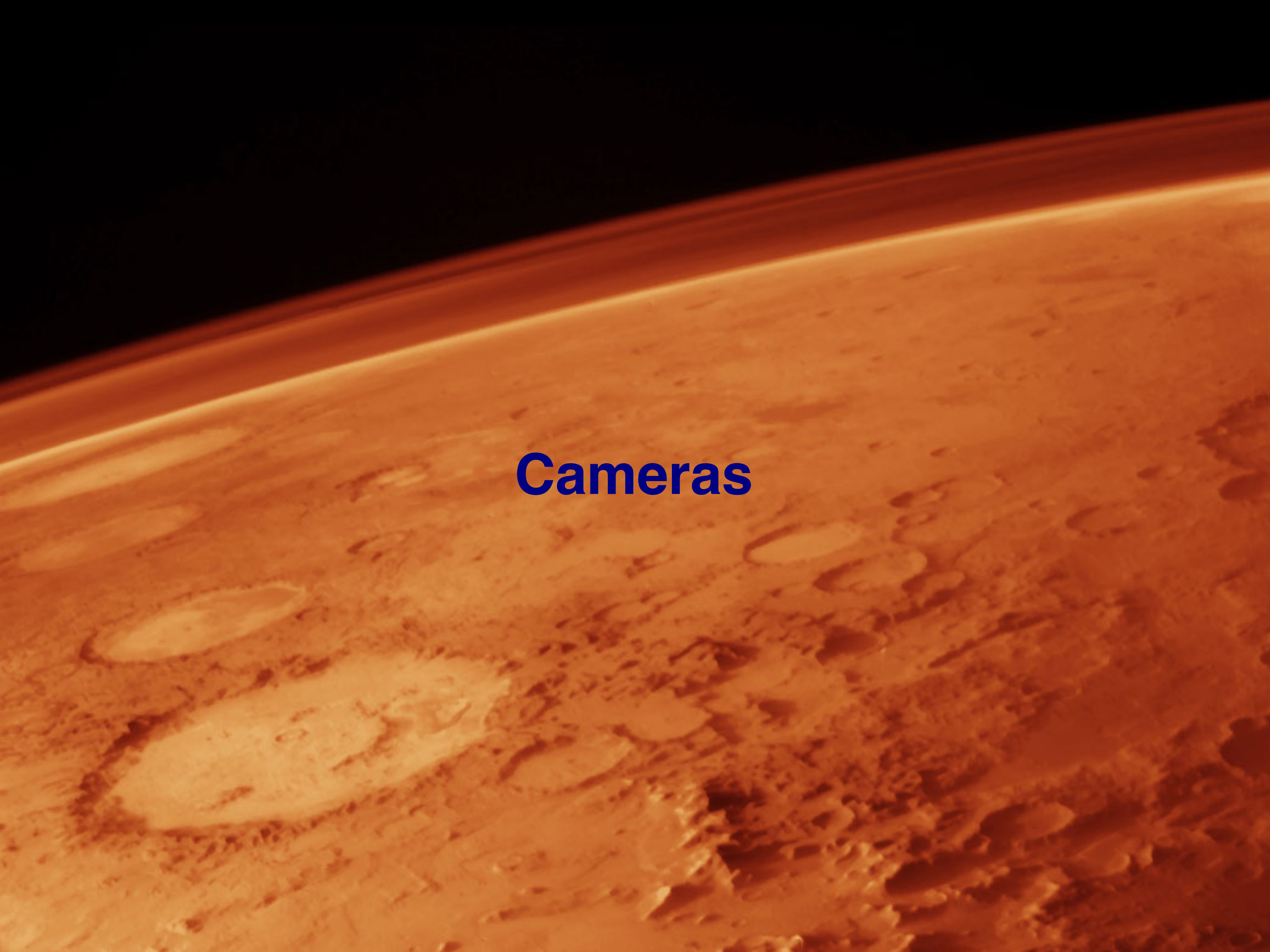
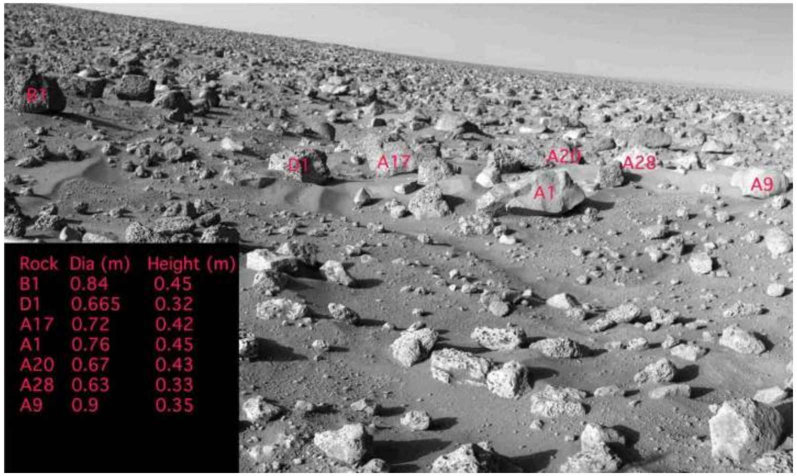


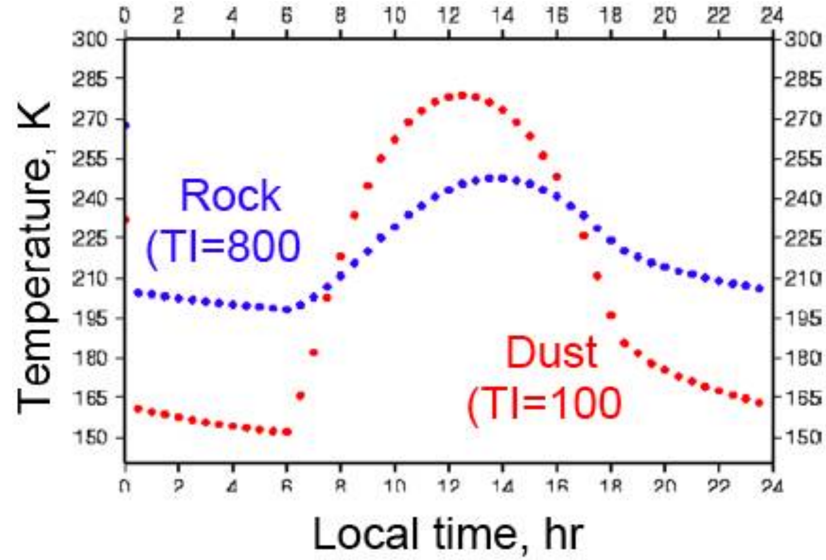
Cameras

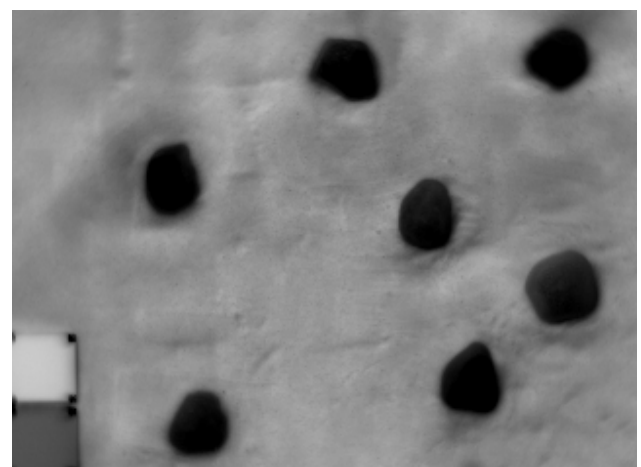
Announcements

- First homework is on the wiki. Due by Tuesday (Monday is a holiday).
  - Hand in at start of class or email to TA (andrea@cds.caltech.edu)
- Will take a poll on-line to decide TA office hours. URL for the poll will be announced via the class mailing list -> make sure you've signed up.

Heat Transfer Characteristics: Thermal Inertia

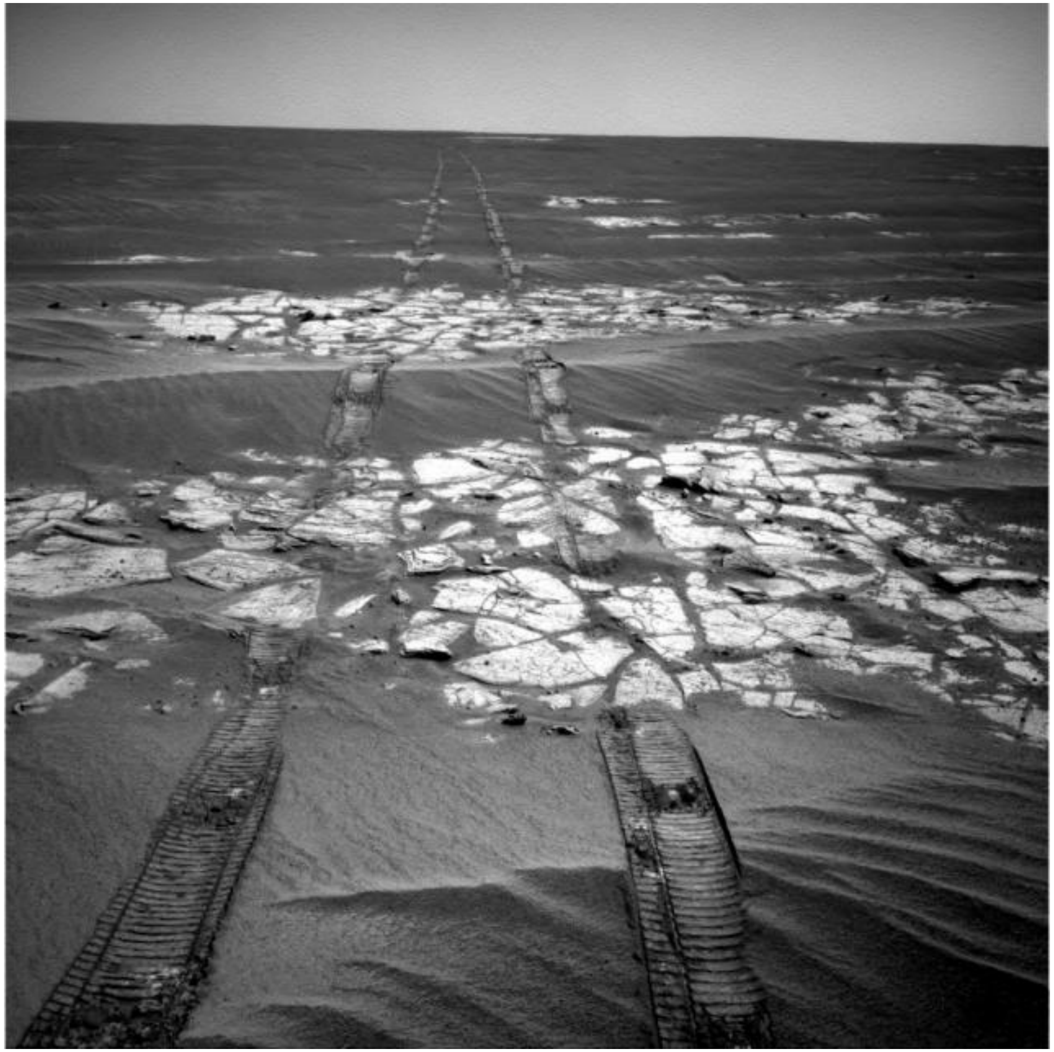






(U. Arizona)

Open Problem:
Terrain Classification for Mars Rovers

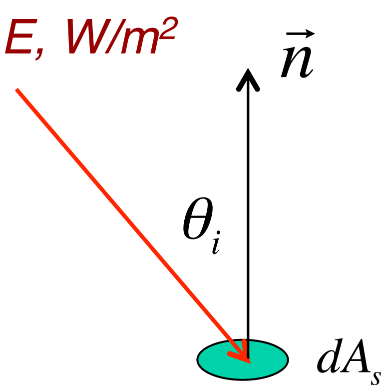


Rovers sometimes get stuck in the ripples; easily cross the bedrock

How to discriminate the two reliably at low cost for sensors and processing?

Surface Irradiance for Various Lighting Conditions

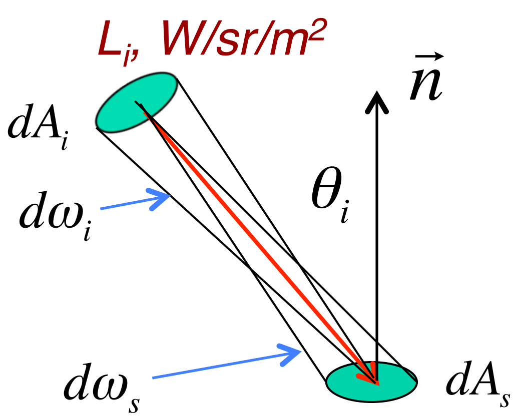
Point source at infinity (e.g. sun)



