Focus on Resolution: Degradations in Image Acquisition

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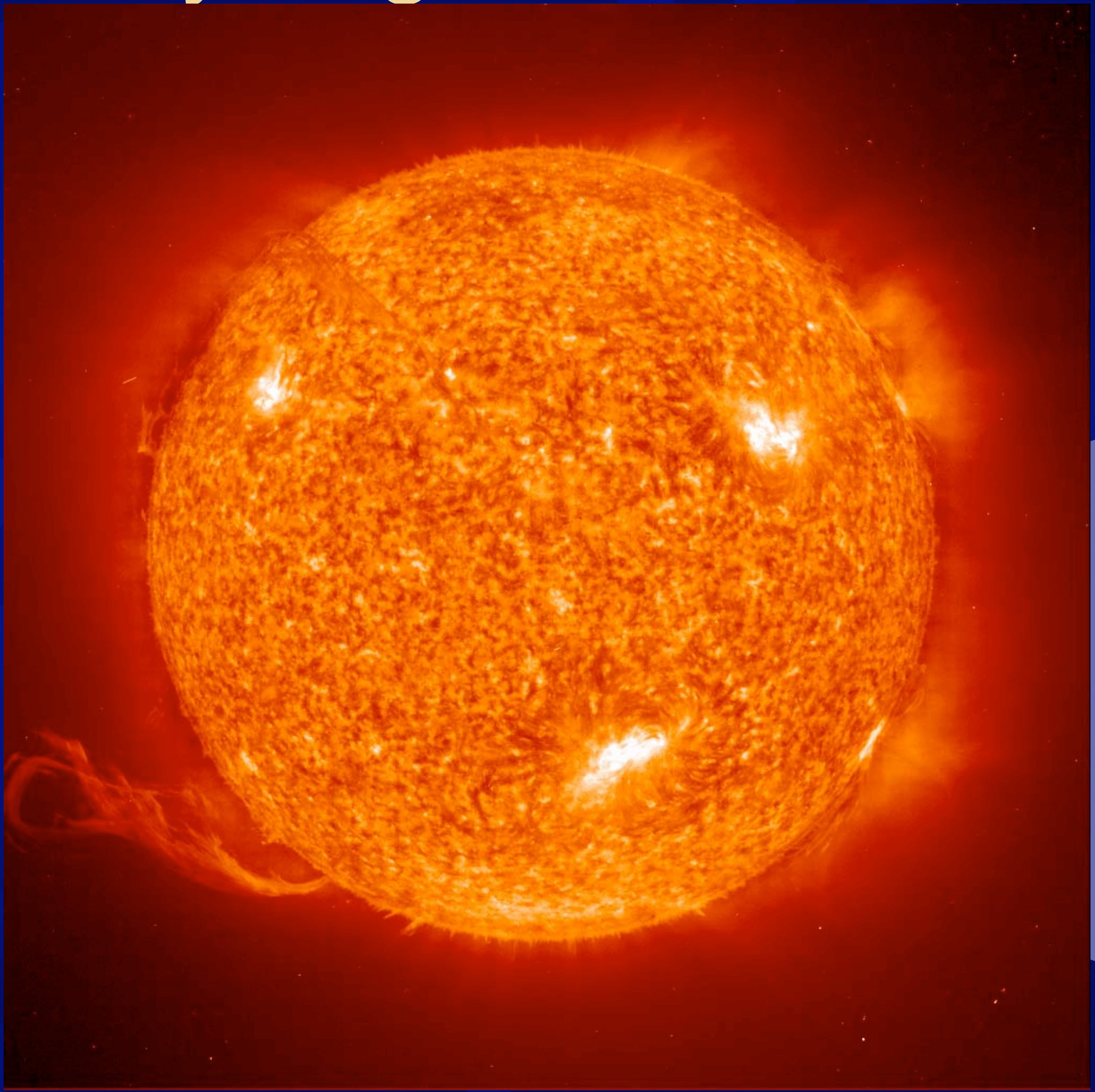
Overview of Talk

- Lens Aberrations
- Diffraction Effects of Apertures
- Image Acquisition Devices
- Resolvability and Sampling Density
- The 70% Rule
- FOV, Focal Length, Pixel Density

The Journey begins here

- 93 million miles away

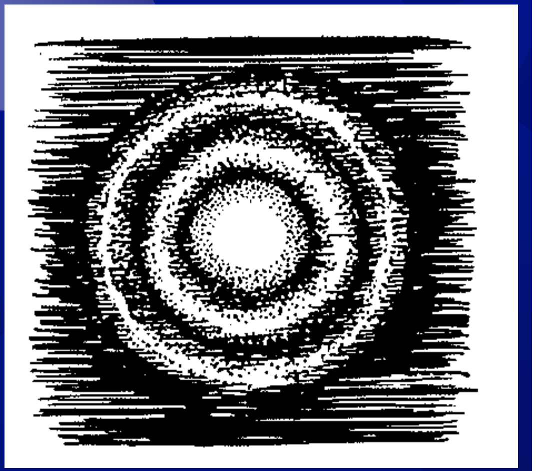


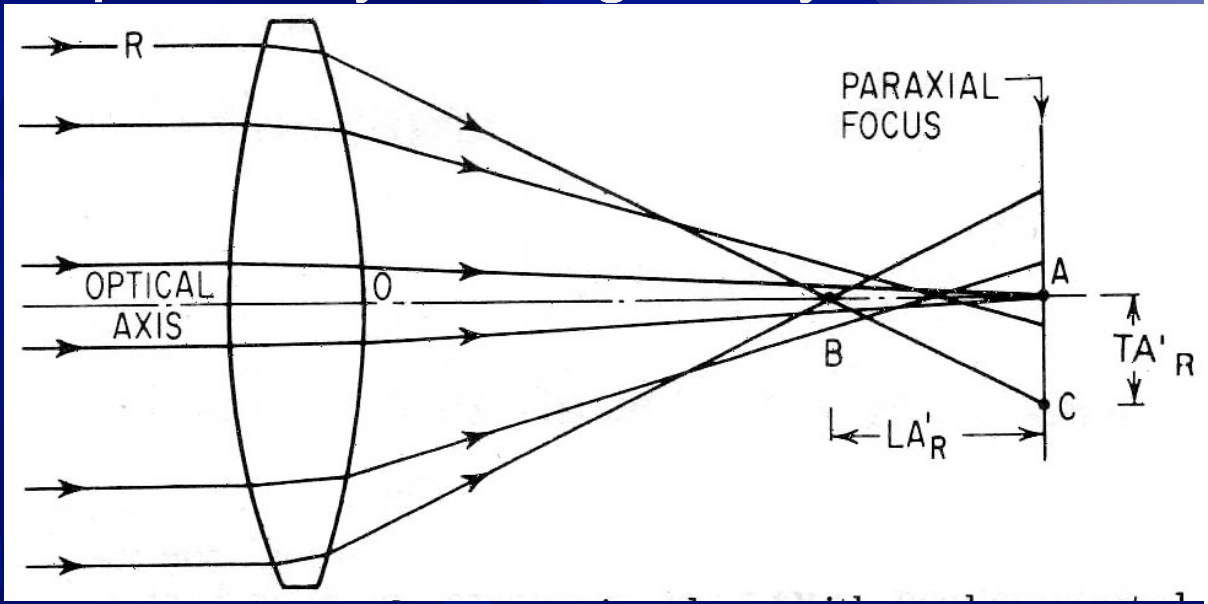
The Journey

- Light interacts with matter
- Light is transported through space and the atmosphere
- Light enters the aperture of the lens

The dual nature of light

- Wave
  - Wavefront propagation analysis
- Particle
  - Geometric optics, ray tracing analysis





Illustrations from Smith, "Modern Optical Engineering"

Lens System

- Compound Lenses
- Point-Spread Function varies
- Aberrations:
  - Spherical aberration, coma, astigmatism, chromatic aberrations
  - Distortion (barrel & pincushion) affects geometry

Spherical Aberration

- Variation of *focus* with aperture
  - either focus at the center, or the edge, but not both

