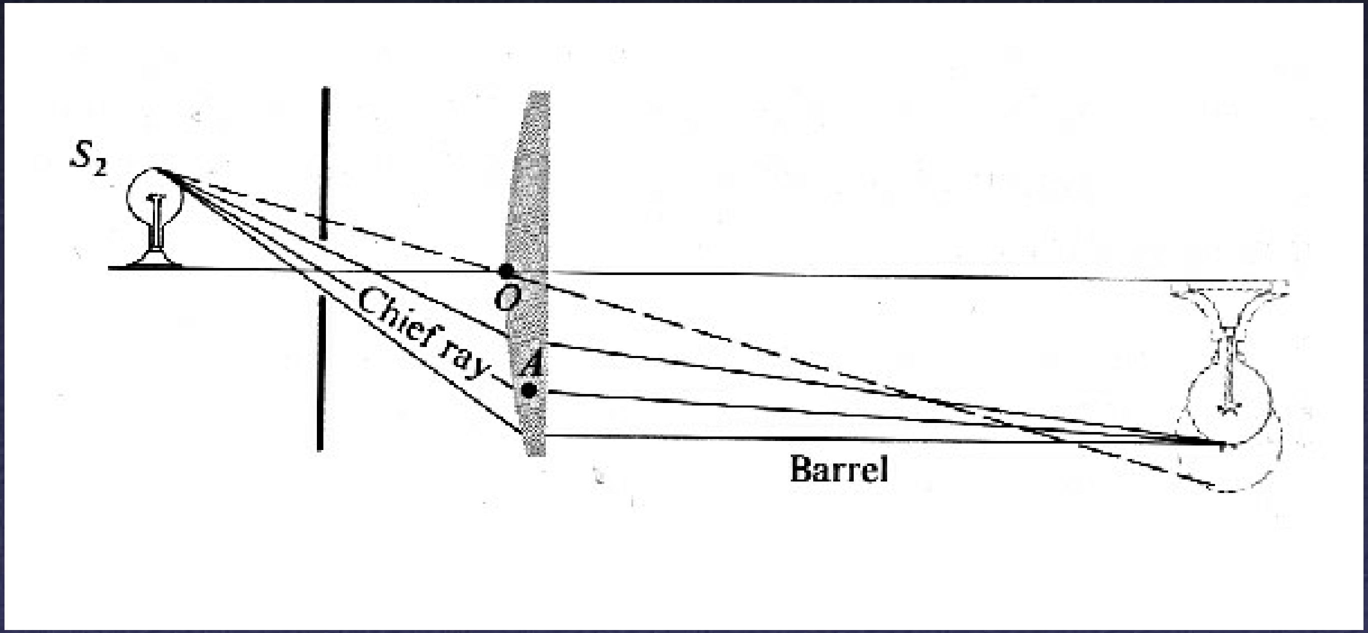
Distortion

- Pincushion or barrel *radial distortion*



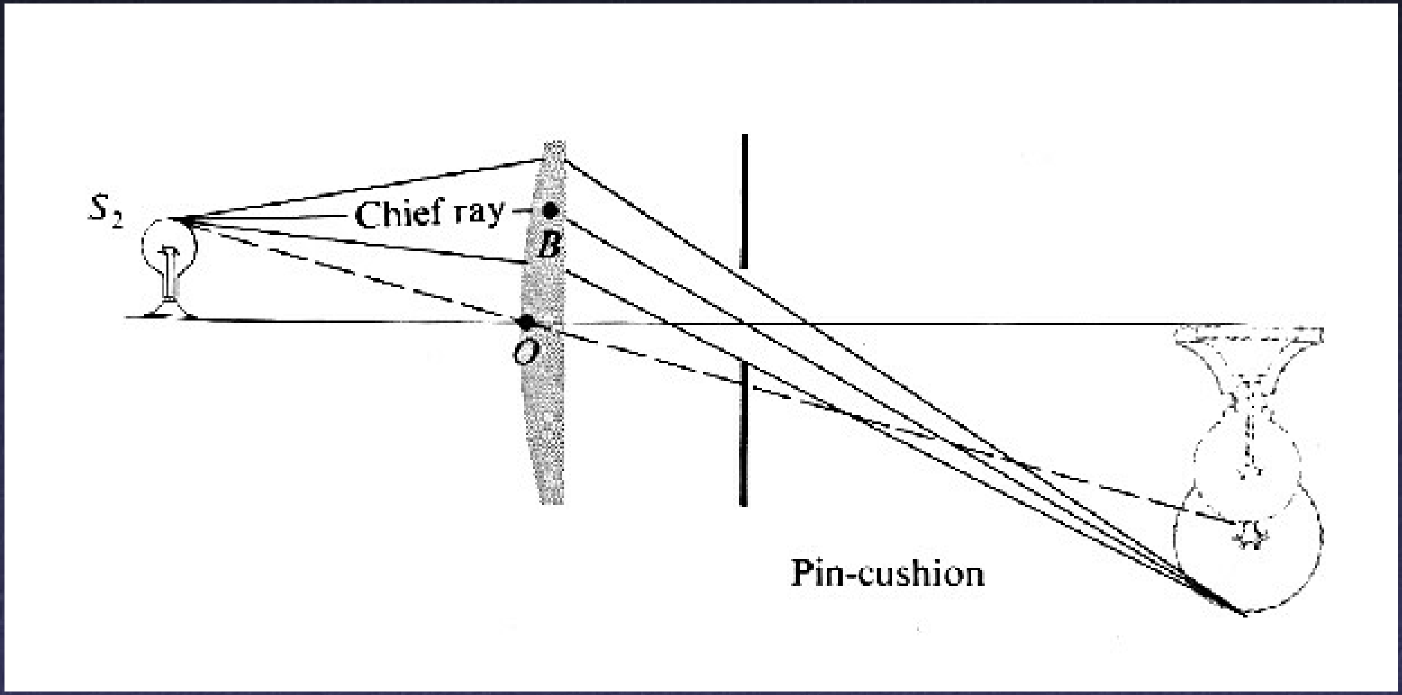