$$E_i = E\cos\theta_i$$

$$d\Phi_i = E_i\, dA_s$$

Extended source at range r

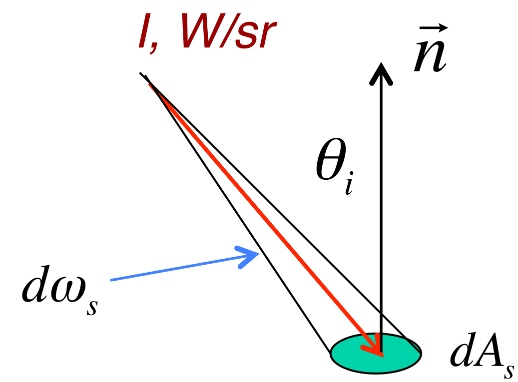


$$d\omega_s = \frac{dA_s\cos\theta_i}{r^2}, \quad d\omega_i = \frac{dA_i}{r^2}$$

$$d\Phi_i = L_i\, d\omega_s\, dA_i = L_i\, d\omega_i\, dA_s\cos\theta_i$$

$$E_i = \frac{d\Phi_i}{dA_s} = L_i\cos\theta_i\, d\omega_i$$

Point source at range r



$$d\omega_s = \frac{dA_s\cos\theta_i}{r^2}$$

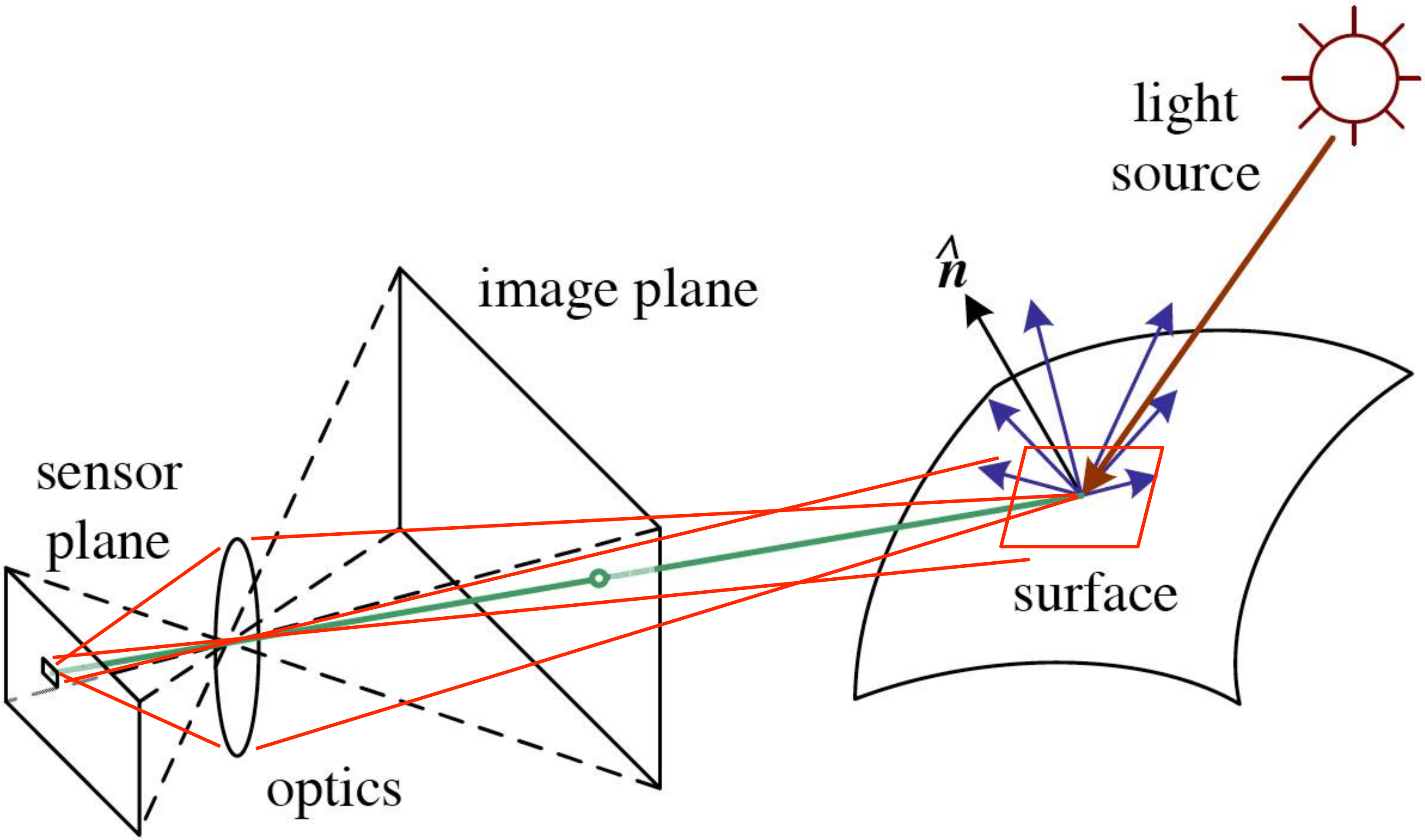
$$d\Phi_i = I\, d\omega_s$$

$$E_i = \frac{I\cos\theta_i}{r^2}$$

Same for extended source at infinity (e.g. sky)

Recap and Where We're Going

Goal: be able to model the light reaching a pixel in the image or to invert this to estimate scene properties from measured image brightness



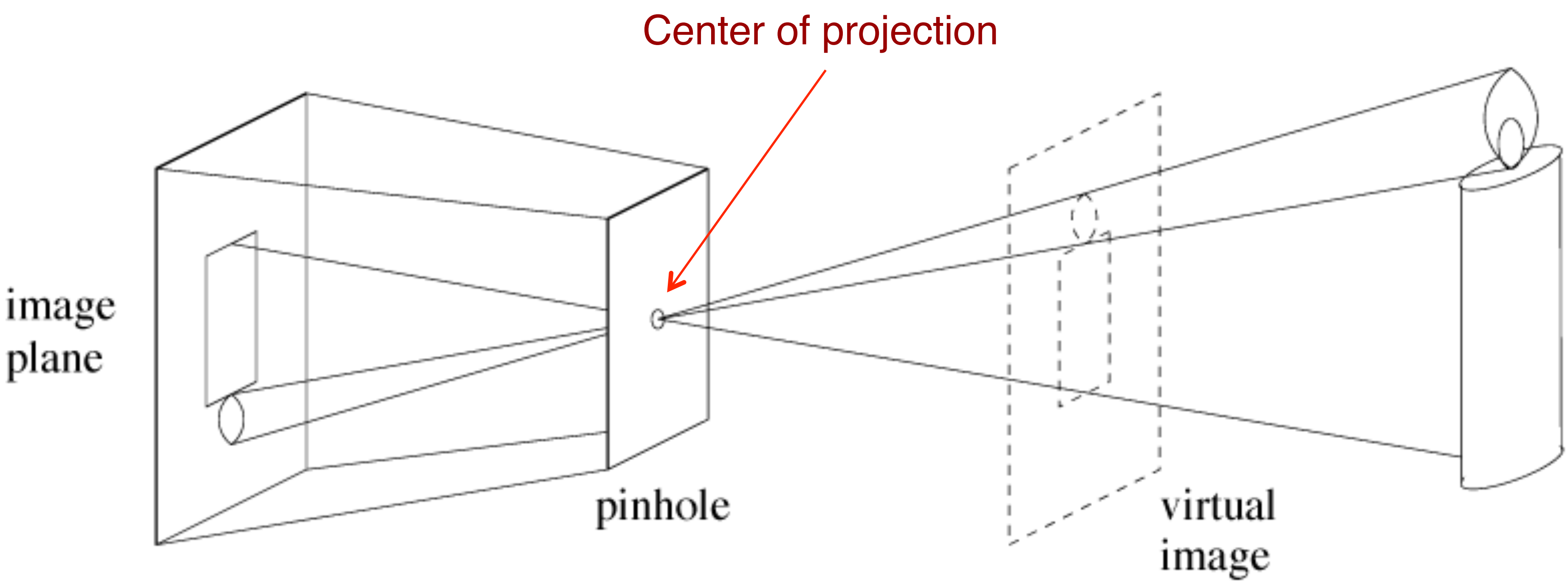
This Lecture

- Basic optics:
  - Pinhole camera model
  - Thin lens
  - Thick lens
- Camera electronics
  - Focal planes: CCD vs CMOS, interline vs frame transfer, etc.
  - Noise models
  - Image processing pipeline within cameras
- Color image acquisition and representation
- Cameras outside the visible spectrum

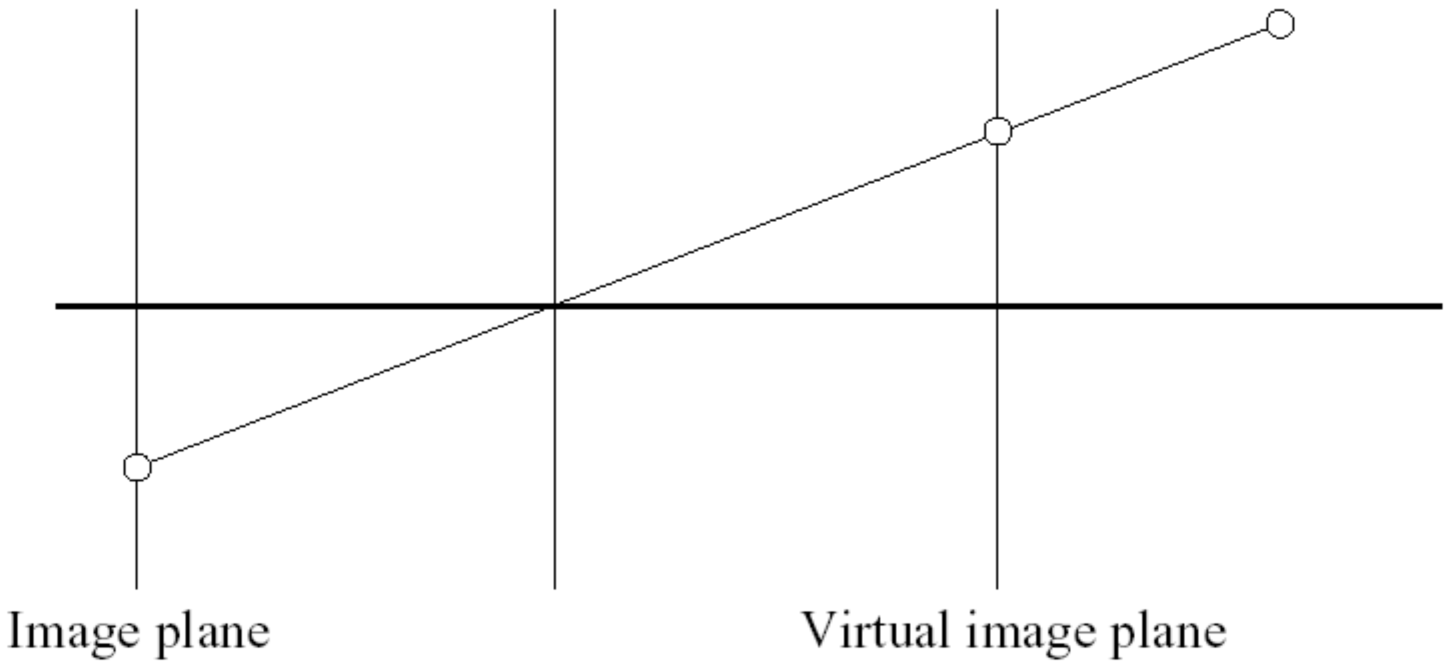
In Context with Coming Lectures

- Today: cameras: optics, detectors
- Thursday: geometric camera modeling and calibration (Adnan Ansar)
- Jan 18: feature detection and matching (Roland Brockers)
- Jan 20: feature quality assessment outlier detection (Yang Cheng)
- Reading material:
  - Today: Szeliski sec. 2.2.3, 2.3, Forsyth ch. 1
  - Thursday: Szeliski sec. 2.1, 6.3; optional: Forsyth chs. 2, 3
- Additional reference material:
  - E. Hecht, *Optics*
  - J. Nakamura, *Image Sensors and Signal Processing for Digital Still Cameras*

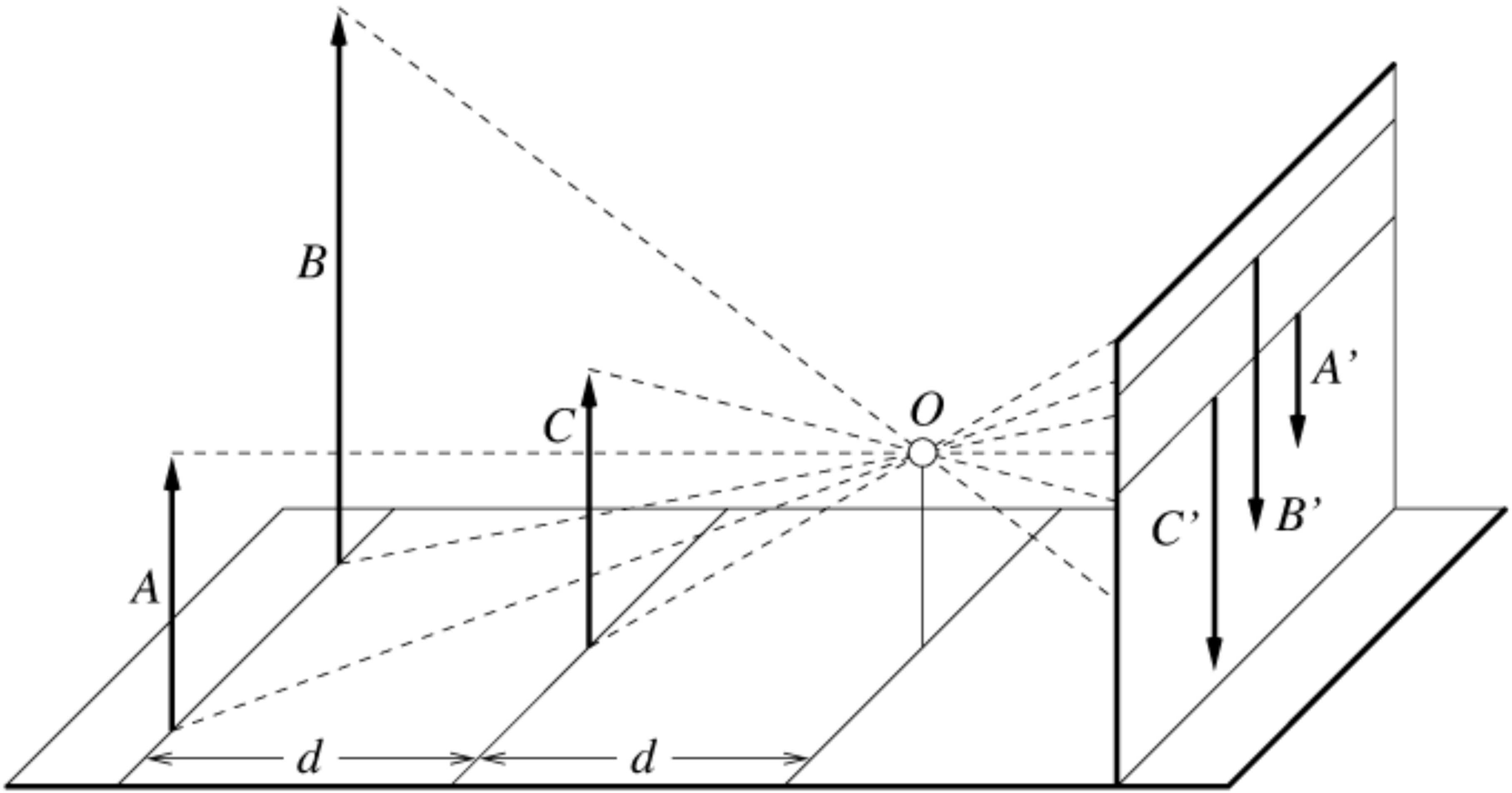
Pinhole Camera



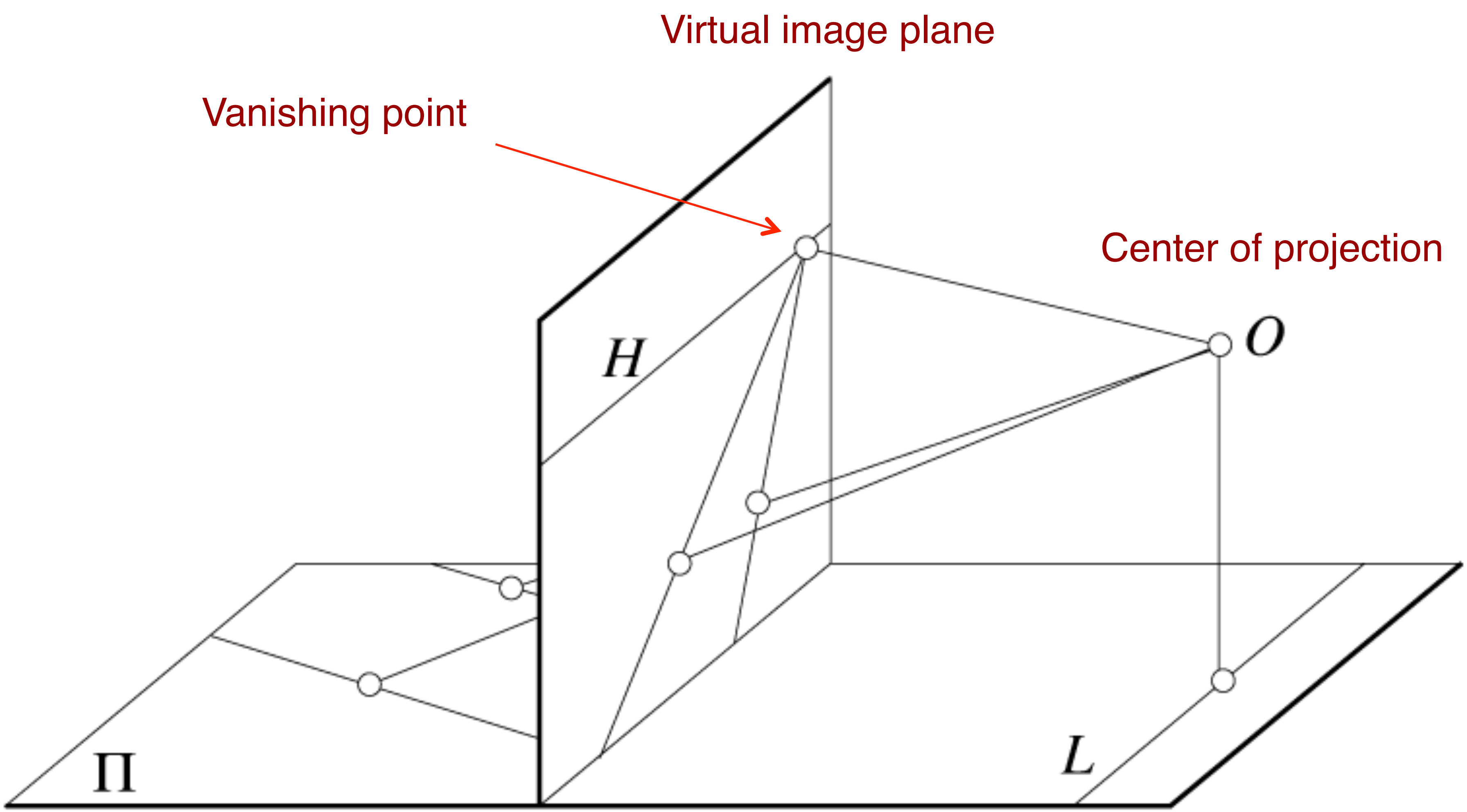
Equivalent Model with Virtual Image Plane