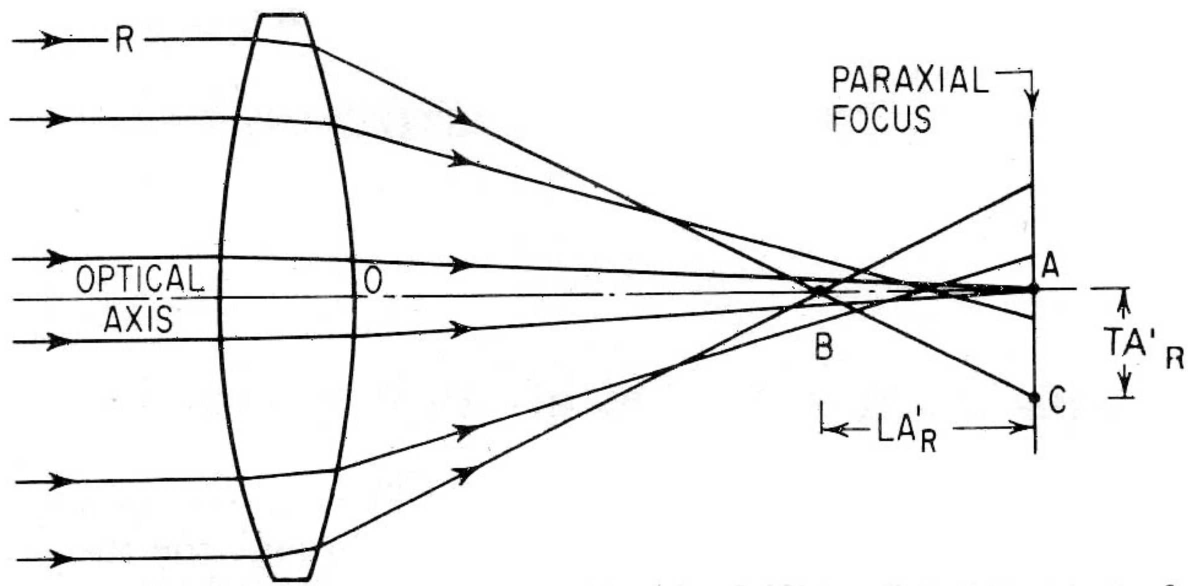


Figure 3.2 A simple converging lens with undercorrected spherical aberration. The rays farther from the axis are brought to a focus nearer the lens.

(from *Modern Optical Engineering*, by Smith 1990)

Coma

- Variation of *magnification* with aperture
  - a point smears into a comet-shaped flare

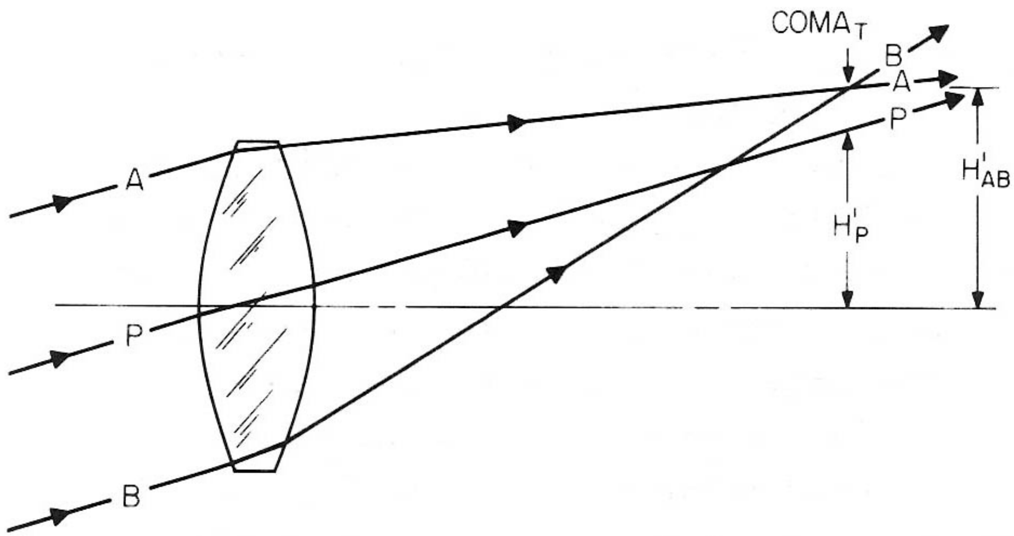


Figure 3.4 In the presence of coma, the rays through the outer portions of the lens focus at a different height than the rays through the center of the lens.
(from *Modern Optical Engineering*, by Smith, 1990)

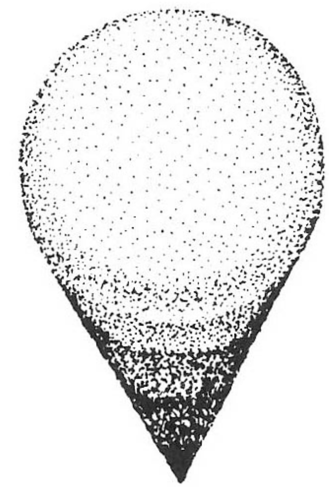


Figure 3.5 The coma patch. The image of a point source is spread out into a comet-shaped flare.
(from *Modern Optical Engineering*, by Smith, 1990)

Astigmatism and Field Curvature

- Non-planar *focal* surface

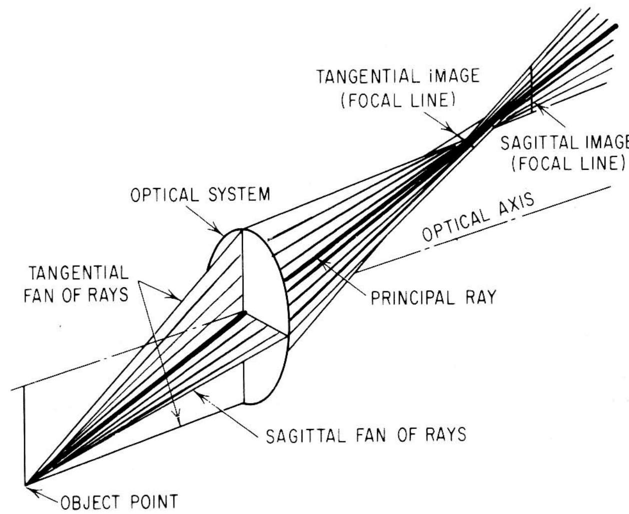


Figure 3.7 Astigmatism.

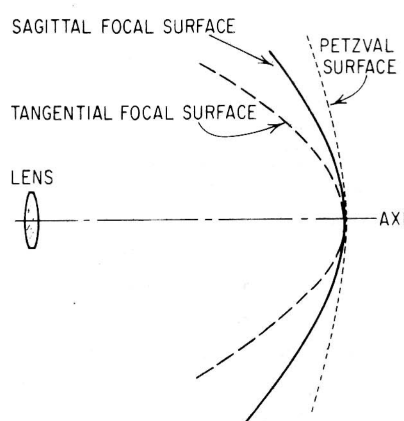


Figure 3.8 The primary astigmatism of a simple lens. The tangential image is three times as far from the Petzval surface as the sagittal image.