- Varies with placement of aperture

Distortion



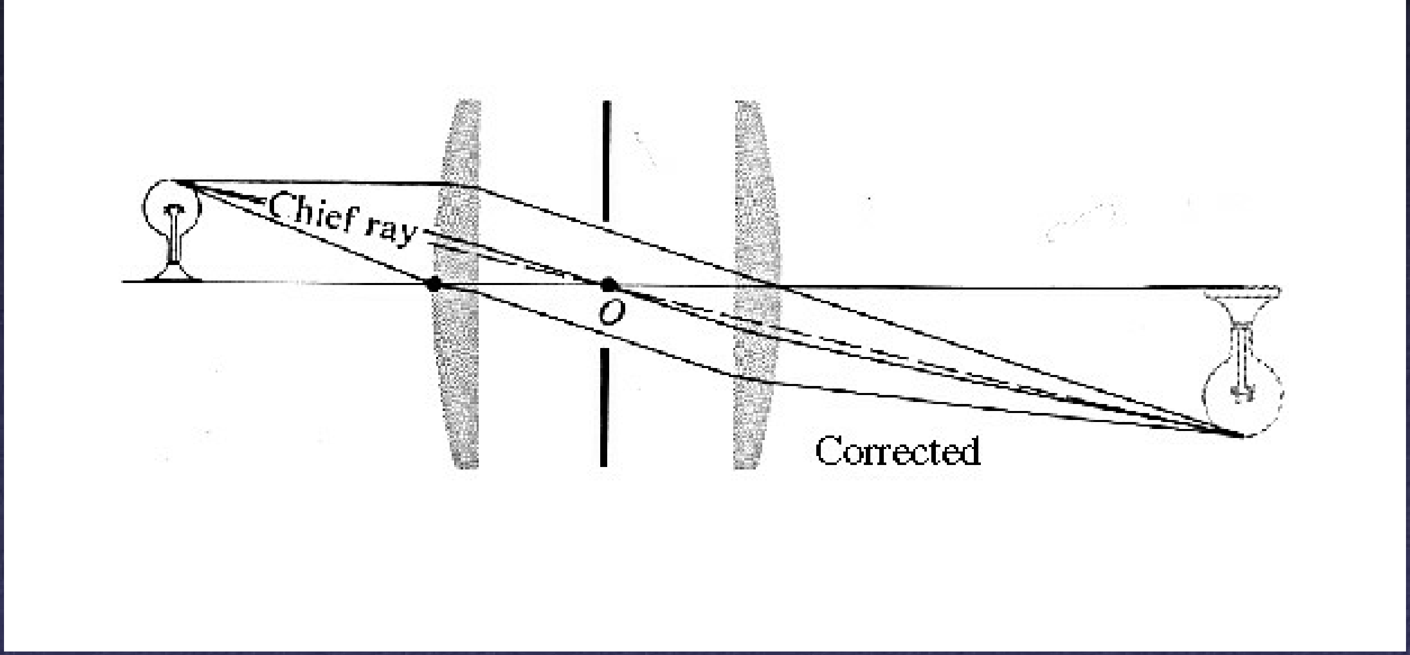
- Varies with placement of aperture

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