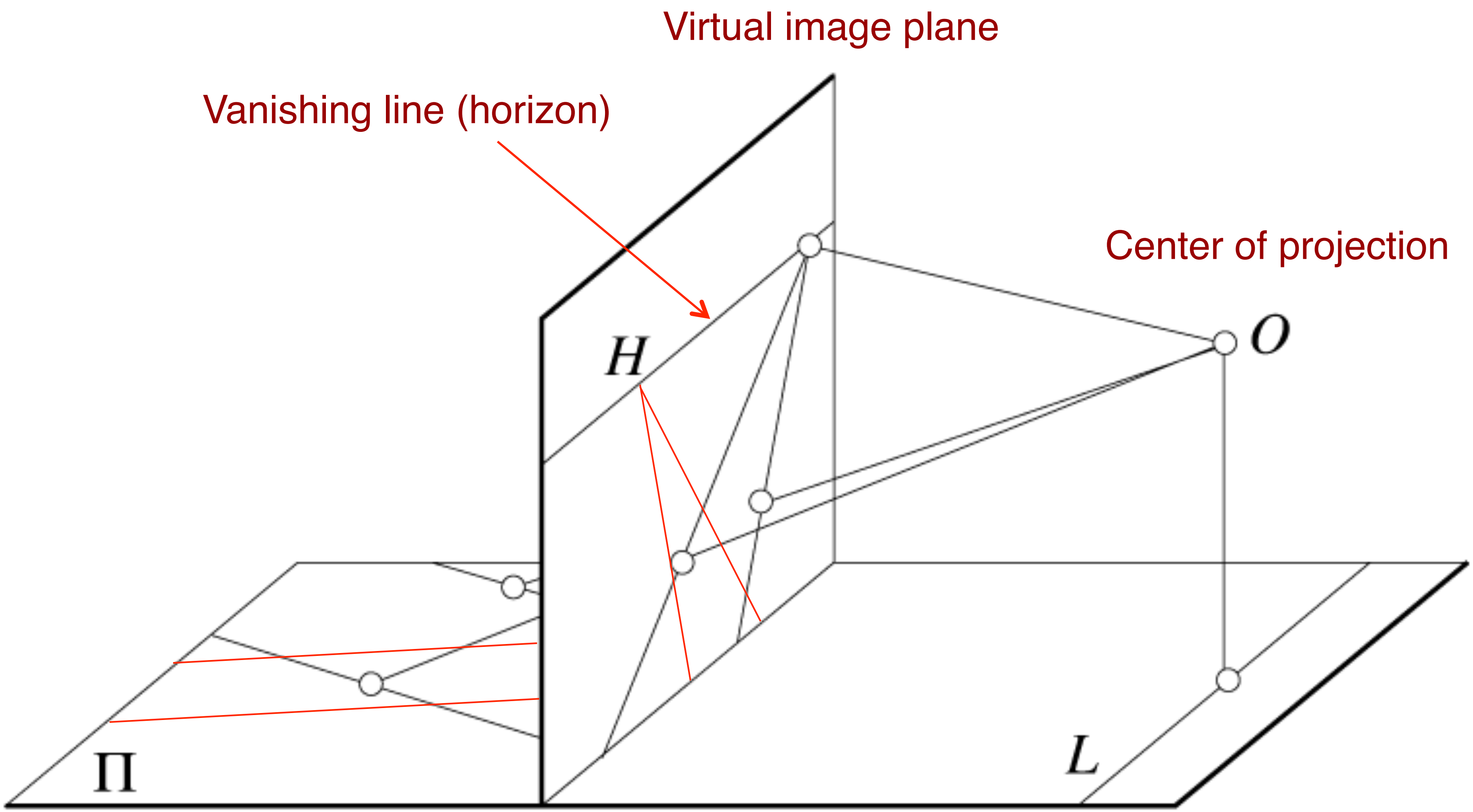
Basic Geometric Properties: (1) Distant Objects are Smaller



Basic Geometric Properties:
(2) Lines Project to Lines and Parallel Lines Meet



Basic Geometric Properties: (3) Multiple Parallel Lines form a Vanishing Line

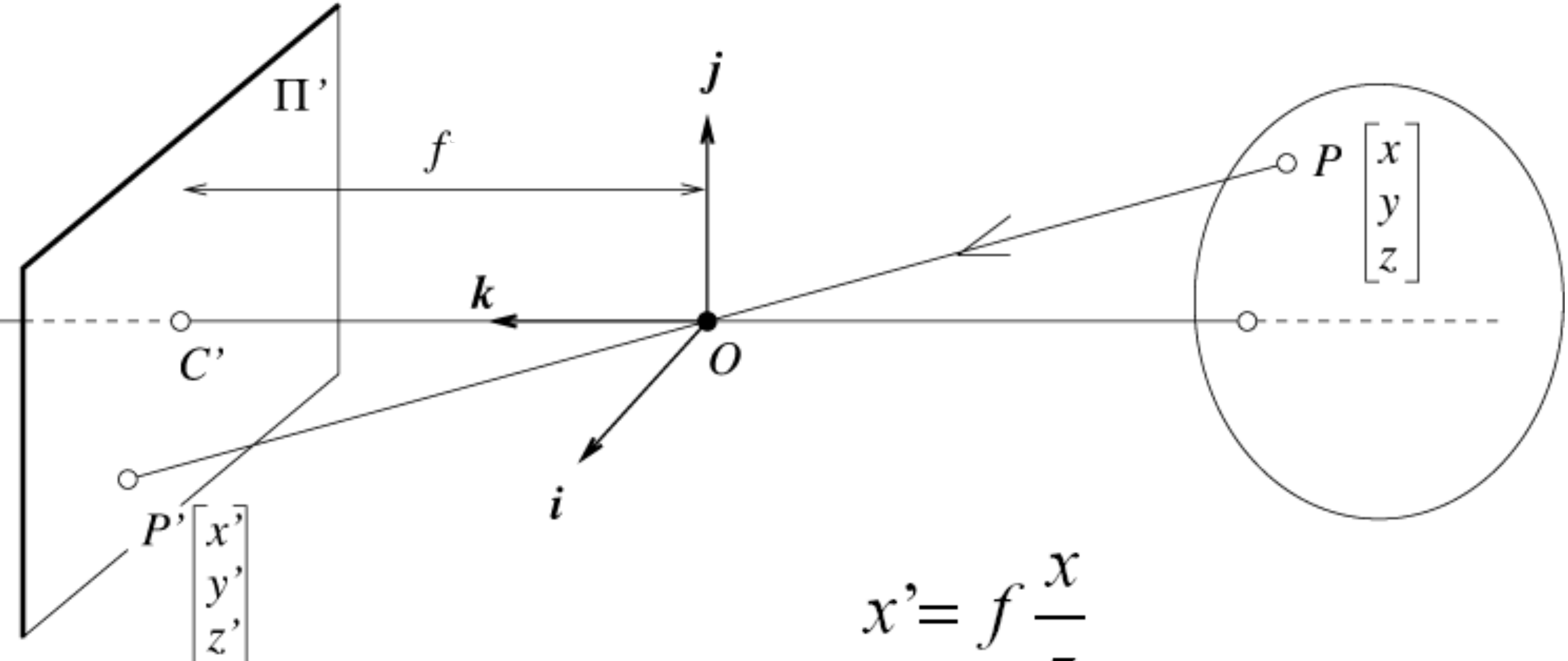


Why Care about Vanishing Points and Lines? Example: Urban Localization from Building Facades

Determine the position and orientation of a robot in a large urban environment.

Position and orientation is based on the recognition of buildings in view.

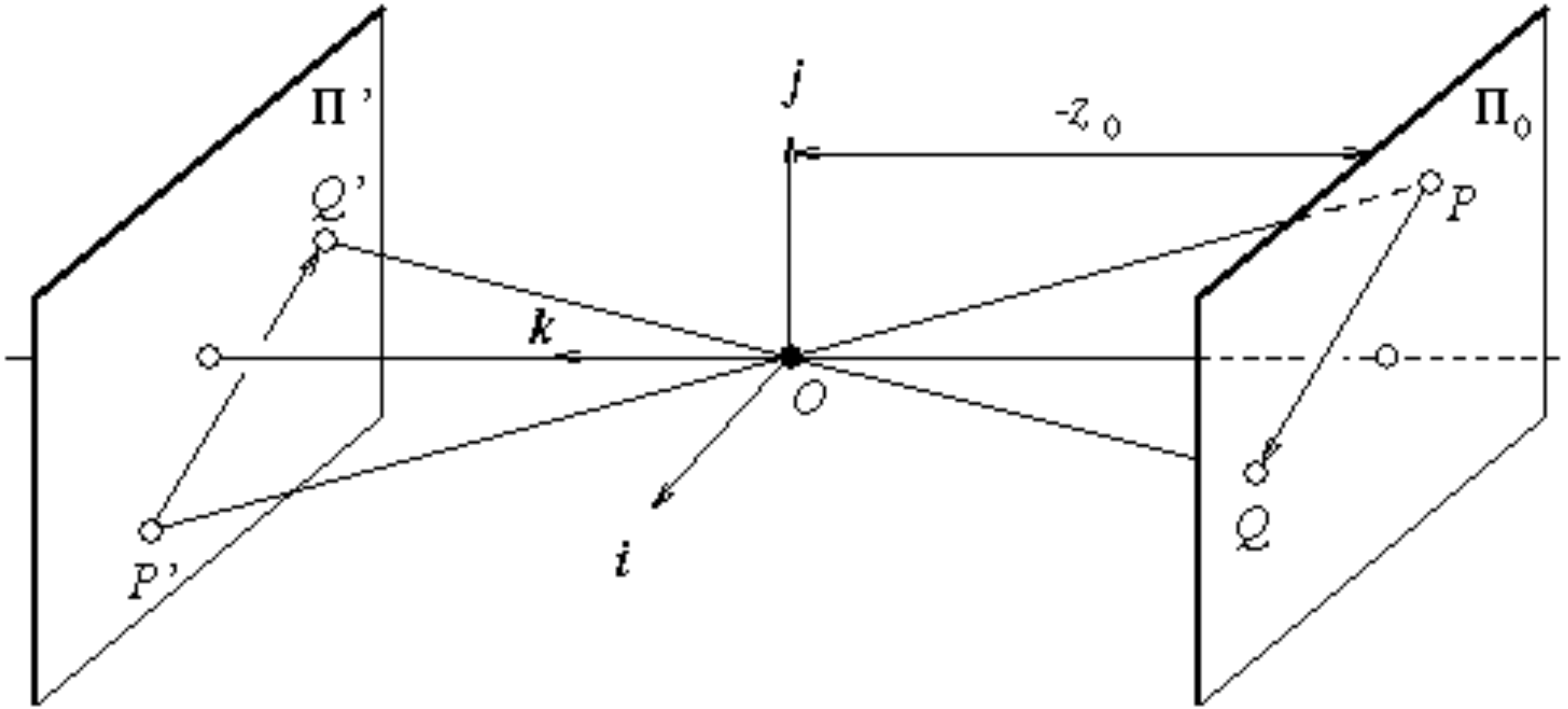
Perspective Projection



$$x' = f\frac{x}{z}$$

$$y' = f\frac{y}{z}$$

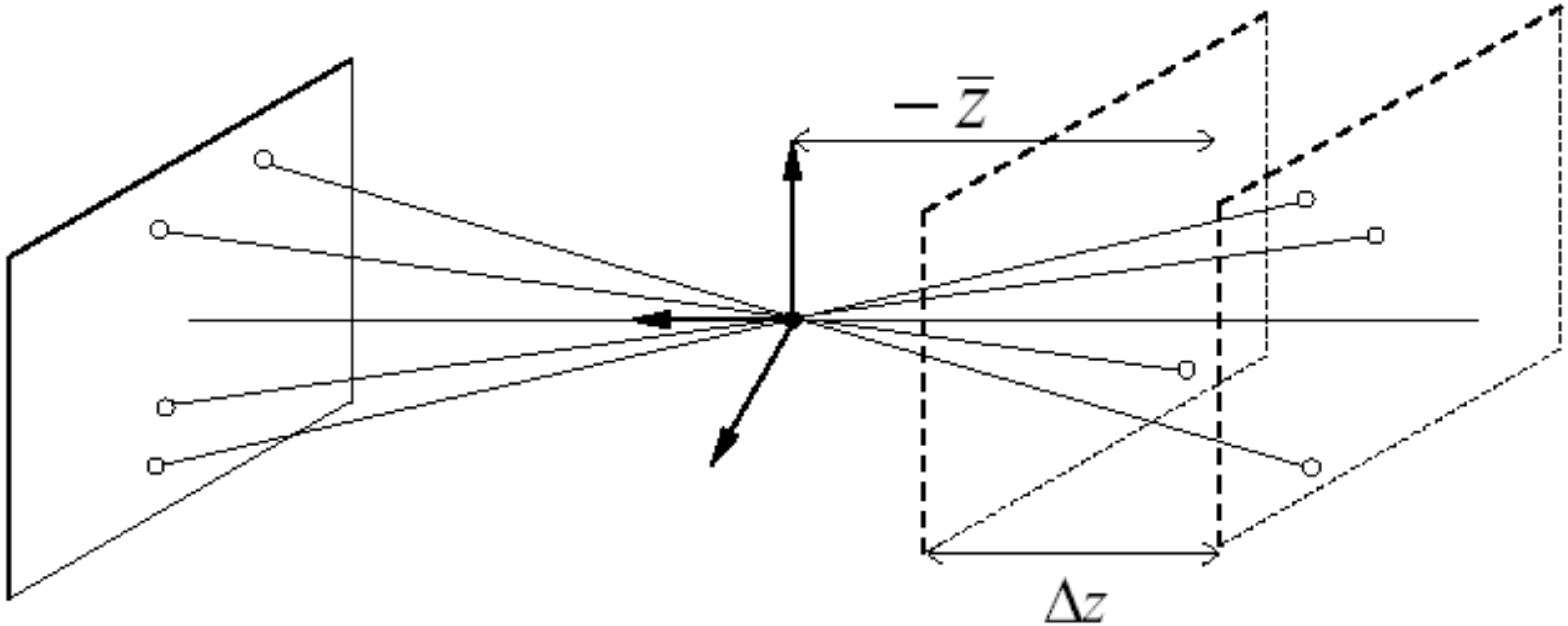
Weak Perspective (Affine Projection)



$$x' \approx -mx \qquad m = -\frac{f'}{z_o}$$
$$y' \approx -my$$

If scene points are in a plane, projections are simply magnified by m

Weak Perspective (Affine Projection)