(from *Modern Optical Engineering*, by Smith, 1990)

Chromatic aberrations

- Variation of aberrations with wavelength
- Magnification aberration is easy to correct

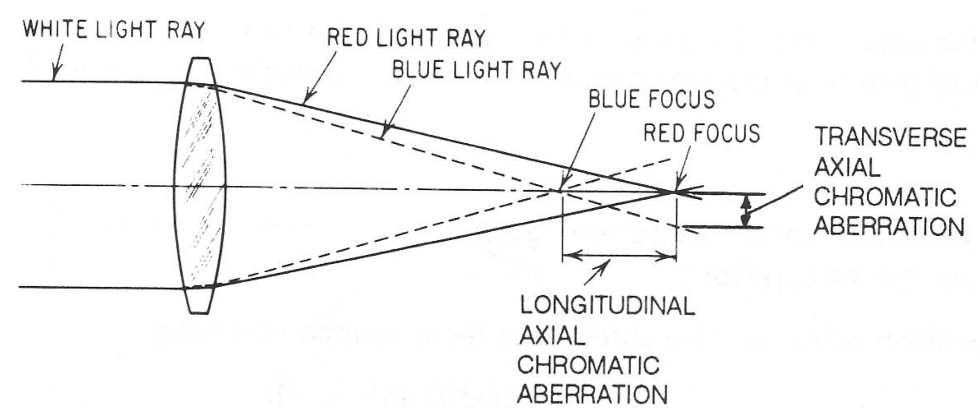


Figure 3.10 The undercorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.
(from *Modern Optical Engineering*, by Smith, 1990)

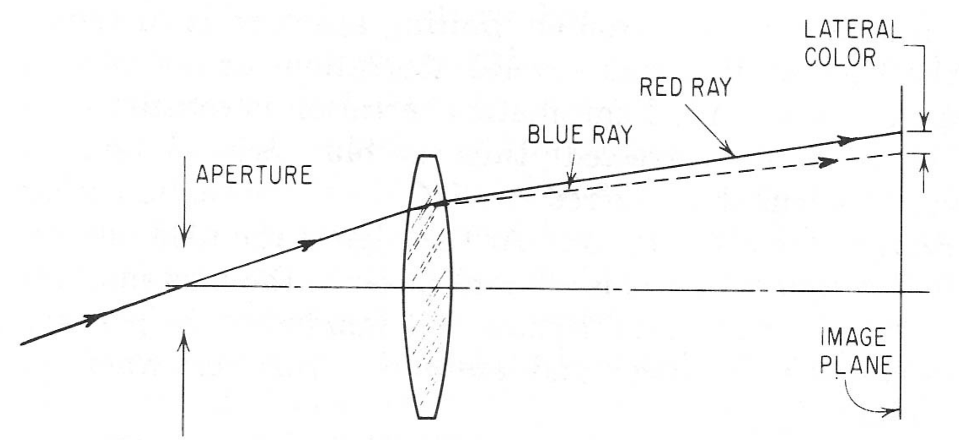


Figure 3.11 Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.
(from *Modern Optical Engineering*, by Smith, 1990)

Geometric distortion

- East to correct

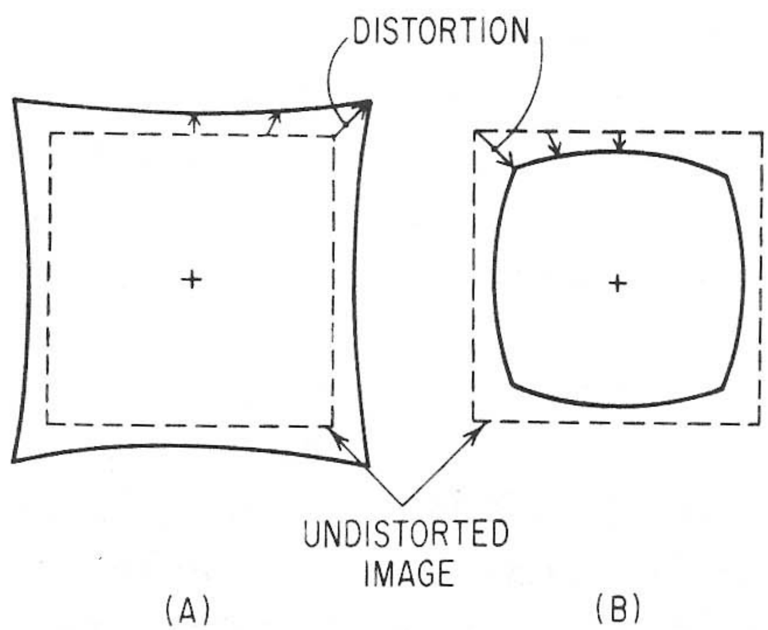


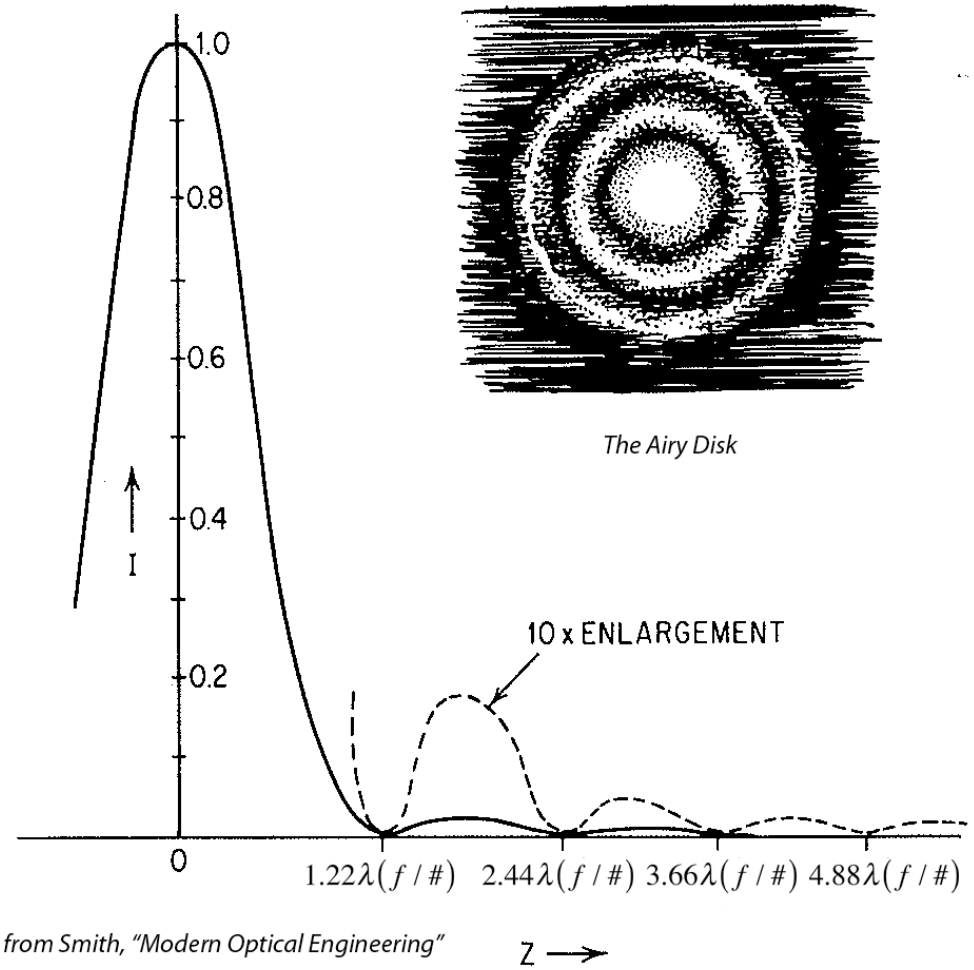
Figure 3.9 Distortion. (a) Positive, or pincushion, distortion. (b) Negative, or barrel, distortion. The sides of the image are curved because the amount of distortion varies as the cube of the distance from the axis. Thus, in the case of a square, the corners are distorted $2\sqrt{2}$ as much as the center of the sides.

(from *Modern Optical Engineering*, by Smith, 1990)

Wave Optics

- Aperture diffraction
- Worse with smaller aperture
- Airy Disk

$$I = I_0 \left[\frac{2J_1(m)}{m} \right]^2$$



from Smith, "Modern Optical Engineering"

