C280, Computer Vision

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Lecture 2: Image Formation

Administrivia

- We’re now in 405 Soda…
- New office hours: Thurs. 5-6pm, 413 Soda.
- I’ll decide on waitlist decisions tomorrow.
- Any Matlab issues yet?
- Roster…

Physical parameters of image formation

- Geometric
  - Type of projection
  - Camera pose
- Optical
  - Sensor’s lens type
  - focal length, field of view, aperture
- Photometric
  - Type, direction, intensity of light reaching sensor
  - Surfaces’ reflectance properties
- Sensor
  - sampling, etc.

Physical parameters of image formation

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- Sensor
  - sampling, etc.

Perspective and art

- Use of correct perspective projection indicated in 1st century B.C. frescoes
- Skill resurfaces in Renaissance: artists develop systematic methods to determine perspective projection (around 1480-1515)

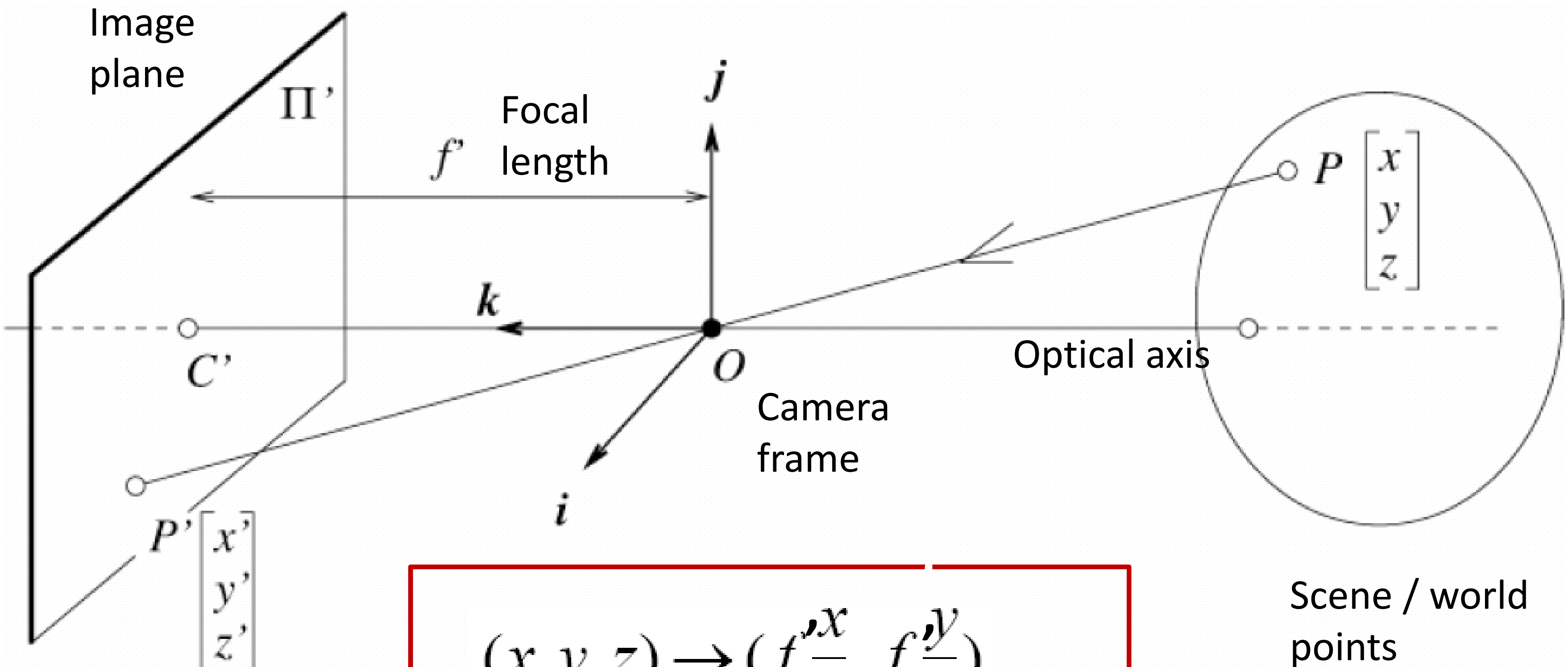
Raphael

Durer, 1525

K. Grauman

Perspective projection equations

- 3d world mapped to 2d projection in image plane



$$(x,y,z) \rightarrow (f'\frac{x}{z}, f'\frac{y}{z})$$

Scene point ⟶ Image coordinates

Forsyth and Ponce

Homogeneous coordinates

Is this a linear transformation?