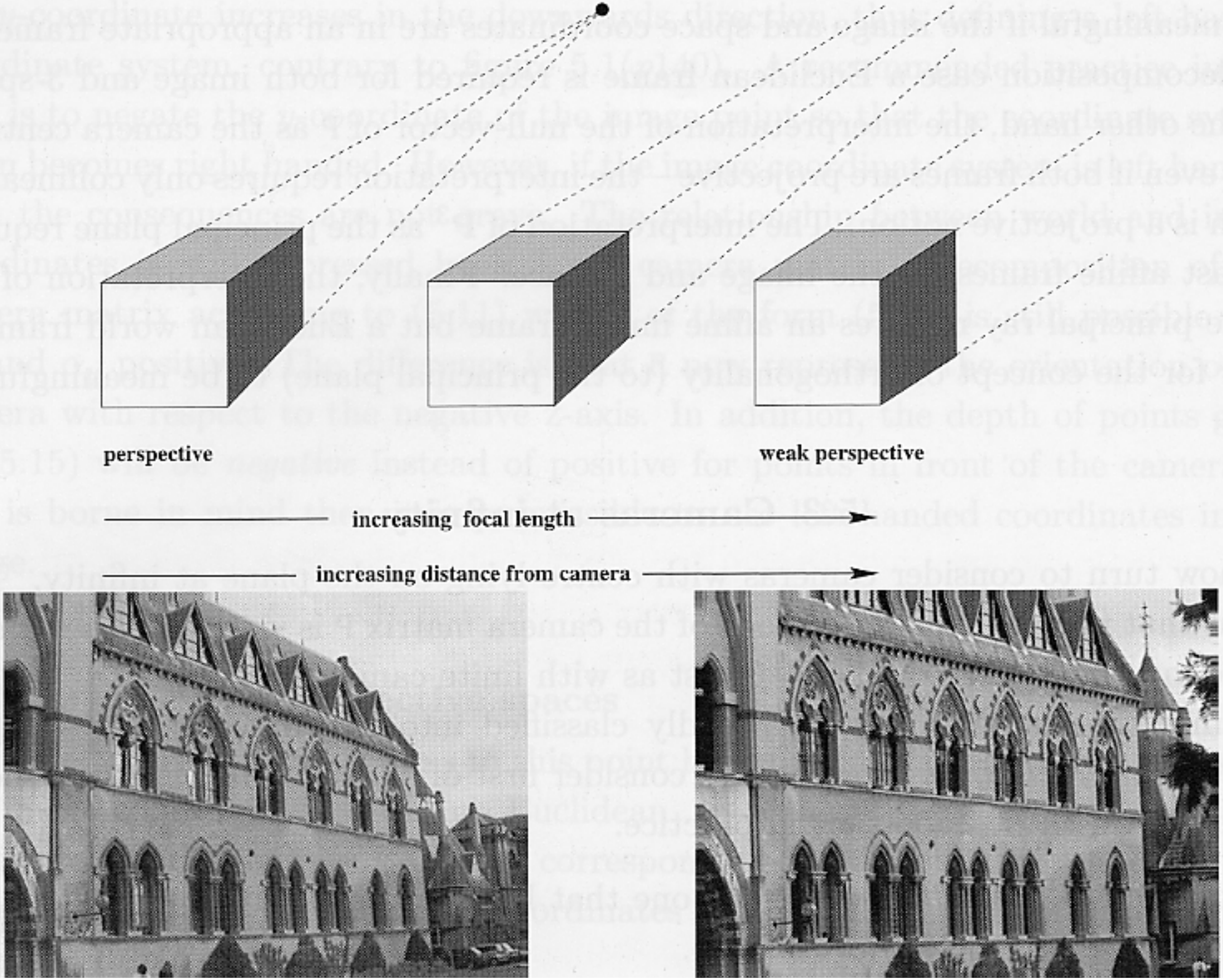
If $\Delta z << -\bar{z}$: $\begin{matrix} x' \approx -mx \\ y' \approx -my \end{matrix}$ $\quad m = -\dfrac{f'}{\bar{z}}$

Justified if scene depth is small relative to average distance from camera

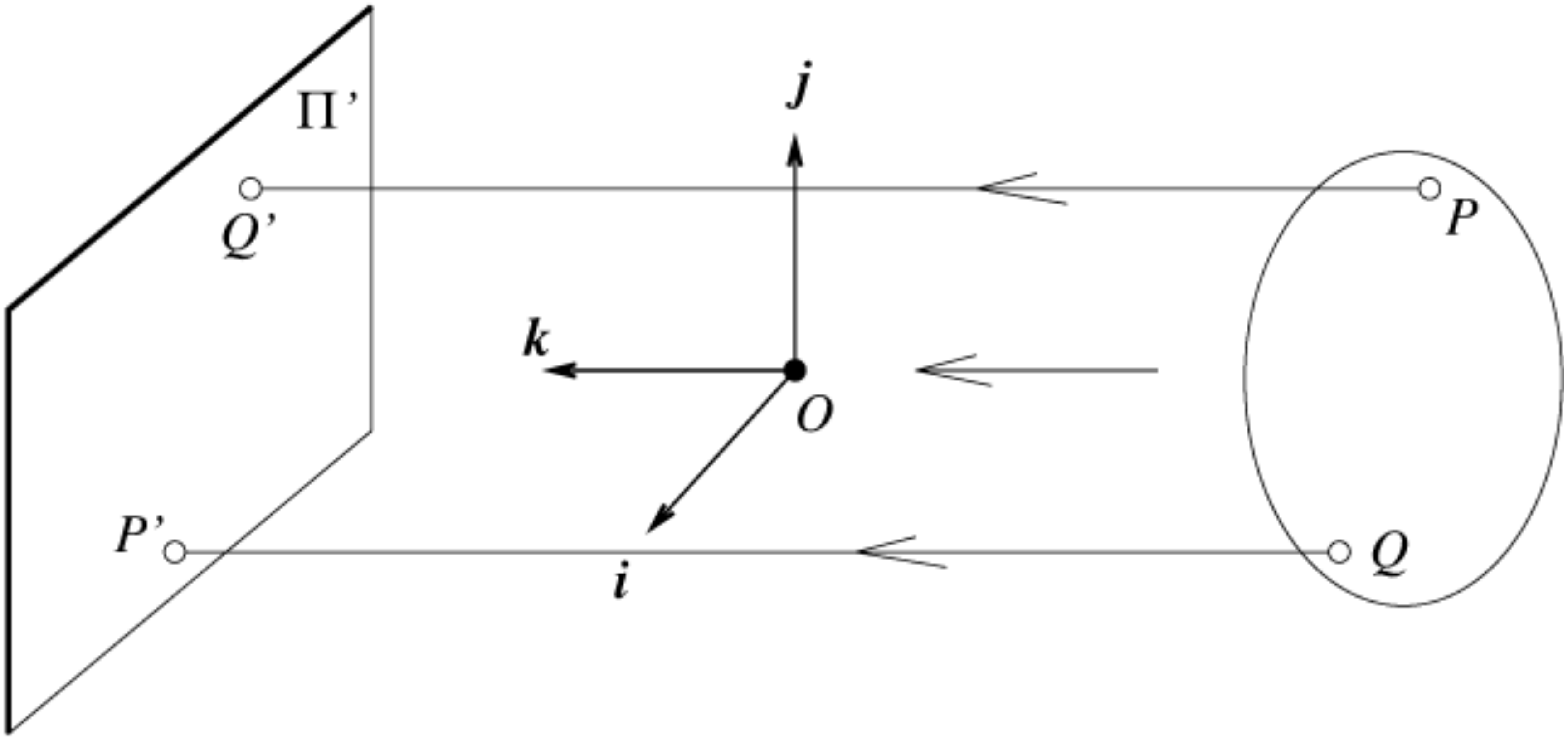
Weak Perspective

Strong perspective:
Angles are not preserved
The projections of parallel lines intersect at one point

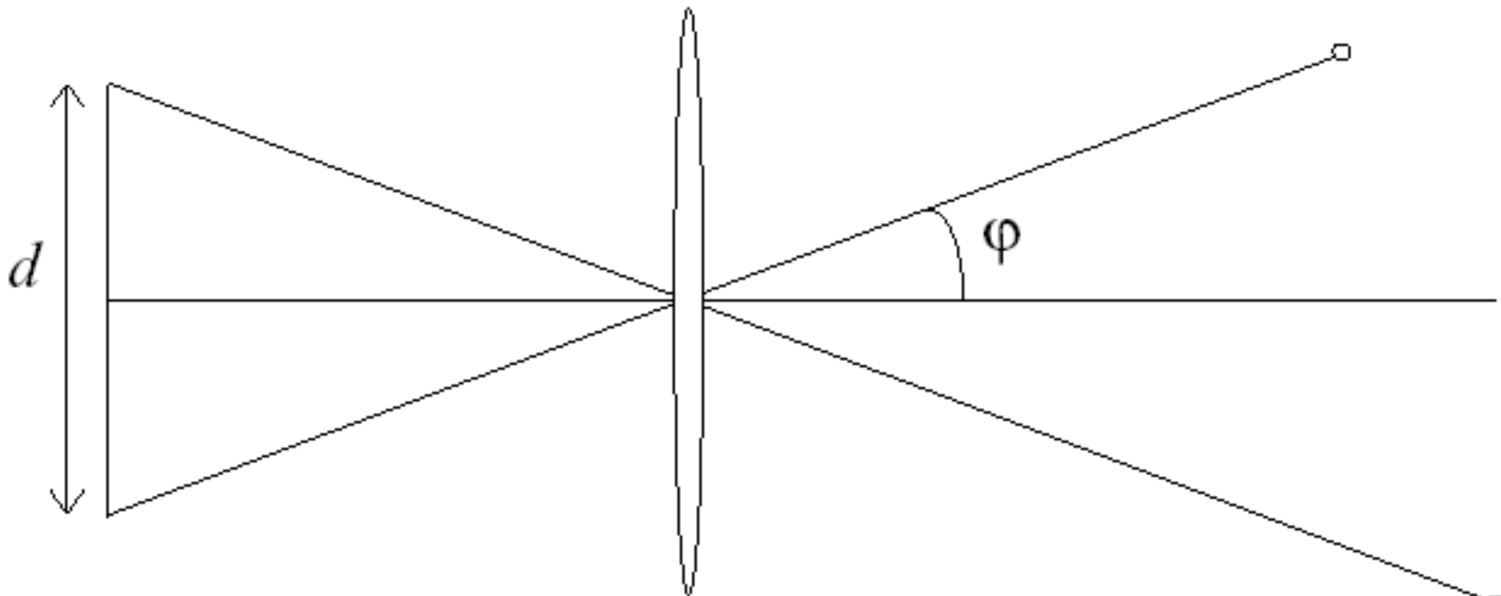
Weak perspective:
Angles are better preserved
The projections of parallel lines are (almost) parallel


perspective
weak perspective
increasing focal length
increasing distance from camera

Orthographic Projection



Finite Field of View



Size of field of view governed by size of the camera retina:

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Homogeneous Coordinates in 2-D

- Physical point $p = \begin{bmatrix} x \\ y \end{bmatrix}$ represented by three coordinates

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad \begin{aligned} x &= u / w \\ y &= y / w \end{aligned}$$

- Two sets of homogeneous coordinate vectors are equivalent if they are proportional to each other:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} \equiv \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} \Leftrightarrow \begin{bmatrix} u \\ v \\ w \end{bmatrix} \equiv \lambda \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} \qquad \lambda \neq 0$$

Homogeneous Coordinates in 3-D

- Physical point $p = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ represented by three coordinates

$$\begin{bmatrix} u \\ v \\ w \\ t \end{bmatrix} \qquad \begin{aligned} x &= u/t \\ y &= v/t \\ z &= w/t \end{aligned}$$

- Two sets of homogeneous coordinate vectors are equivalent if they are proportional to each other:

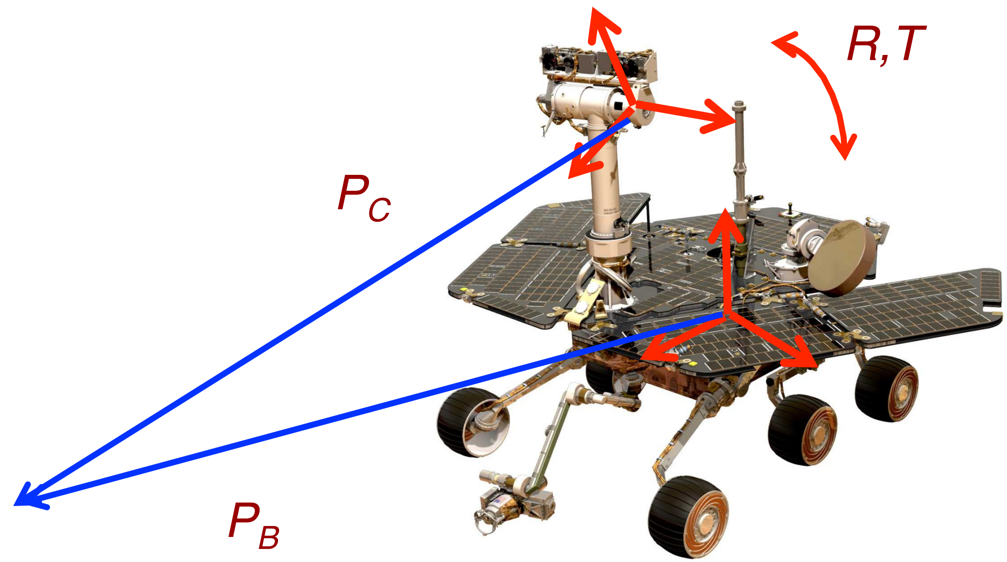
$$\begin{bmatrix} u \\ v \\ w \\ t \end{bmatrix} \equiv \begin{bmatrix} u' \\ v' \\ w' \\ t' \end{bmatrix} \quad \Leftrightarrow \quad \begin{bmatrix} u \\ v \\ w \\ t \end{bmatrix} \equiv \lambda \begin{bmatrix} u' \\ v' \\ w' \\ t' \end{bmatrix} \qquad \lambda \neq 0$$

Matrix Representation of Perspective Projection

$$p = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} x \\ y \\ z/f \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/f & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = P$$