):

$$r' = r\,(1 + \kappa r^2)$$

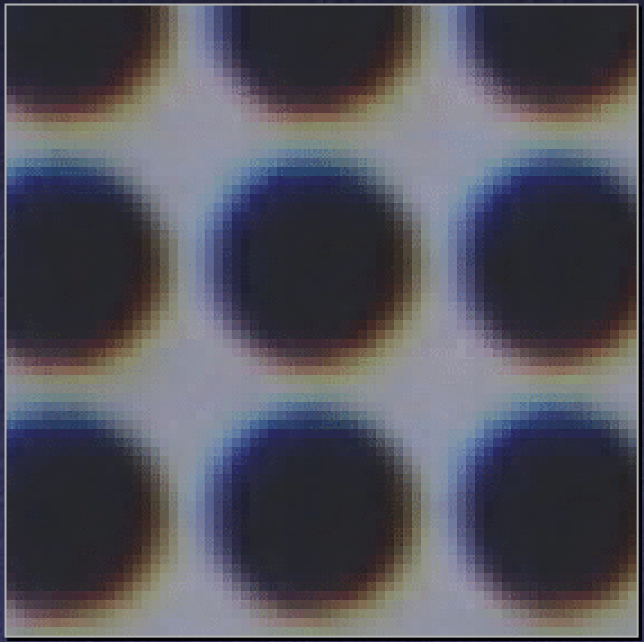
$$r = \text{ideal distance to center of image}$$