- no—division by z is nonlinear

Trick: add one more coordinate:

$$(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

homogeneous image coordinates

$$(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

homogeneous scene coordinates

Converting *from* homogeneous coordinates

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)$$

$$\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow (x/w, y/w, z/w)$$

Slide by Steve Seitz

Perspective Projection Matrix

- Projection is a matrix multiplication using homogeneous coordinates:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1/f' & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z/f' \end{bmatrix} \Rightarrow \left(f'\frac{x}{z}, f'\frac{y}{z}\right)$$

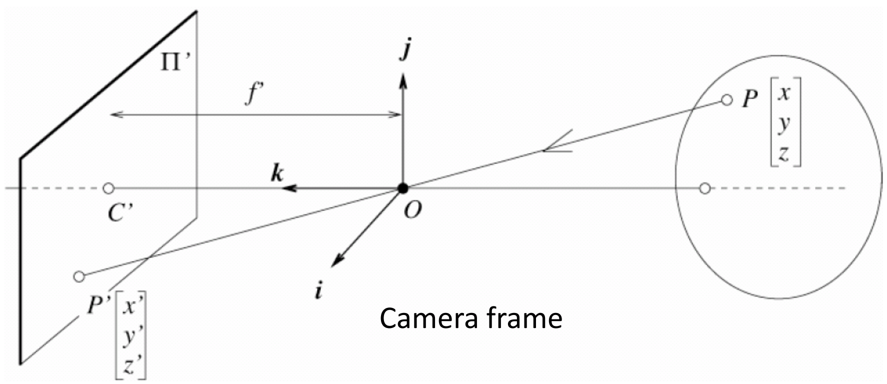
divide by the third coordinate to convert back to non-homogeneous coordinates

Complete mapping from world points to image pixel positions?

Slide by Steve Seitz

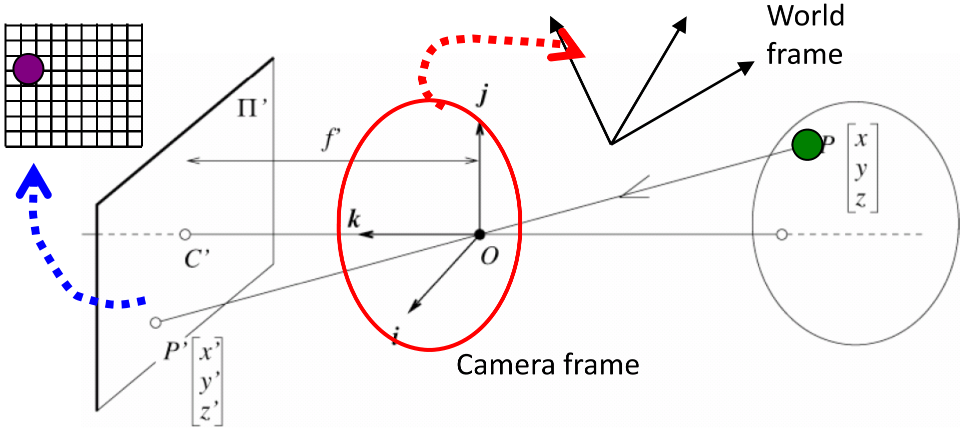
Perspective projection & calibration

- Perspective equations so far in terms of *camera's* reference frame….
- Camera's *intrinsic* and *extrinsic* parameters needed to calibrate geometry.