Diffraction-Limited Resolution

- Lord Rayleigh's criterion

$$Z = \frac{0.61\lambda}{NA} = 1.22\lambda(f/\#)$$

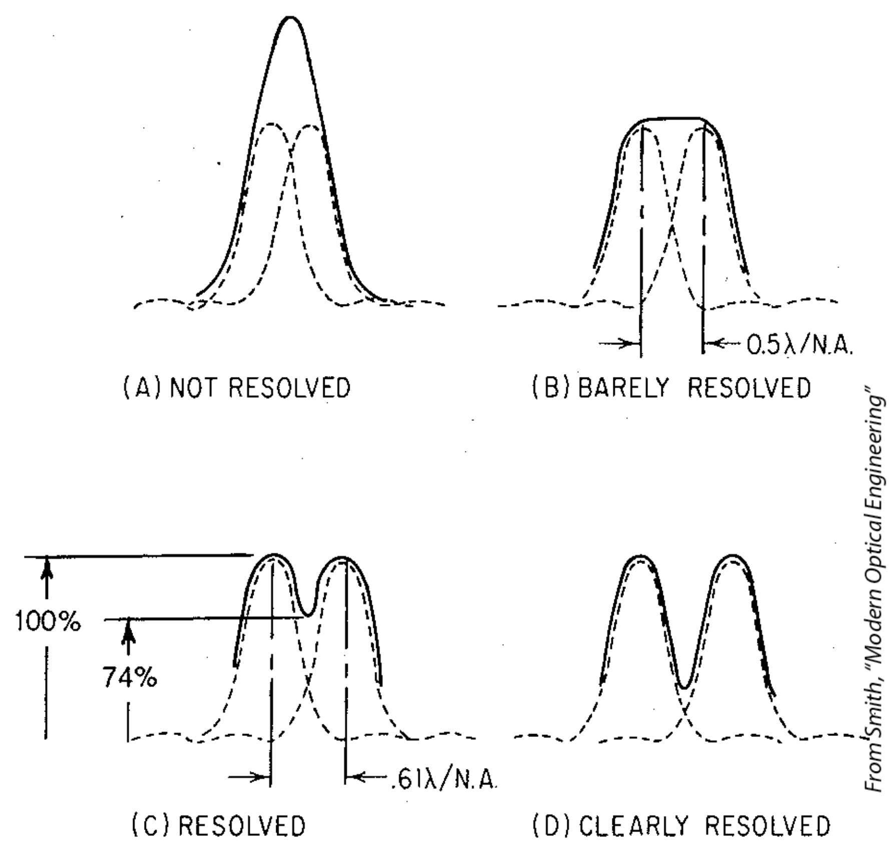


Figure 6.17 The dashed lines represent the diffraction patterns of two point images at various separations. The solid line indicates the combined diffraction pattern. Case (b) is the Sparrow criterion for resolution. Case (c) is the Rayleigh criterion.

From Smith, "Modern Optical Engineering"

Implications for Cameras

- Visible light ~400-700 nm
- For red light @ *f*/11

  $$Z = 1.22\left(700 \times 10^{-9}\right)(11) \approx 9.4\mu m$$

- For blue light @ *f*/11

  $$Z = 1.22\left(400 \times 10^{-9}\right)(11) \approx 5.4\mu m$$

- pixel sizes: 6 μm (typical DSLR)
  2.2-3.2 μm (cells, point&shoot),
  1.75 μm (Micron CMOS)
- The optics *can't* deliver RGB pixels at *f*/11!
- The optics can barely deliver Bayer pixels to DSLR at f/11 (with 1.4X pixel size factor)

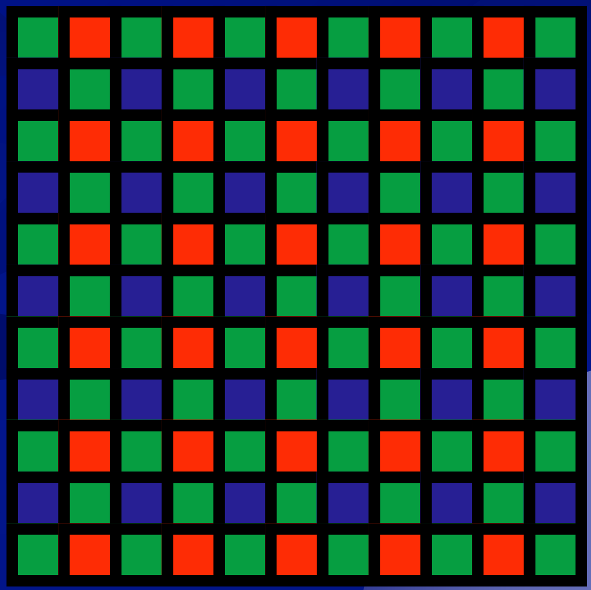
Image Acquisition Devices

- Film
- CCD sensors
- CMOS sensors
- Splitters / Layers / Bayer
- 2D array / 1D array
- Anatomy of a CCD

Film

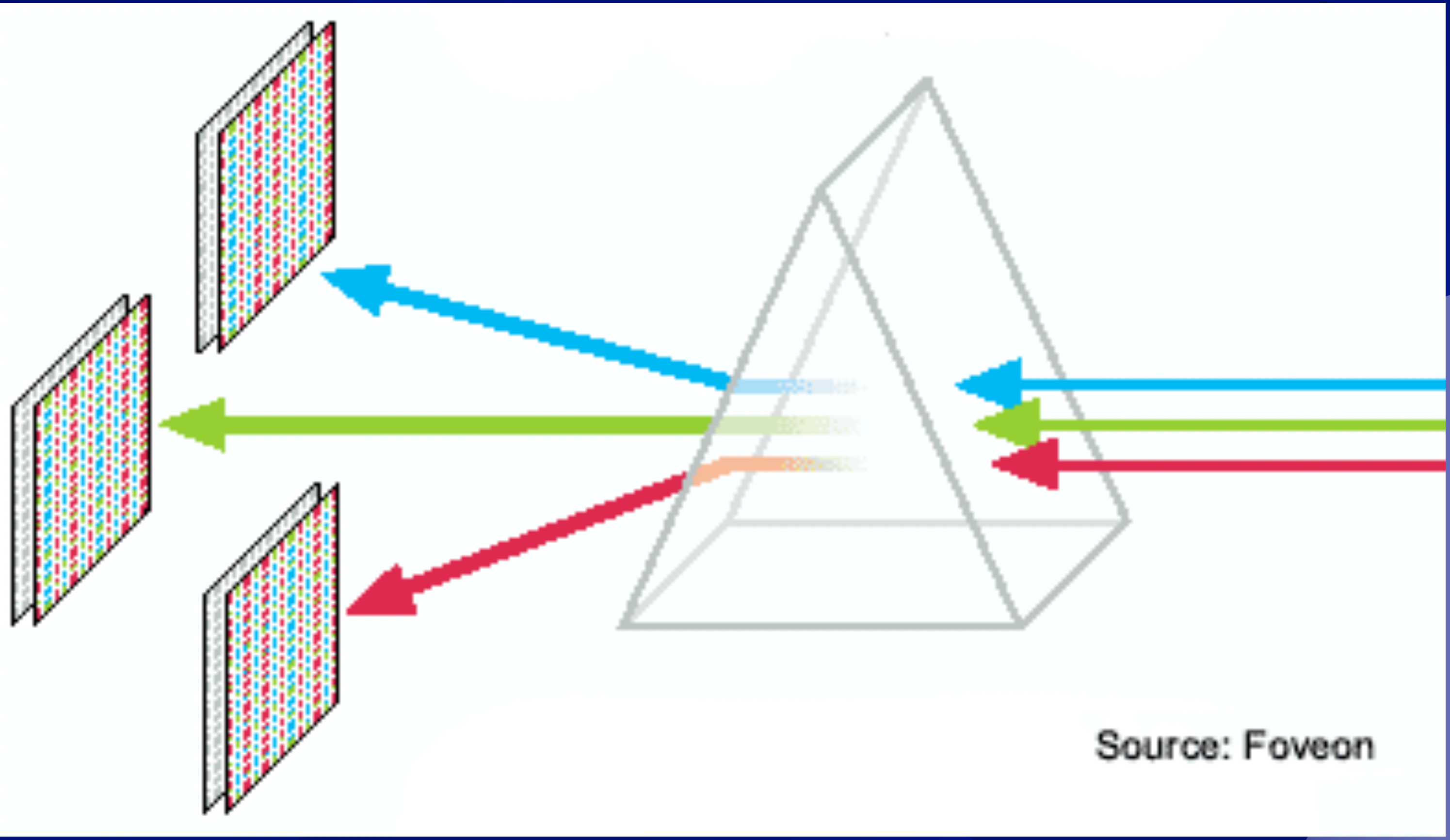
- 3 Layers
- Color-sensitive grain in each layer
- Grain size and density determine resolution