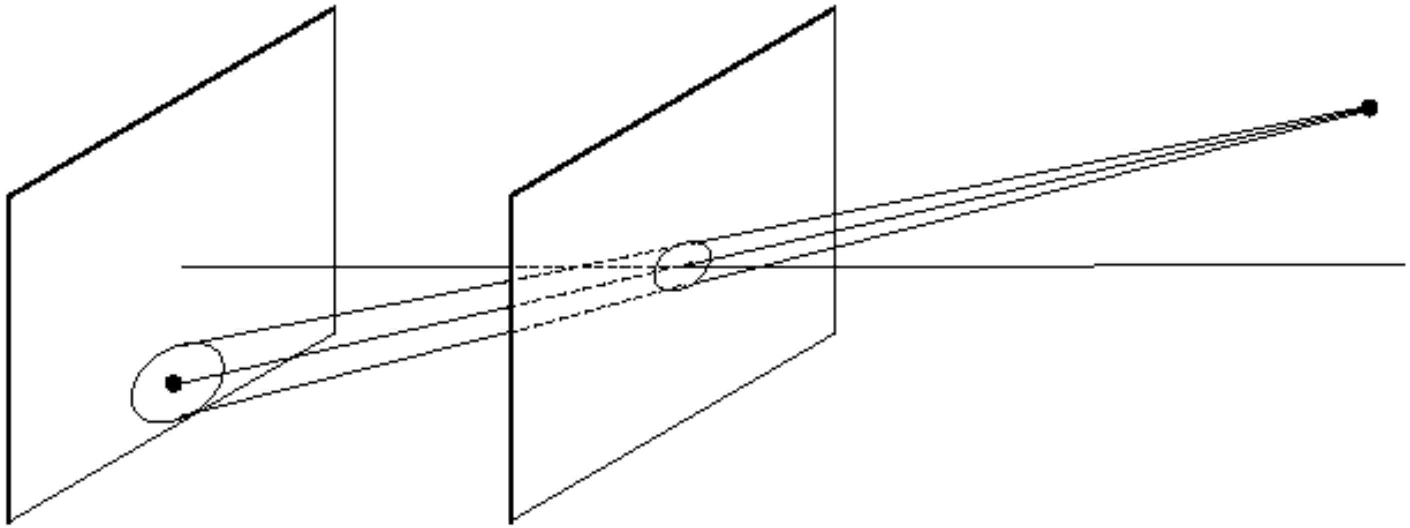
$$\begin{matrix} x' \\ y' \end{matrix} = \begin{matrix} u/w \\ v/w \end{matrix}$$

$$p = C\left[R|T\right]P_B$$

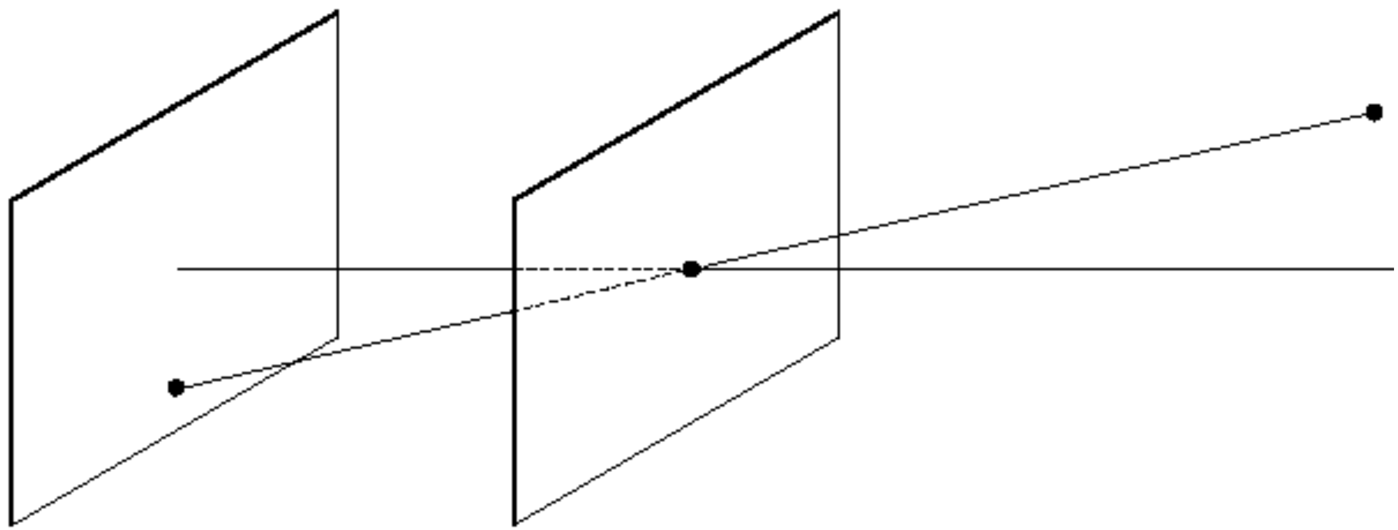


Limitations of Pinhole Cameras/Models

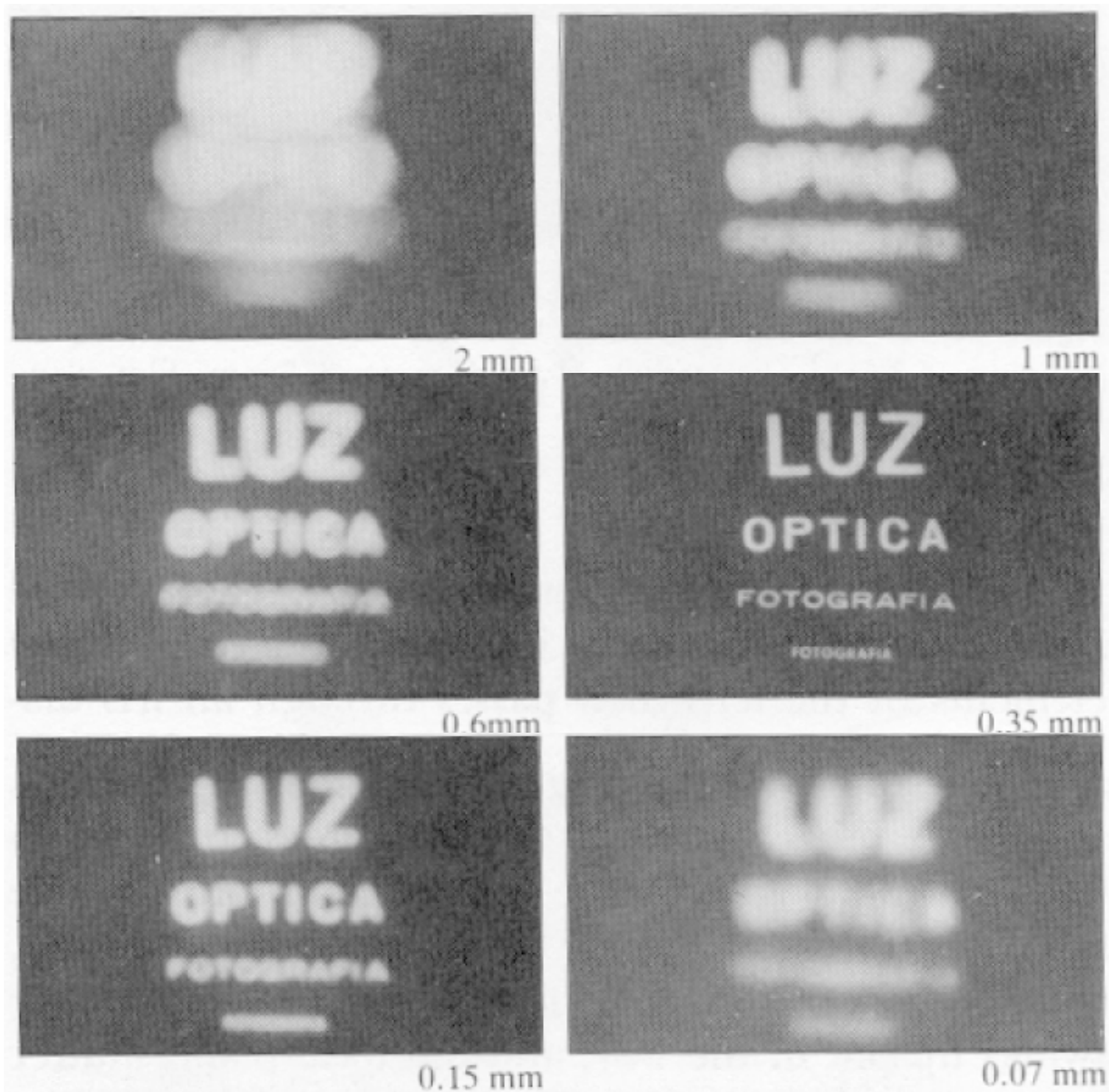
Finite-size pinhole:
Single scene point generates extended image.
Resulting image is blurry



Ideal pinhole:
Single scene point generates single image but:
Diffraction
Low light level