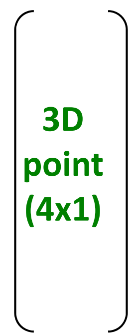
K. Grauman

Perspective projection & calibration



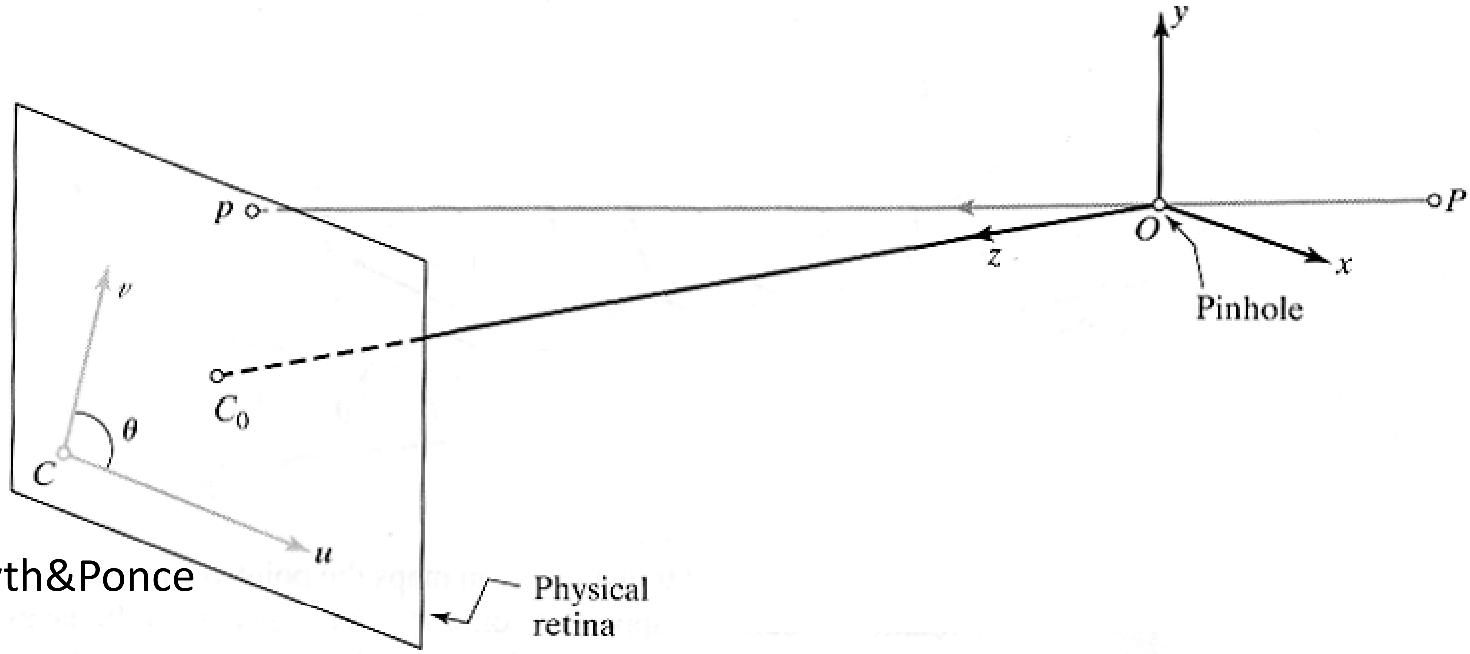
Extrinsic:
Camera frame ←→World frame

Intrinsic:
Image coordinates relative to camera ←→ Pixel coordinates



K. Grauman