Common Digital CCD / CMOS Sensor



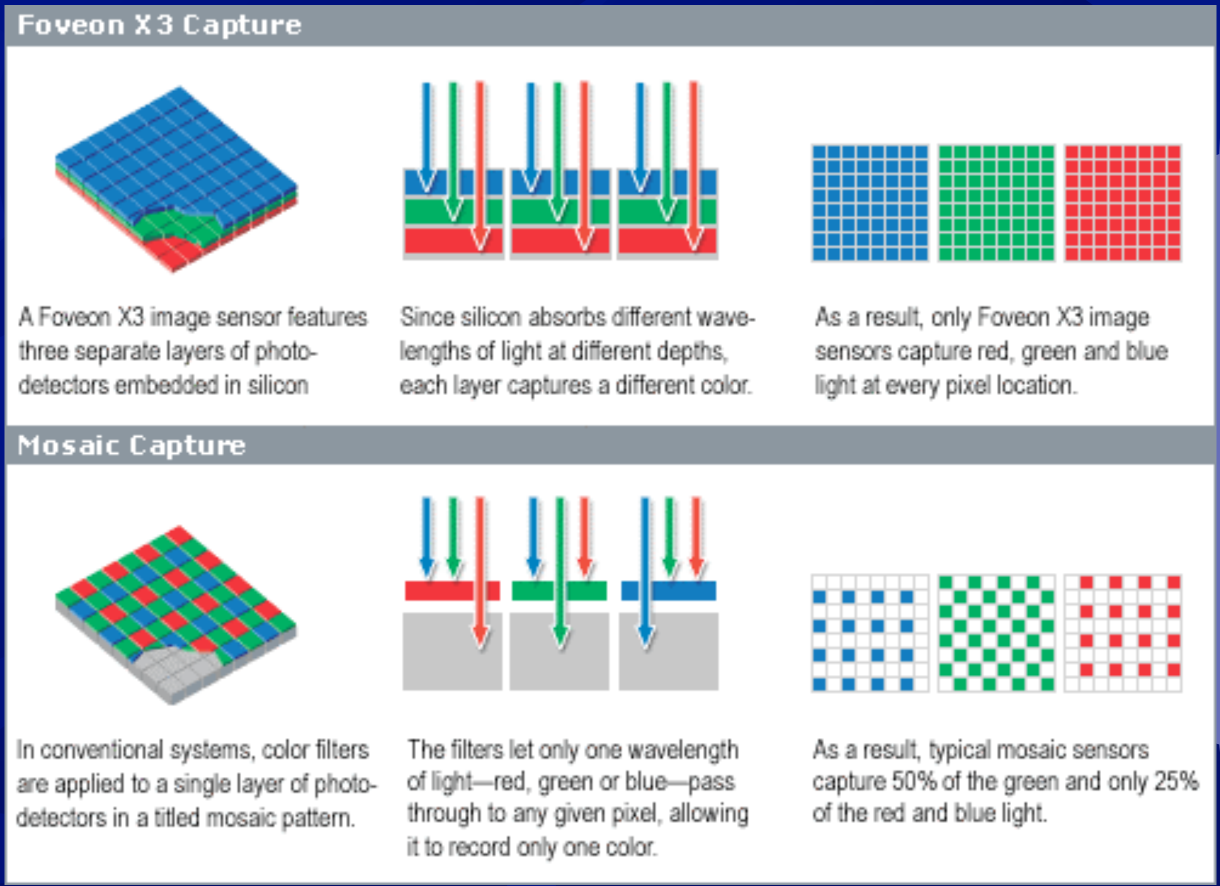
- Bayer Sampling Pattern
  - No RGB pixels
  - Only R, G, and B pixels
- Convert to RGB by interpolation
- If 1000 pix/mm, then 707 G pix/mm and 500 R and B pix/mm, i.e. R and B are sampled every 2 pixels, G is sampled every 1.4 pixels
- 8 Mpix CCD has 4 Mpix G, 2 Mpix R&B, 2 Mpix ≤ RGB ≤ 4 Mpix

3 CCD Sensors



Layered CMOS Sensors

- R, G & B pixels at each location!

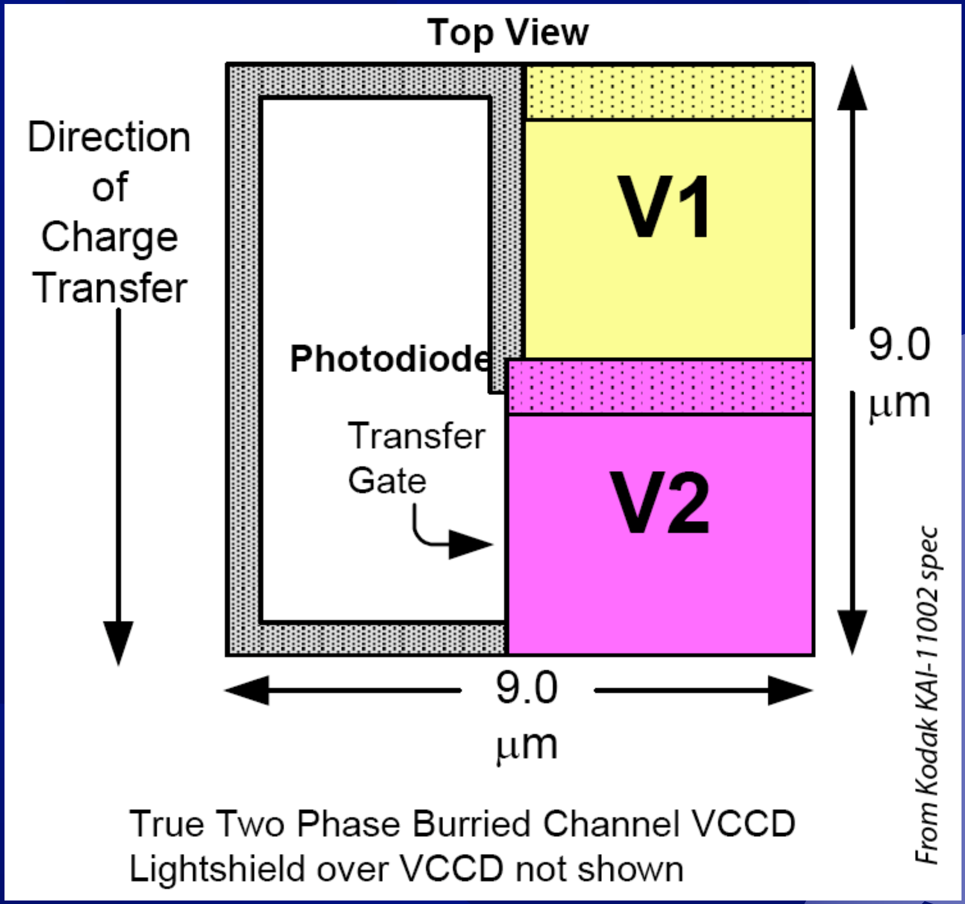


Panoramic (cylindrical-scan) cameras

- Rotate a linear (1D, not 2D) CCD imaging array
- Rotate too fast ==> aliasing
- Rotate too slow => blurring because CCD cell overlaps

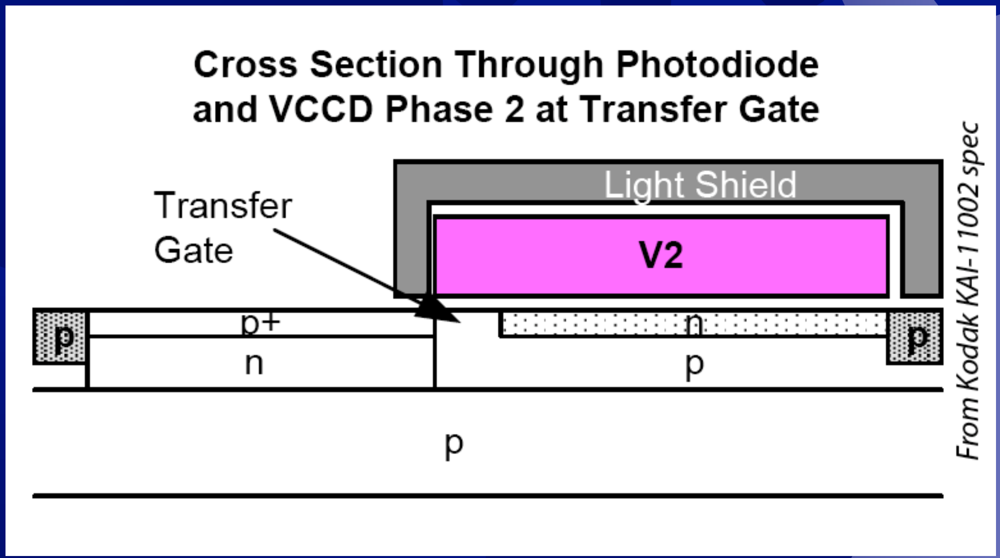
Anatomy of an interline CCD (plan view)

- Active area is a small part of the total cell
- E.g. 8x4 μm in 9x9 μm cell
- Warning: 2X faster *aliasing* potential!
- Warning: Tossing half the light!