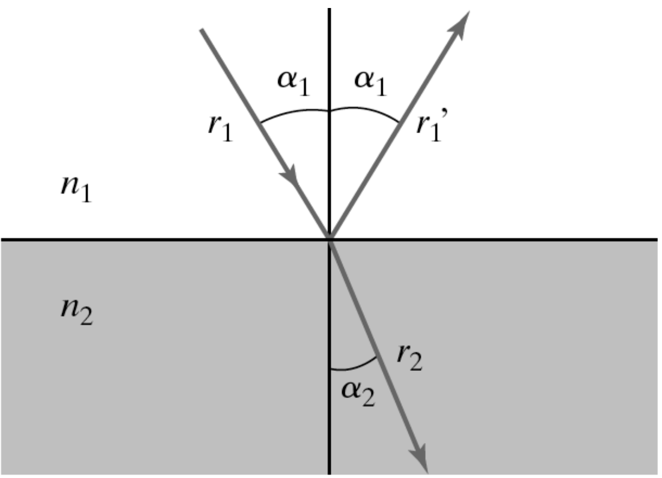


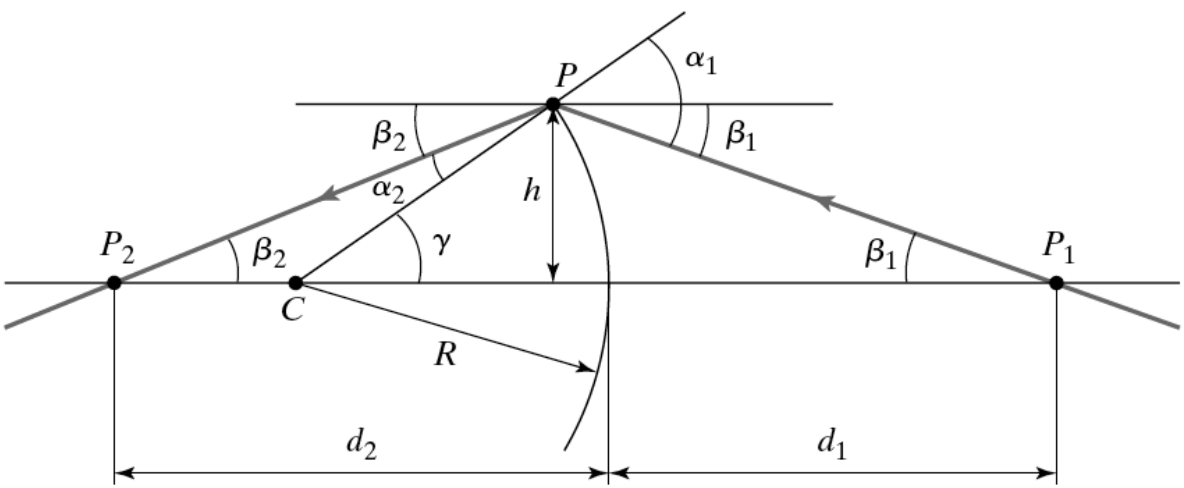
Limitations of Pinhole Cameras/Models



From Hecht, *Optics*

Snell's Law, Spherical Surfaces, and Paraxial Optics

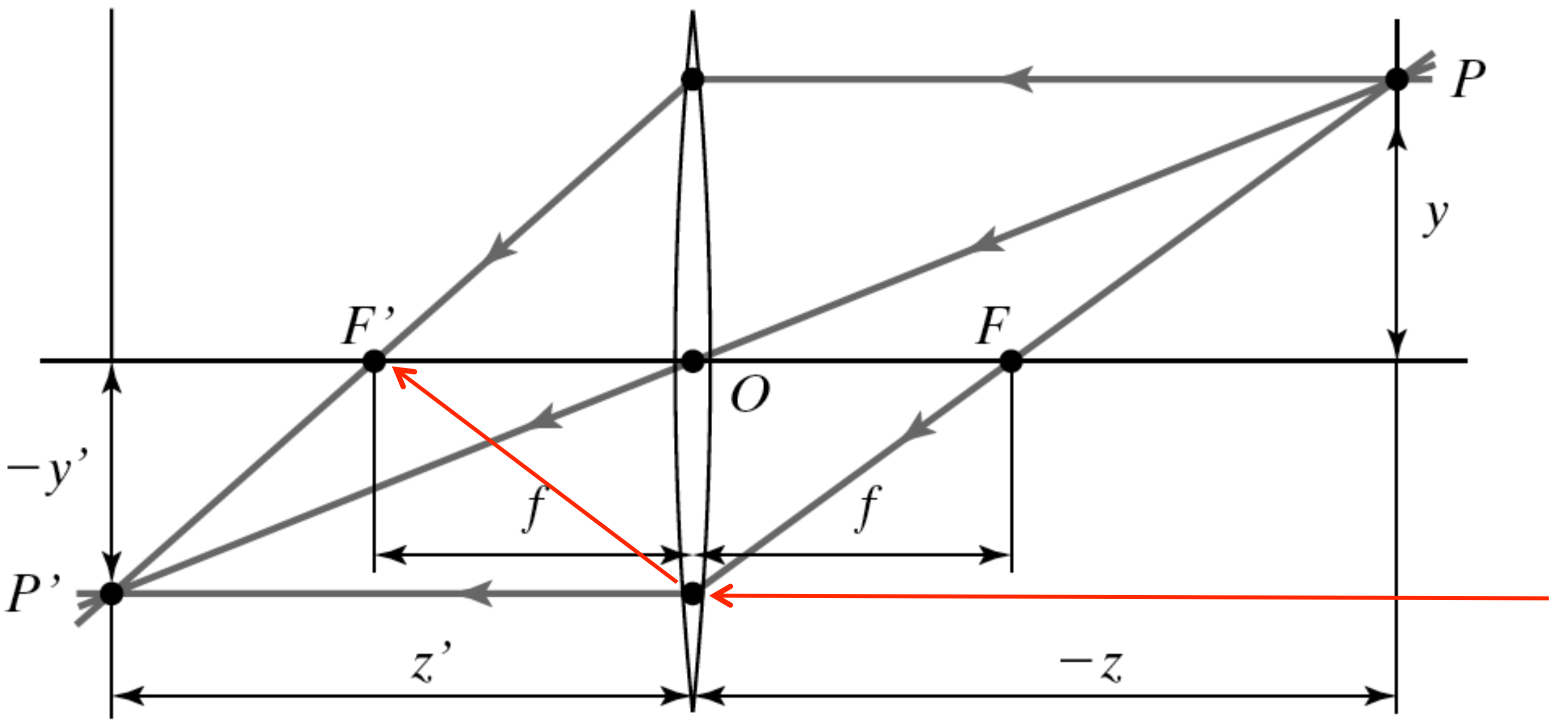




$$n_1 \sin\alpha_1 = n_2 \sin\alpha_2$$

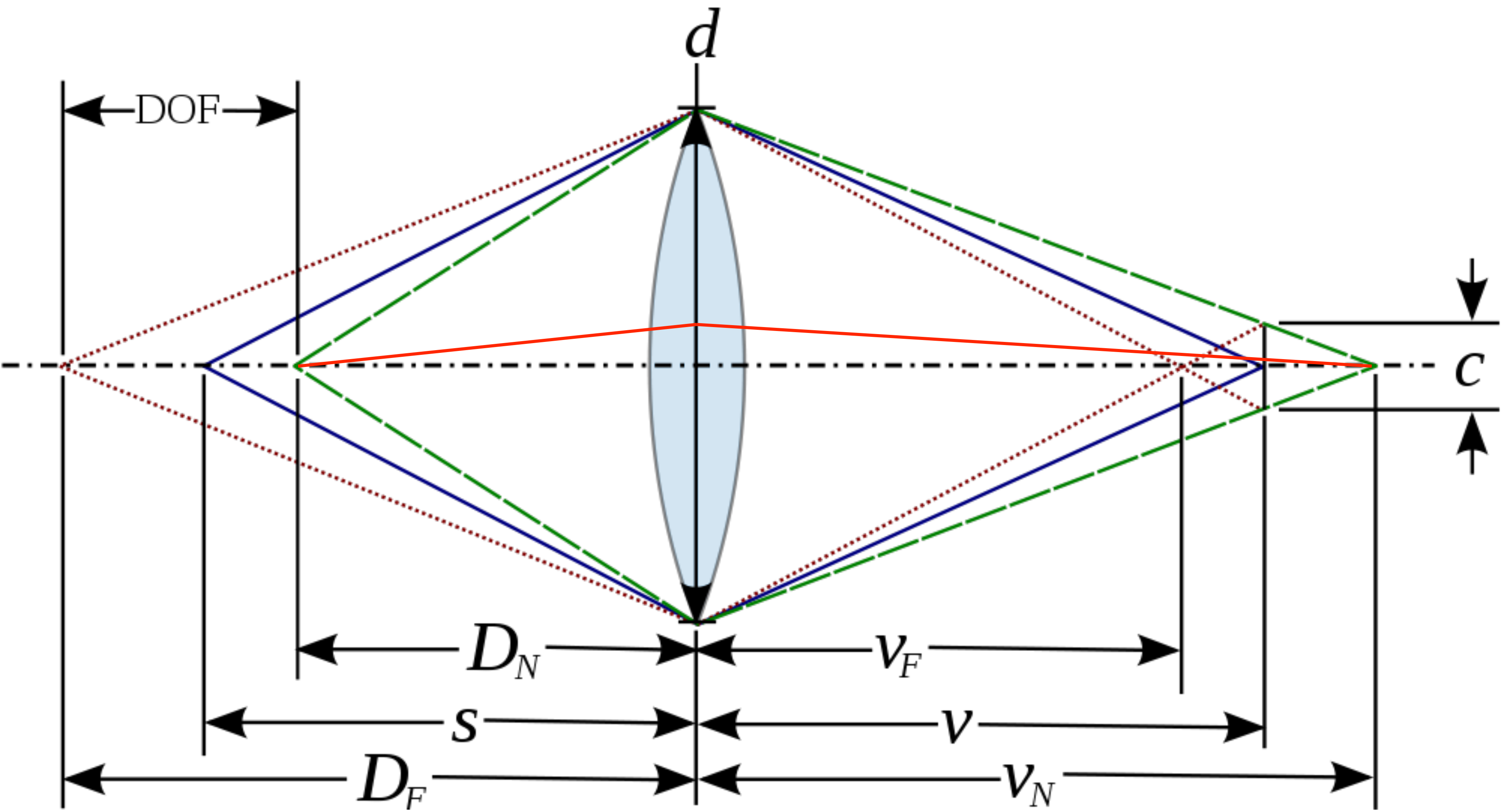
$$n_1 \alpha_1 = n_2 \alpha_2$$

The Thin Lens Model

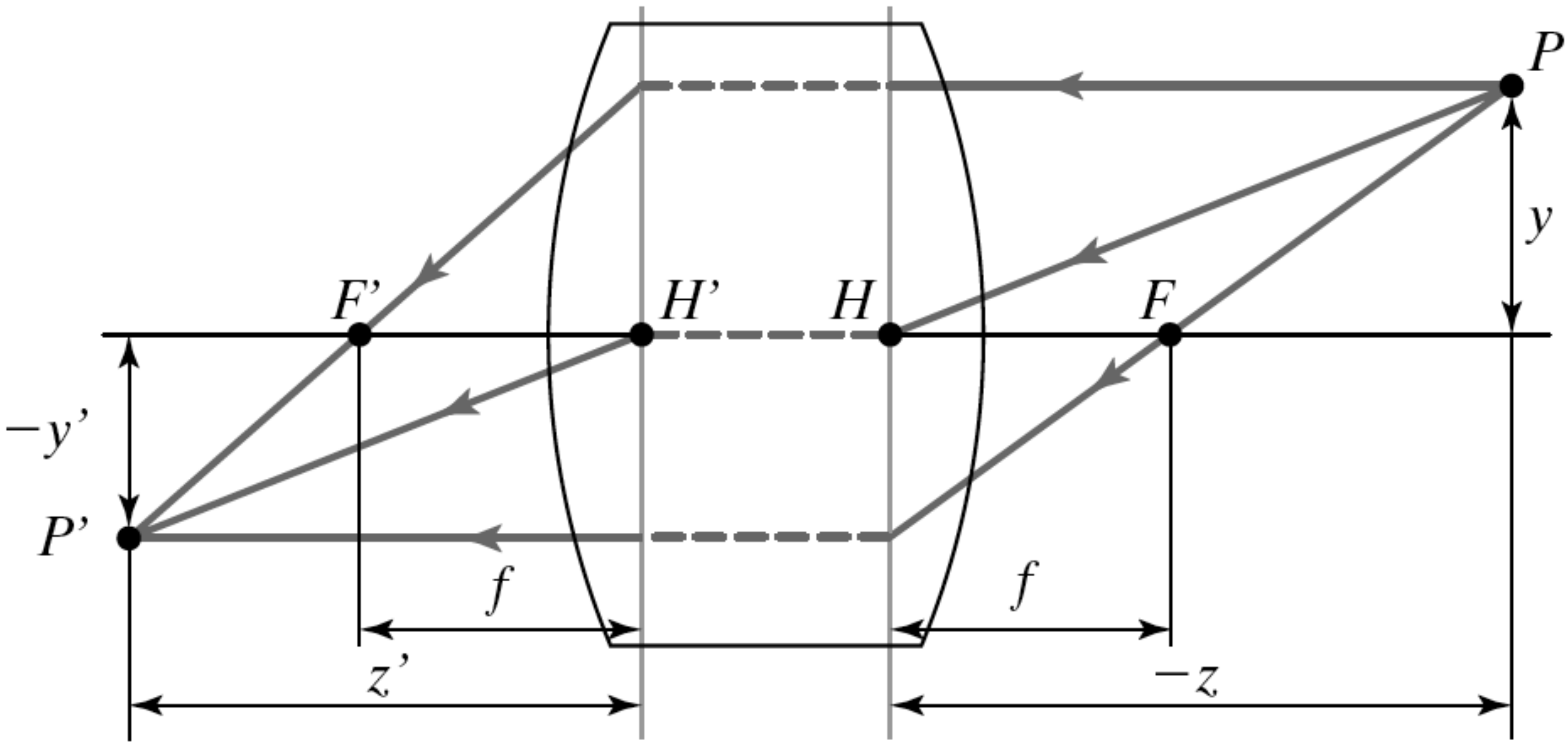


$$\frac{1}{z'} - \frac{1}{z} = \frac{1}{f}$$

Depth of Field and the Effect of Aperture



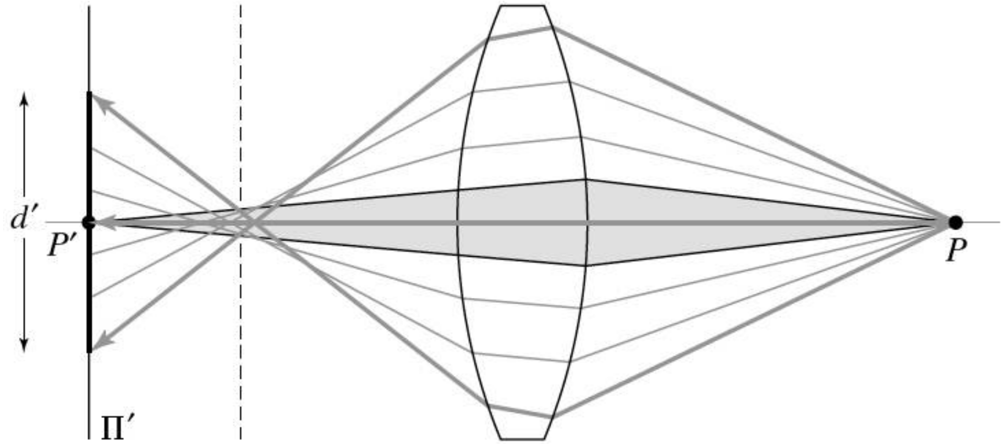
The Thick Lens Model



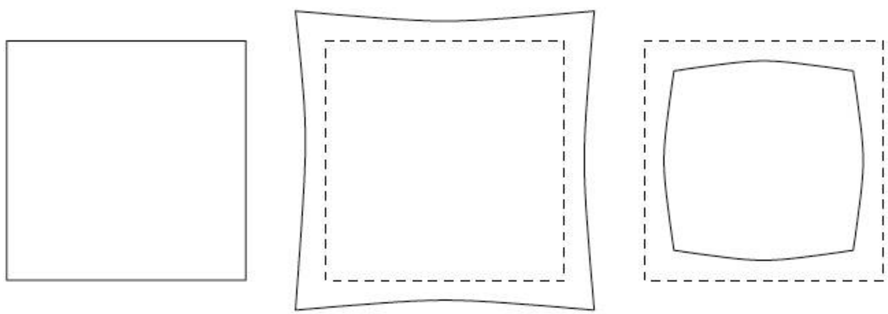
Thin lens equation still applies if *z* and *z'* are relative to *H* and *H'*

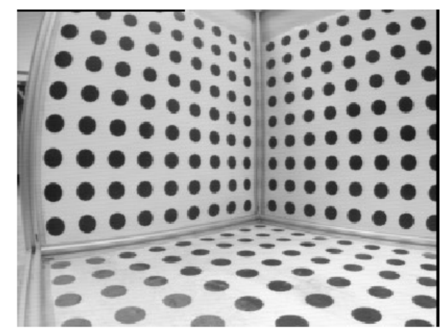
Aberrations

Spherical
(among others)

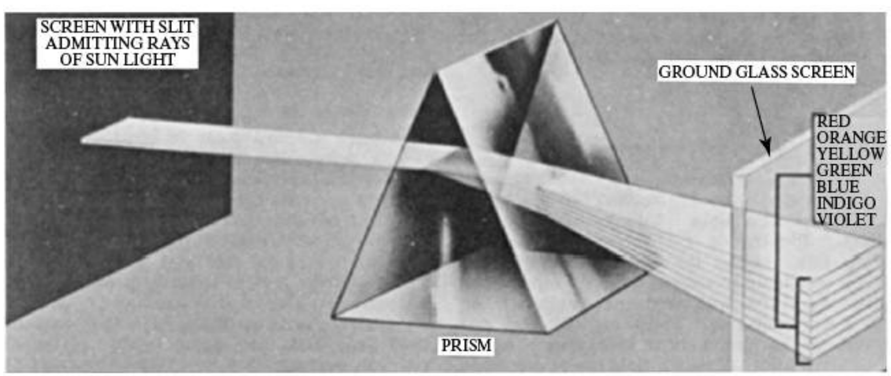


Distortion
(we'll model it)

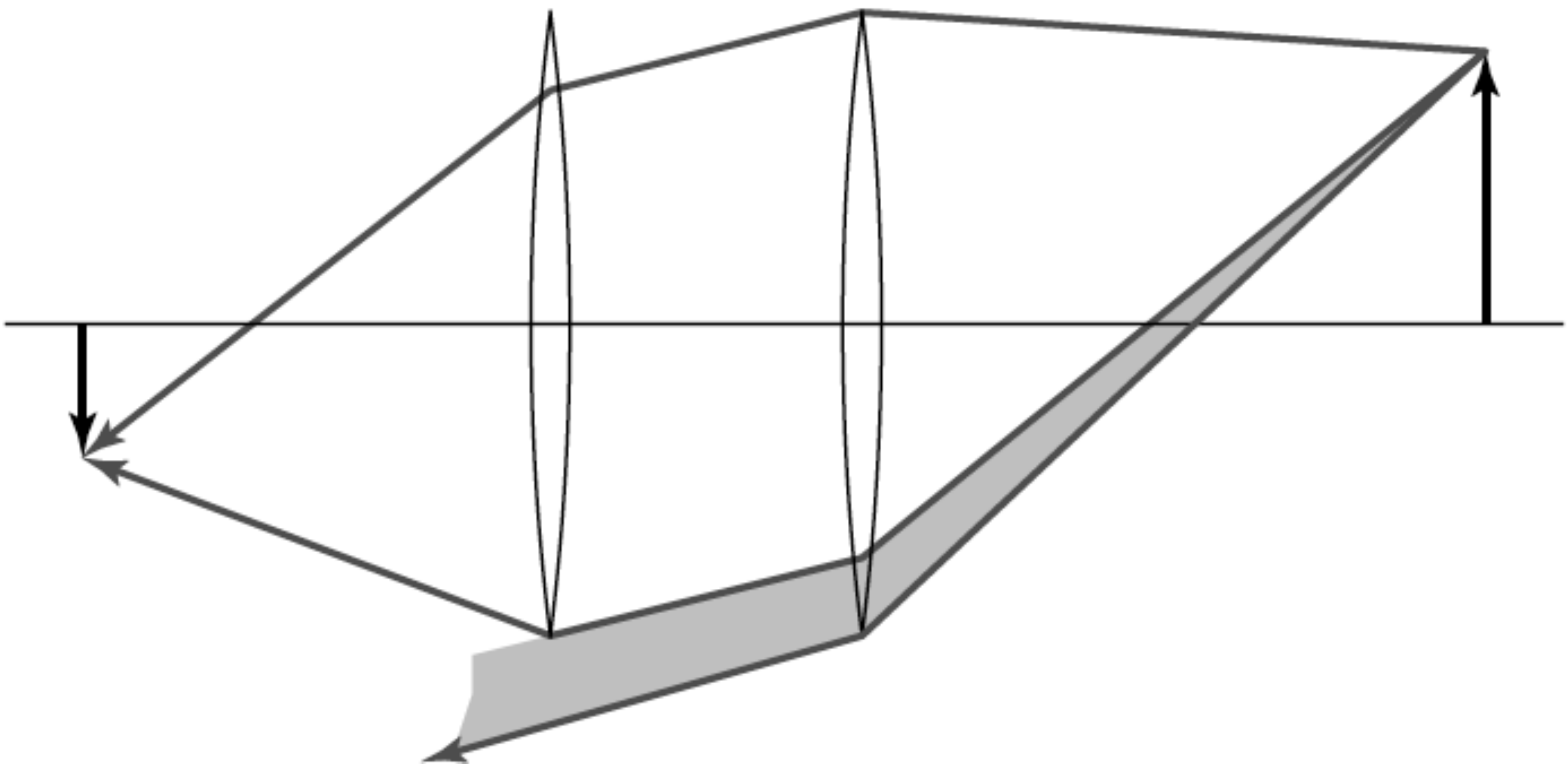




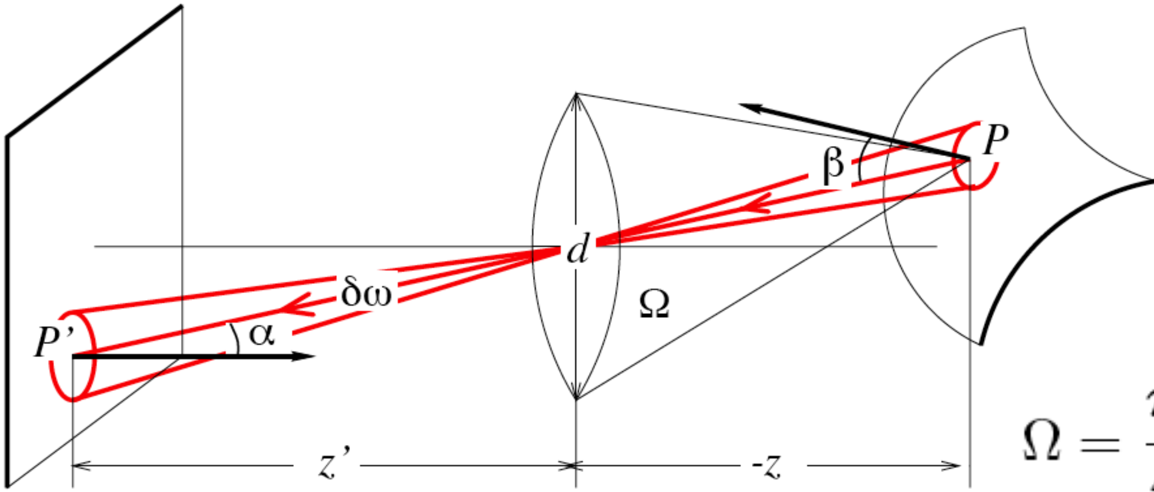
Chromatic



Mechanical Vignetting



Natural Vignetting



$$\Omega = \frac{\pi}{4}\frac{d^2\cos\alpha}{(z/\cos\alpha)^2} = \frac{\pi}{4}(\frac{d}{z})^2\cos^3\alpha$$

$$\delta P = L\Omega\delta A\cos\beta = \frac{\pi}{4}(\frac{d}{z})^2 L\delta A\cos^3\alpha\cos\beta$$