Intrinsic parameters: from idealized world coordinates to pixel values



Forsyth&Ponce

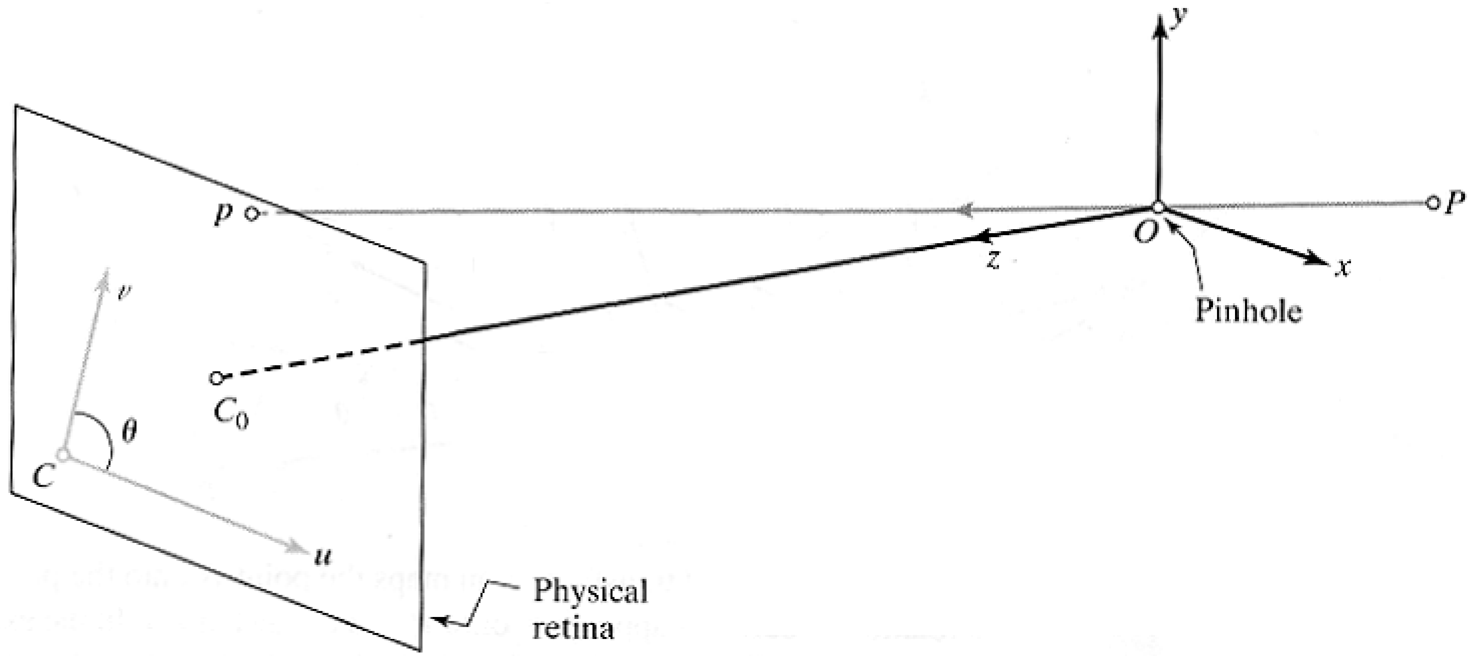
Perspective projection

$$u = f\,\frac{x}{z}$$

$$v = f\,\frac{y}{z}$$

W. Freeman

Intrinsic parameters



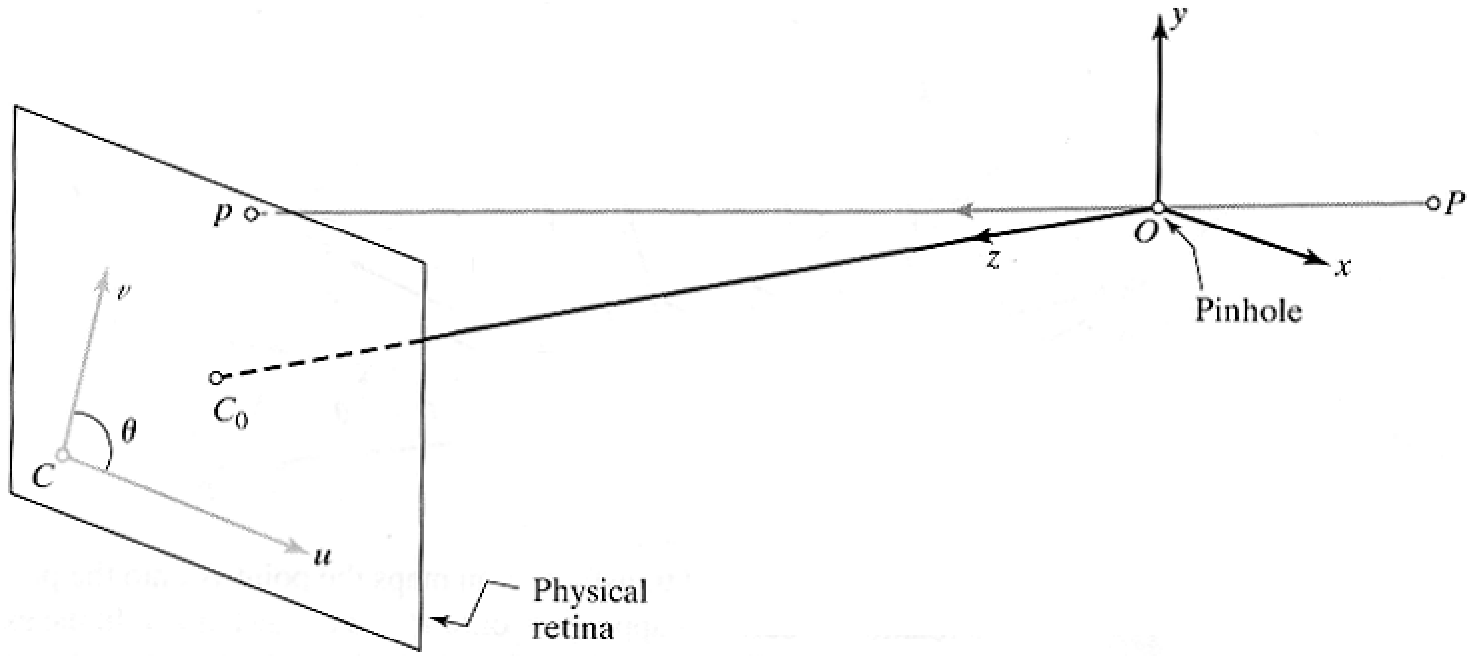
But “pixels” are in some arbitrary spatial units