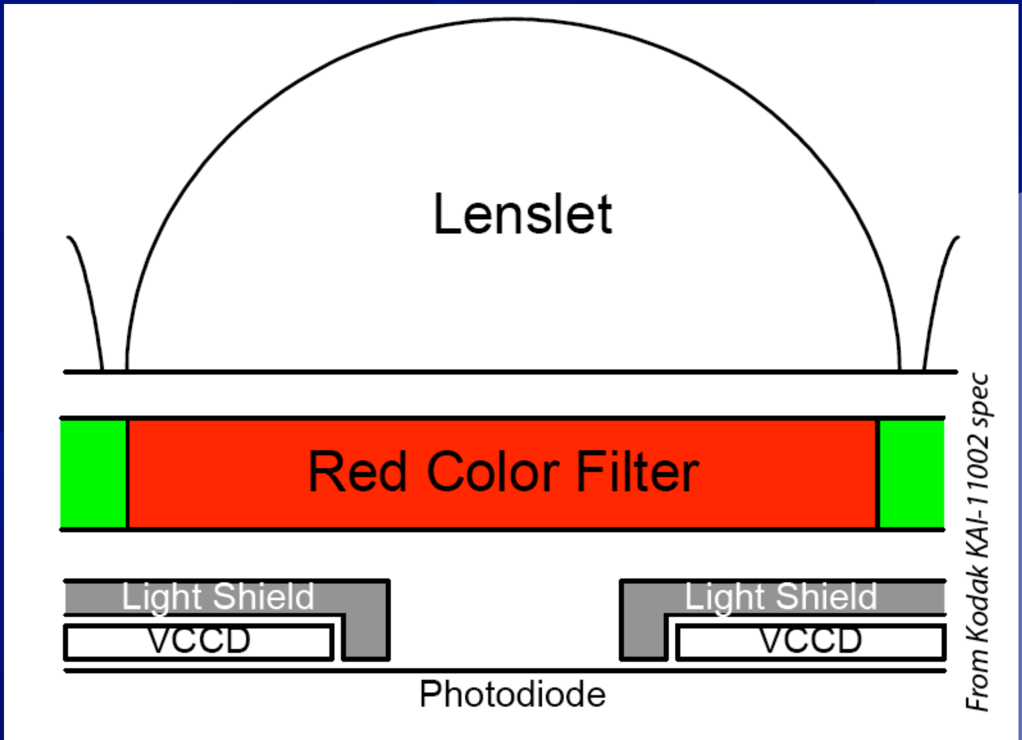
Anatomy of a CCD (cross section)

- Pixel takes cover under light shield for readout



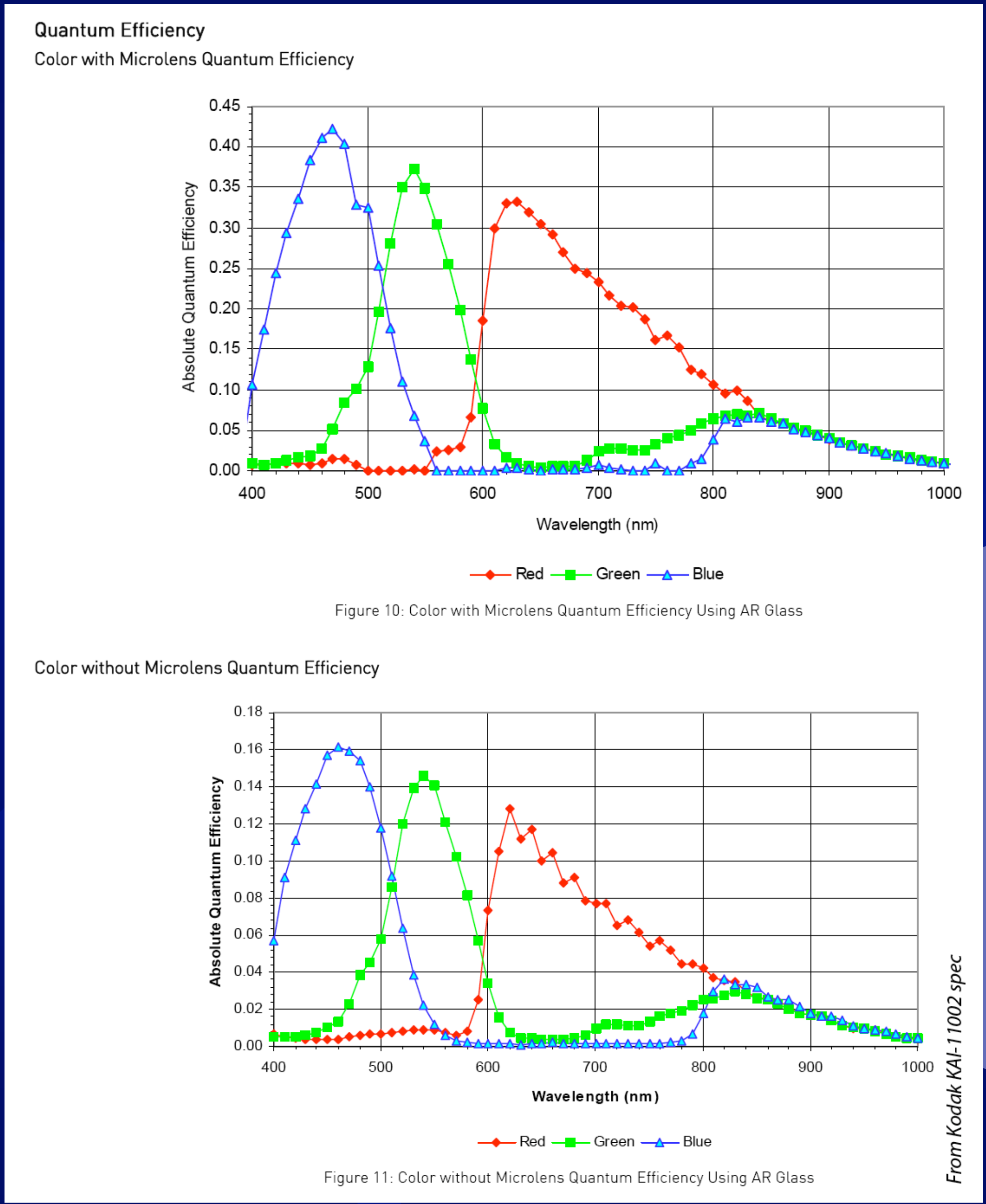
Recovering the light

- Lenslets redirect light into the photodiode well (horizontally)