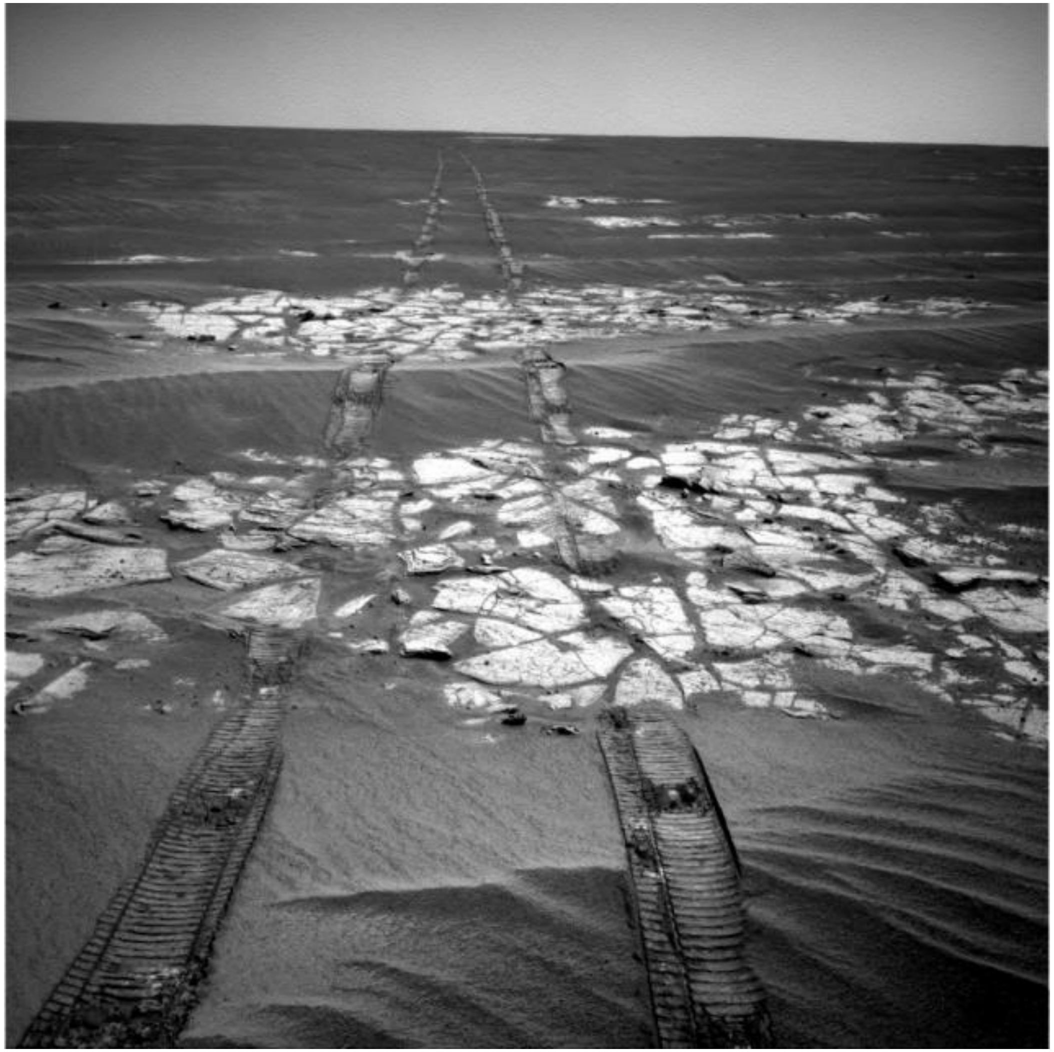
$$\delta\omega = \frac{\delta A'\cos\alpha}{|\overrightarrow{OP'}|^2} = \frac{\delta A'\cos\alpha}{(z'/\cos\alpha)^2}$$

$$\delta\omega = \frac{\delta A\cos\beta}{|\overrightarrow{OP}|^2} = \frac{\delta A\cos\beta}{(z/\cos\alpha)^2},$$

$$\frac{\delta A}{\delta A'} = \frac{\cos\alpha}{\cos\beta}(\frac{z}{z'})^2.$$

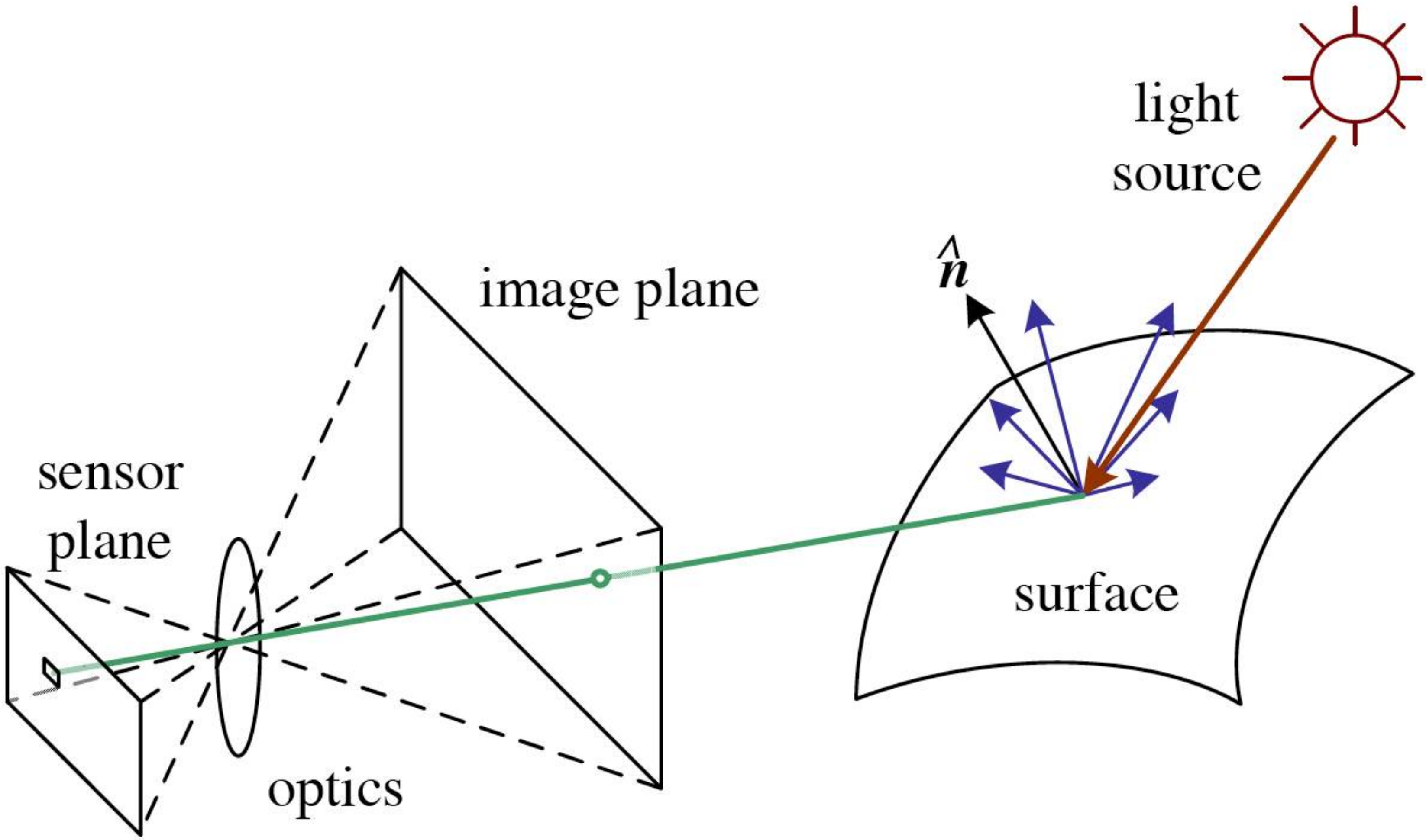
$$E = \frac{\delta P}{\delta A'} = \frac{\pi}{4}(\frac{d}{z})^2 L\frac{\delta A}{\delta A'}\cos^3\alpha\cos\beta$$

$$E = [\frac{\pi}{4}(\frac{d}{z'})^2\cos^4\alpha]L$$

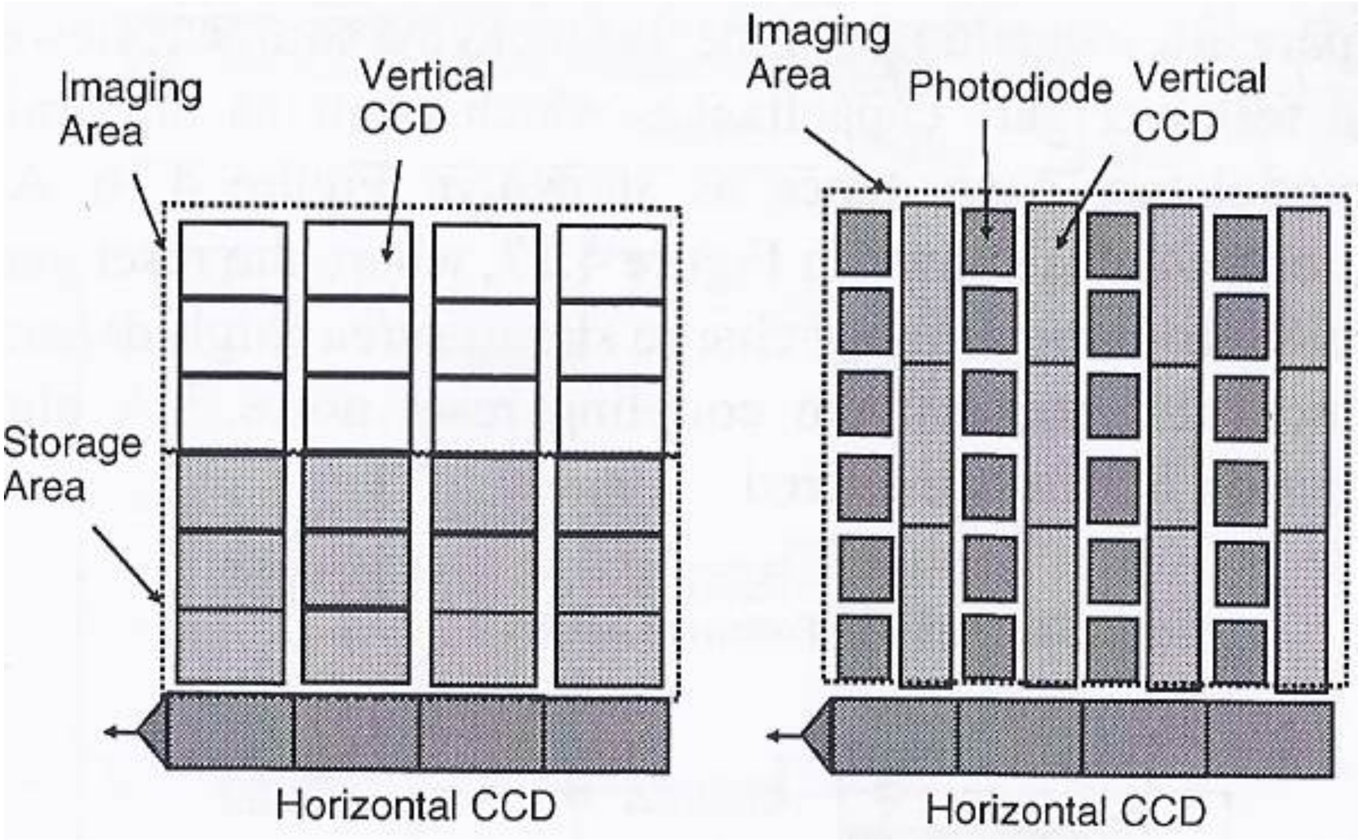


Recap and Where We're Going

Goal: be able to model the light reaching a pixel in the image or to invert this to estimate scene properties from measured image brightness