$$u = \alpha \frac{x}{z}$$

$$v = \alpha \frac{y}{z}$$

W. Freeman

Intrinsic parameters



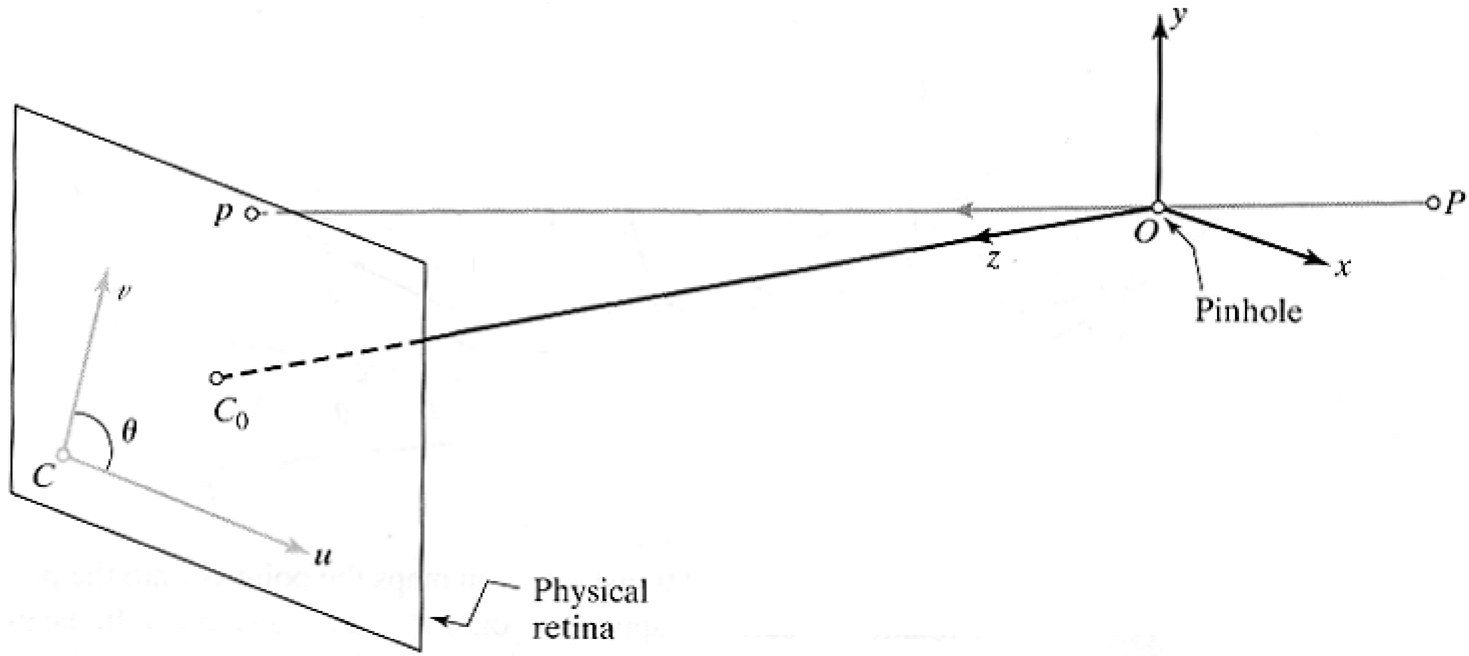
Maybe pixels are not square