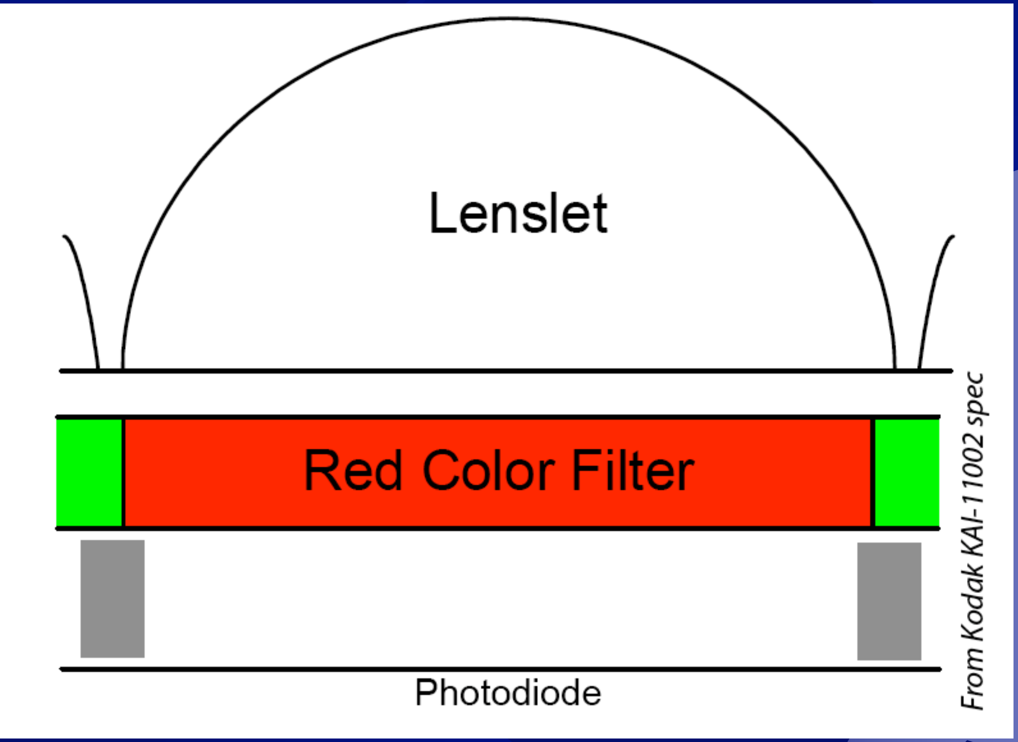
Recover Light

- 3X more light with lenslets!



Color Pollution

- Rays from adjacent color cells enter obliquely



Resolution

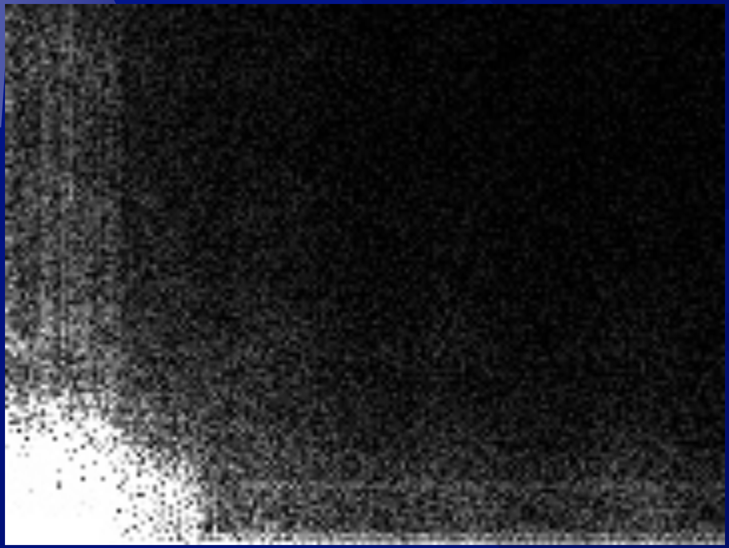
- The difference between resolution and pixel sampling density
- Determining resolution
- Intimate relationship between resolution and focal length

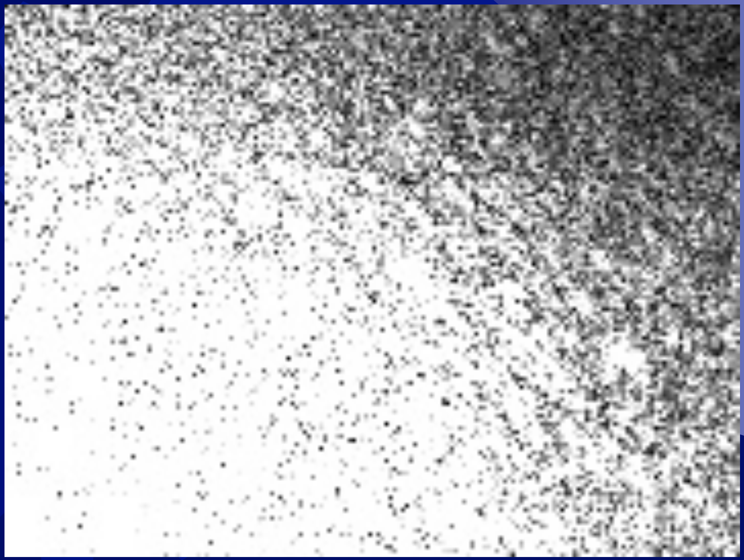
What is the resolution?

- Both images have the same number of pixels (360x270).

Determining Resolution with the Fourier Transform

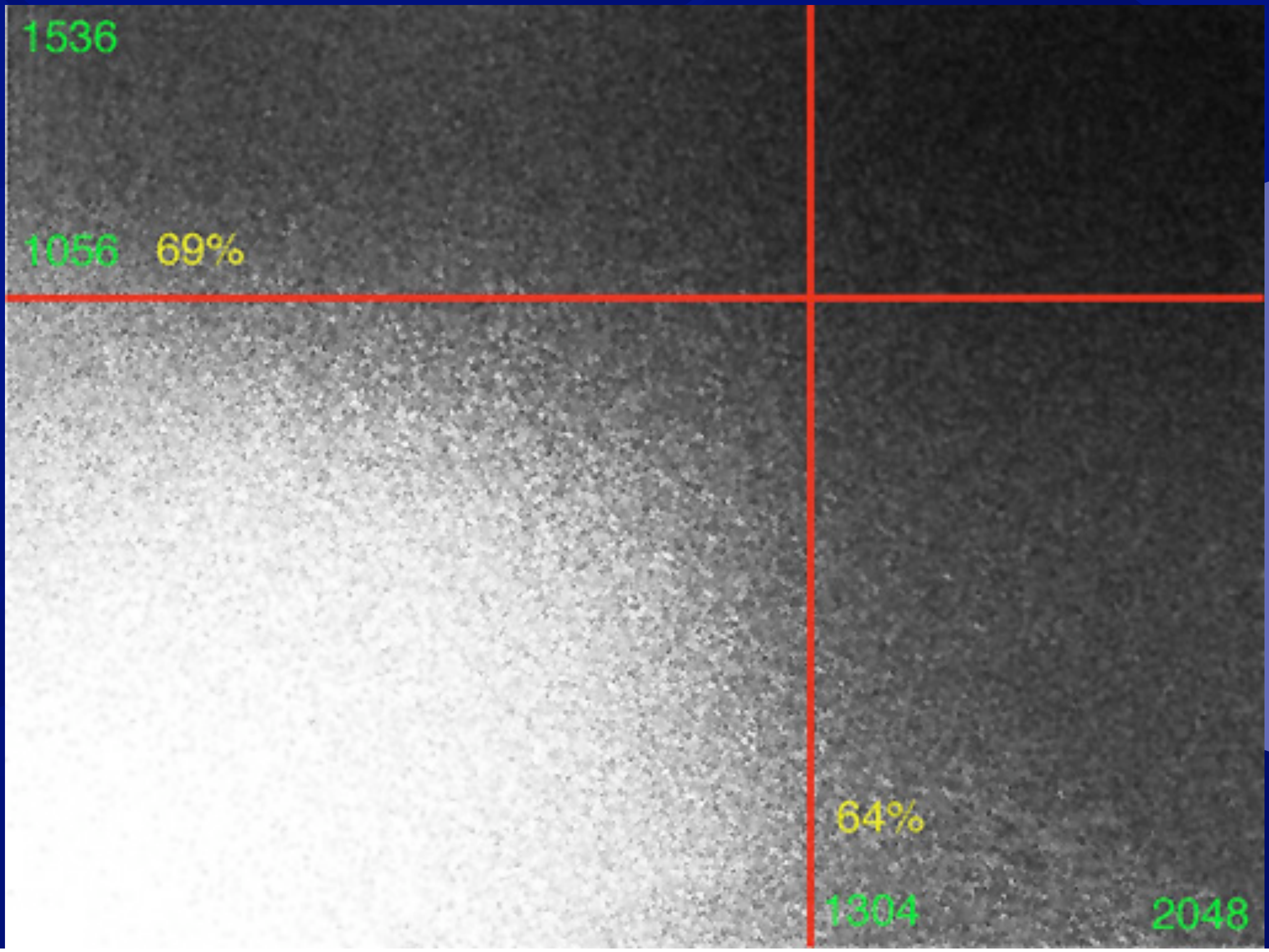
- Bright ==> high energy
- Horizontal & vertical frequency (detail) increases to the right and up