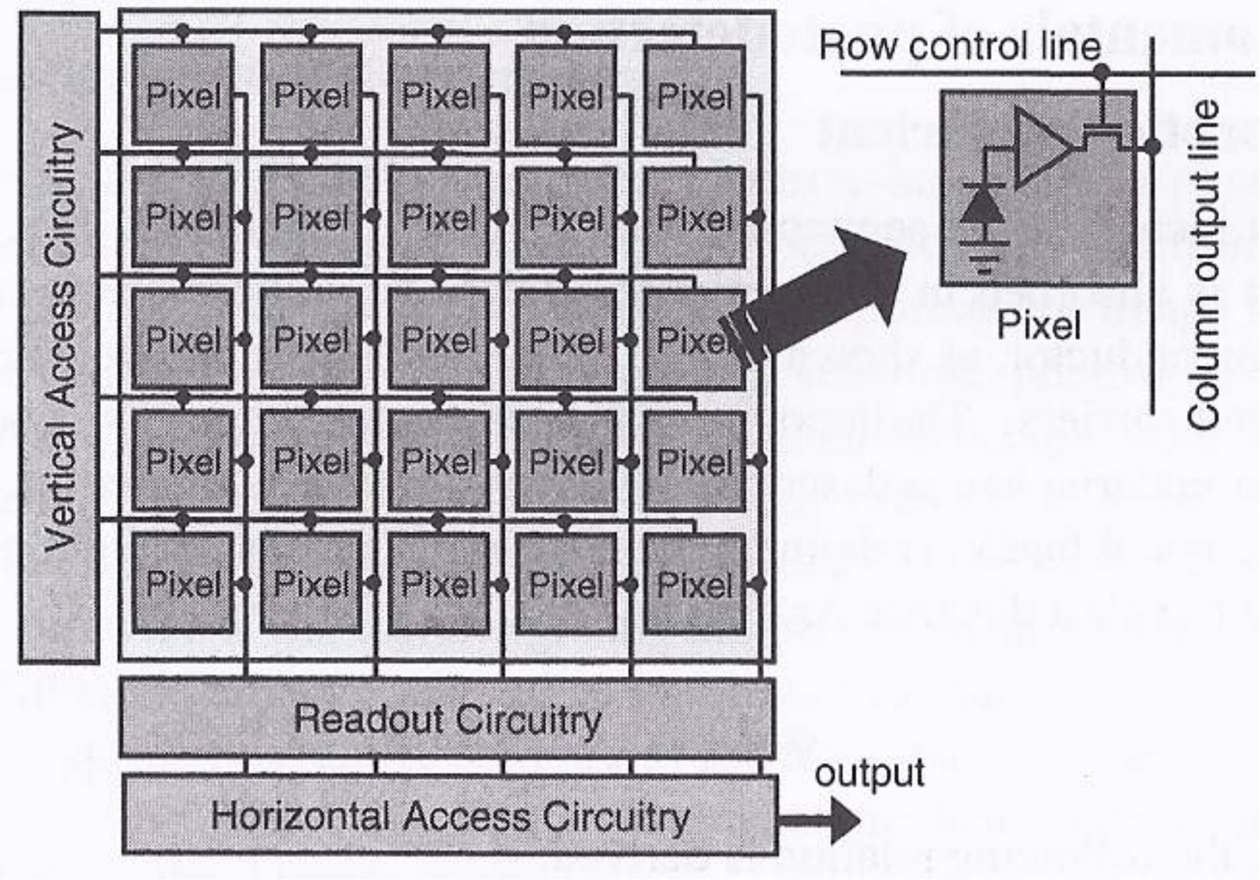
Focal Plane Architectures: CCD Imagers



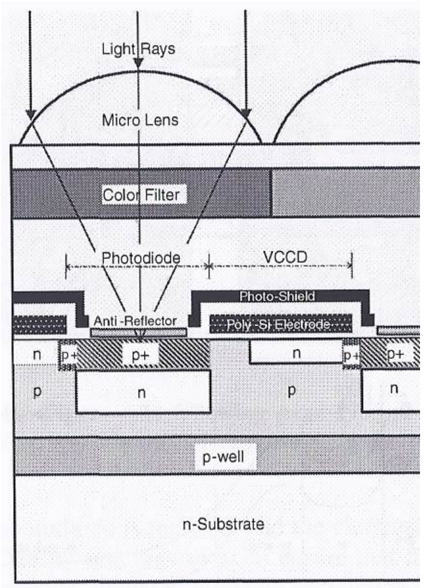
Frame transfer   Interline transfer

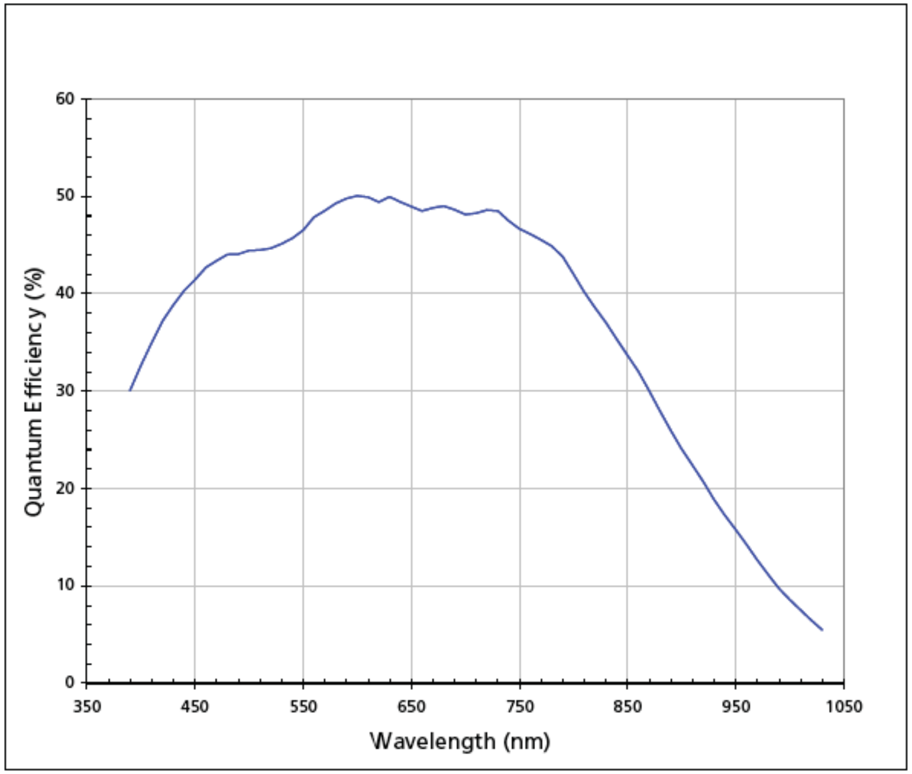
J. Maki, et al., “Mars Exploration Rover Engineering Cameras,” *Journal of Geophysical Research*, vol. 108, no. E12, 2003

Focal Plane Architectures: CMOS Imagers



Fill Factor and Quantum Efficiency



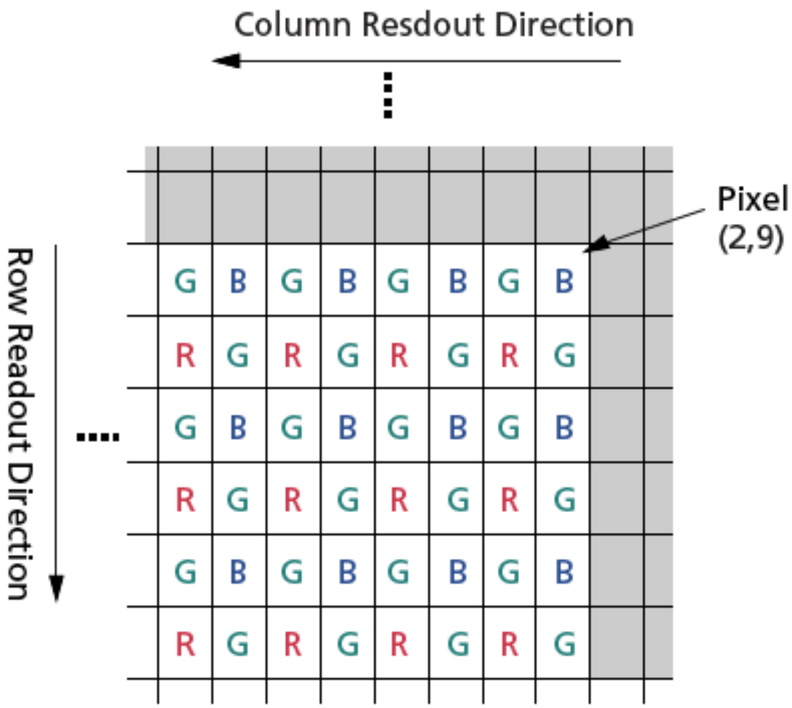


Full well: maximum charge that can be stored in a pixel

Front vs back illumination

Color Camera Architectures

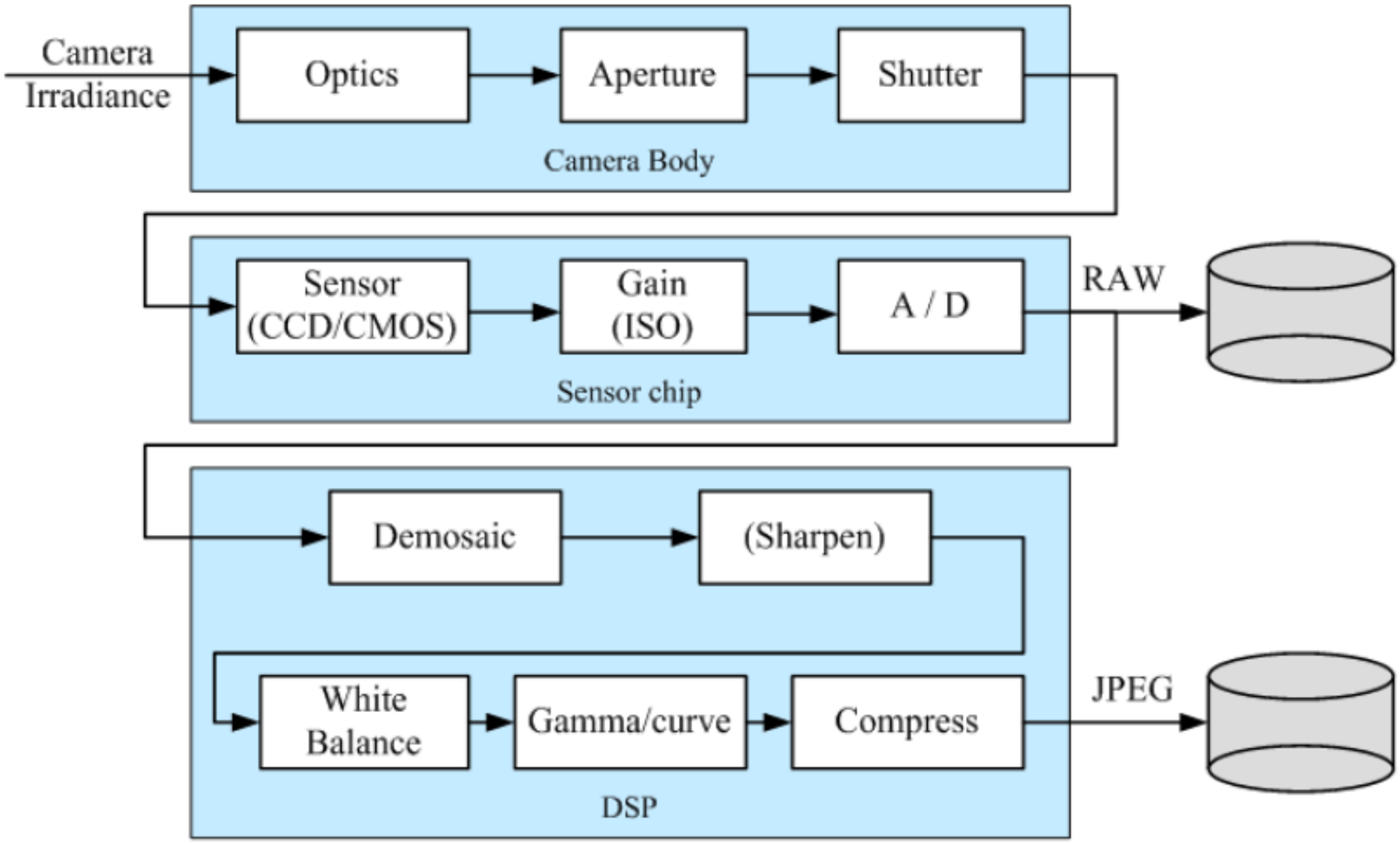
- Color mosaic filters (usually 3)
- Beam-splitters (2, 3, or 4 way)
- Stacked response
- Line-scan spectrometers
- Tunable filters



Noise Sources in Digital Imagers

- Photon shot noise:
  - Photon arrivals have a Poisson distribution. Variance is equal to the mean.
- Dark current shot noise:
  - Charge accumulates even without incident light. Proportion to integration time; strongly temperature dependent (terms with $T^{3/2}$ and T3)
- Read noise: from the readout amplifier
- Spatial non-uniformities (fixed pattern noise)
- Quantization
- Smear, blooming
- Defects (bad pixels)

Digital Camera Architecture



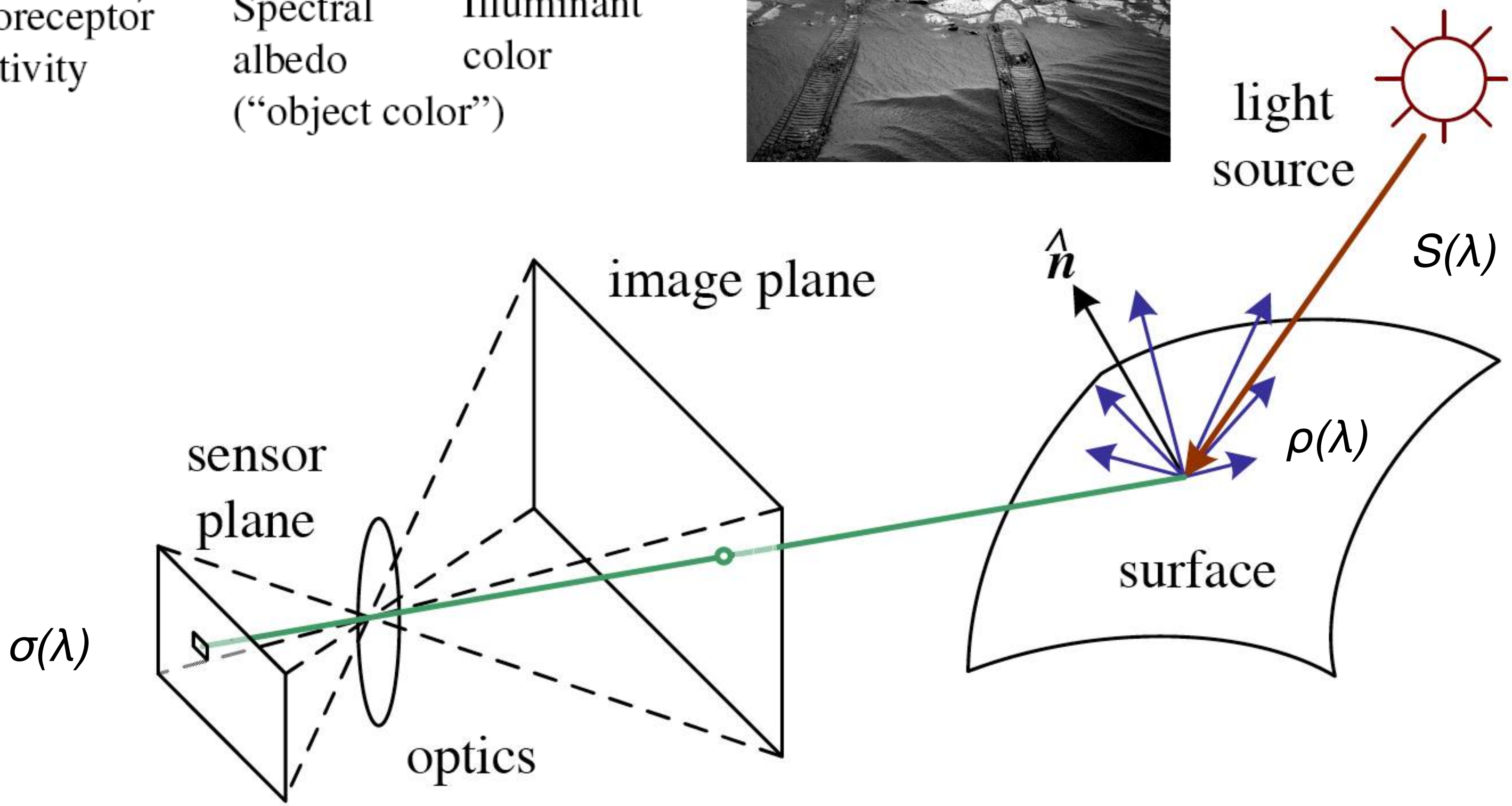
Color Response in Cameras

$$p = \int \sigma(\lambda)\rho(\lambda)S(\lambda)d\lambda$$

Photoreceptor sensitivity

Spectral albedo (“object color”)

Illuminant color



Infrared Detectors