$$u = \alpha \frac{x}{z}$$

$$v = \beta \frac{y}{z}$$

W. Freeman

Intrinsic parameters



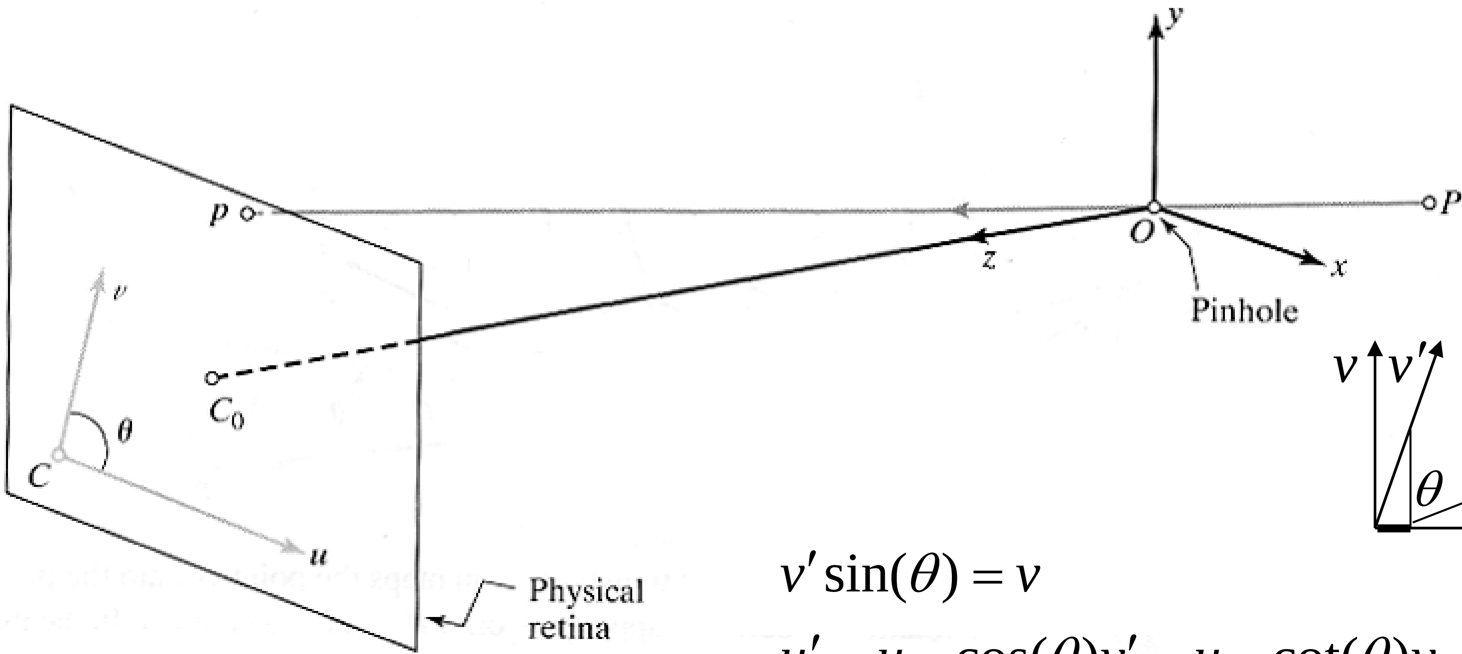
We don't know the origin of our camera pixel coordinates