The Empirical 70% Rule

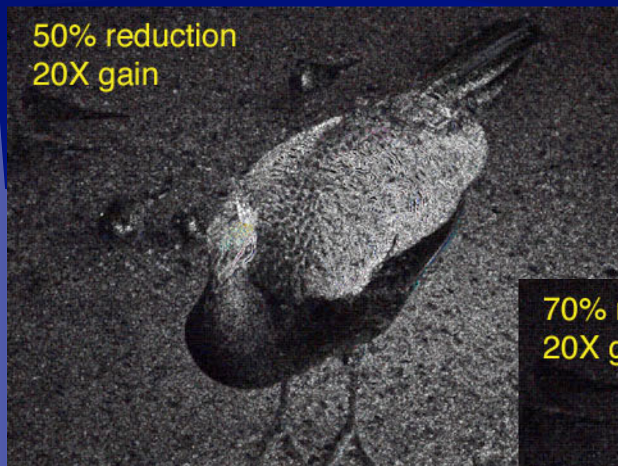
- Negligible loss of quality when shrunk by 70%
- Half the pixels

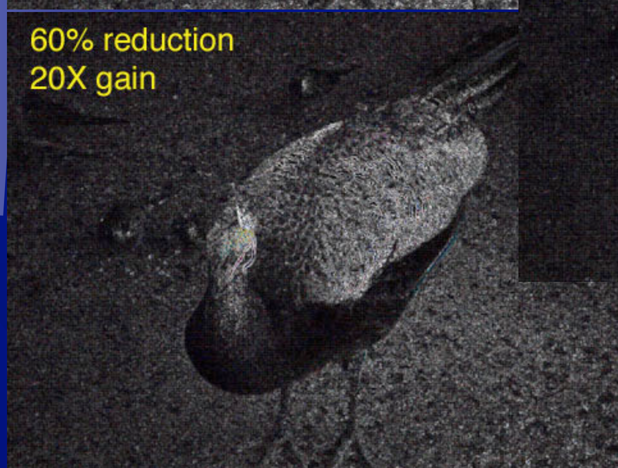


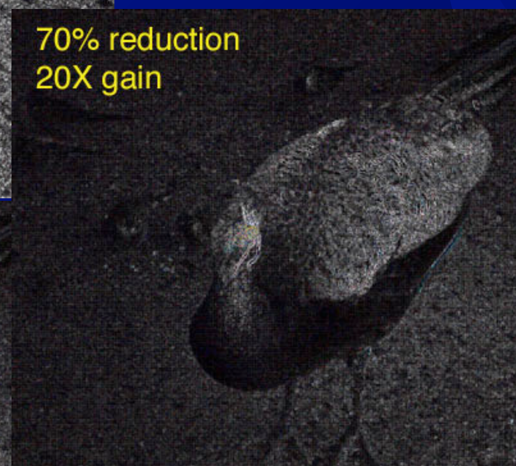
Determining Resolution by Resizing

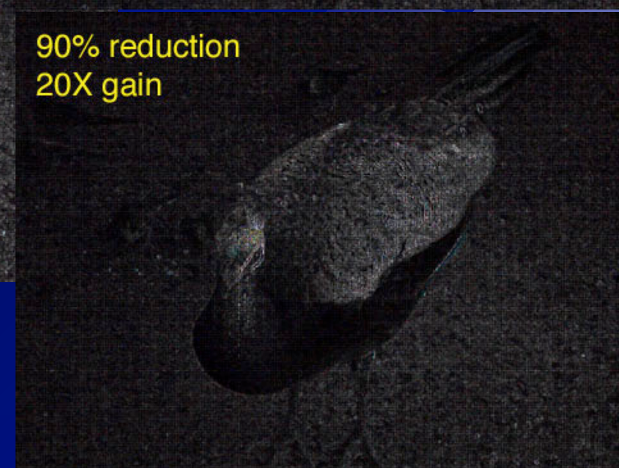
- Shrink, expand, subtract, amplify:
  - Reduce size
  - Increase back to original size
  - Apply Image > Difference
  - Enhance contrast

Resolution in Photoshop









Units of Panorama Resolution

- How do you compare the resolution of a cylindrical, cubic, and spherical panorama?
- Pixels?
- Pixels / inch?
- Pixels / degree!

Panorama resolution (pix/°)

- Cylindrical or spherical
  circumference / 360
- Round 180° fisheye
  (diameter - 1) / 180
- Cubic
  (faceWidth - 1) * π / 360

- E.g. 2496 pixel cylindrical circumference =
  1249 pixel 180° fisheye diameter
  795 pixel cube face =
  6.9 pixels / degree

Definitions: panoramic resolution and focal length

- Panoramic resolution: the angular pixel density as determined by the focal length.
- The focal length: the distance to the imaging surface at the center of projection.
- More details at http://www.worldserver.com/turk/quicktimevr/panores.html

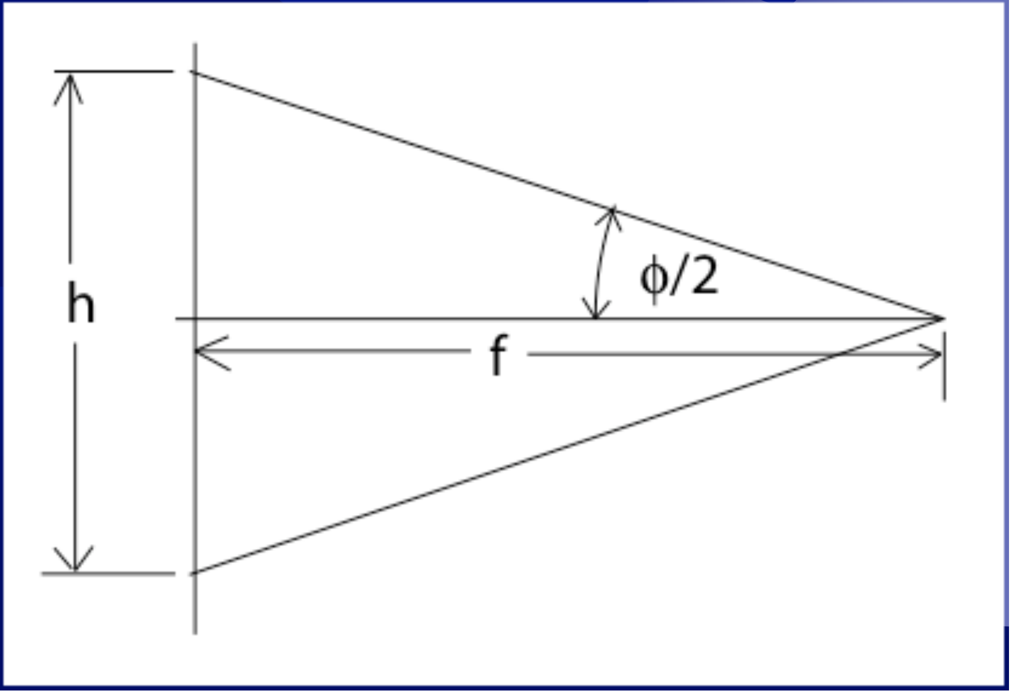
Focal Length & Resolution

- Intimate relationship between the focal length and panoramic resolution in pixels per degree.
- Lens focal length in mm (per radian)
- Sensor: pixels / mm
- (pix/mm)*(mm/rad)*(rad/deg)=pix/deg

  sensor   focal length   unit conversion

Why is focal length mm/radian?

- From elementary trigonometry: $\tan(\phi/2) = h/(2f)$
- With small ϕ, expressed in radians, $\phi/2 \approx h/(2f)$
- Or $f \approx h / \phi$ (mm/rad)



Conclusion

- Know where your pixels have been
- Pixel sampling density ≠ resolution
- Don't use more pixels than you need
- Apply the 70% rule
- Focal length = pixel sampling density (resolution)