$$r' = \text{distorted distance to center of image}$$

- Higher-order models are possible

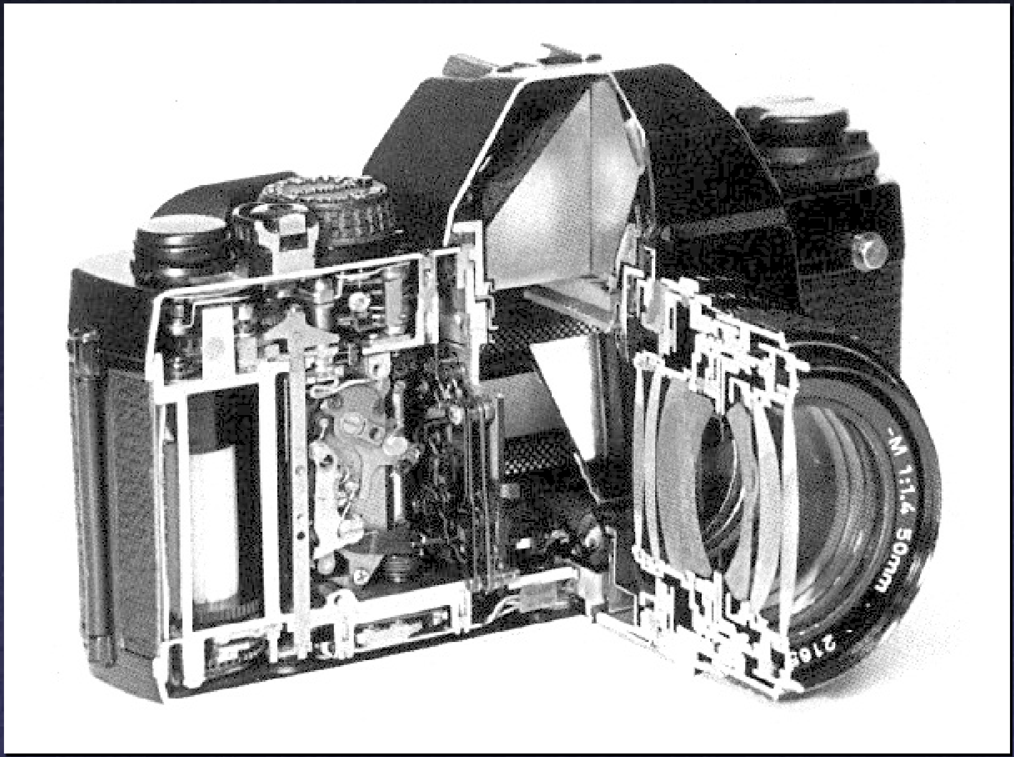
Chromatic Aberration

- 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

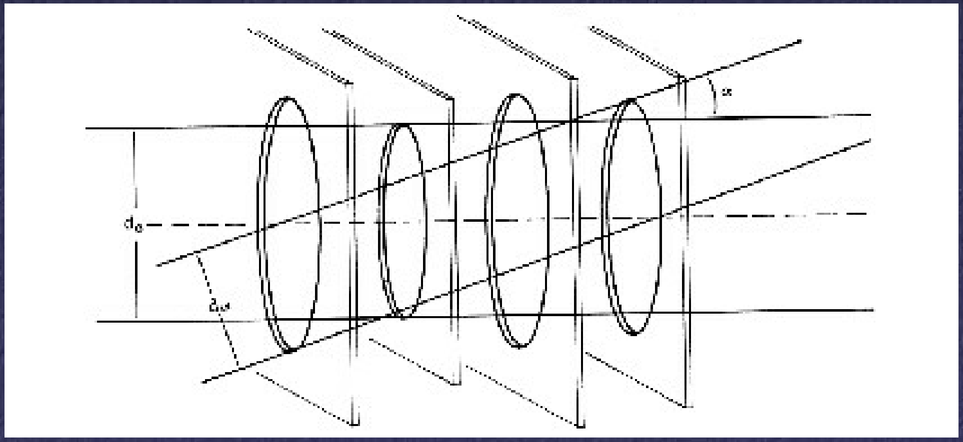
- High-quality compound lenses use multiple lens elements to “cancel out” distortion and aberration



- Often 5-10 elements, potentially many more for zooms

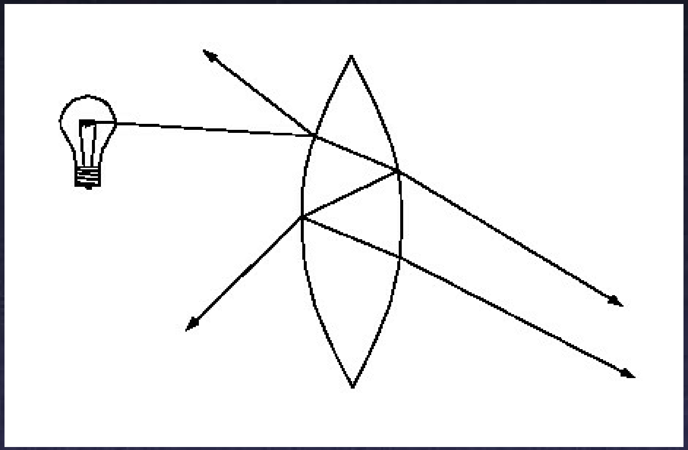
Other Limitations of Lenses

- Optical vignetting: less power per unit area transferred for light at an oblique angle
  - Transferred power falls off as $\cos^4 \varphi$
  - Result: darkening of edges of image
- Mechanical vignetting: due to 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

Tanaka

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 / 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: Signal = E^{γ}, $\gamma \approx 1/2.5$
- CRT (televisions) naturally obey a power law with gamma ≈ 2.3–2.5
- Result: video signal standard has gamma of 1/2.5
- CCDs and CMOS linear, but gamma ≈ 2.2 almost always applied

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