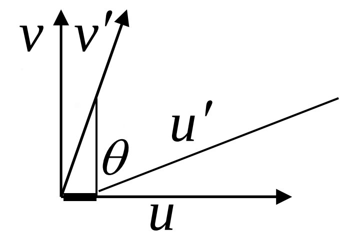
$$u = \alpha \frac{x}{z} + u_0$$

$$v = \beta \frac{y}{z} + v_0$$

W. Freeman

Intrinsic parameters





$$v' \sin(\theta) = v$$

$$u' = u - \cos(\theta) v' = u - \cot(\theta) v$$

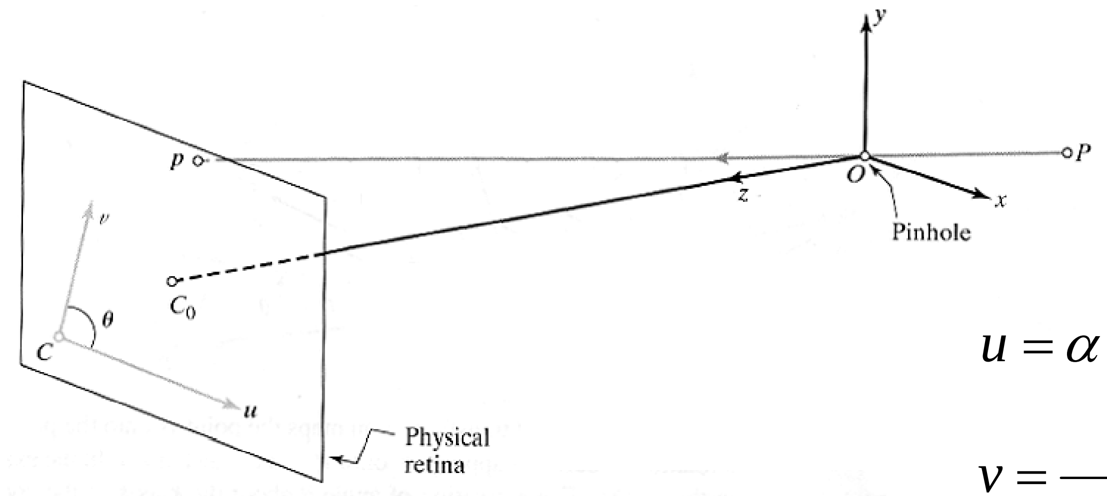
May be skew between camera pixel axes

$$u = \alpha \frac{x}{z} - \alpha \cot(\theta) \frac{y}{z} + u_0$$

$$v = \frac{\beta}{\sin(\theta)} \frac{y}{z} + v_0$$

W. Freeman

Intrinsic parameters, homogeneous coordinates



$$u = \alpha \frac{x}{z} - \alpha \cot(\theta) \frac{y}{z} + u_0$$

$$v = \frac{\beta}{\sin(\theta)} \frac{y}{z} + v_0$$

Using homogenous coordinates, we can write this as:

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha & -\alpha \cot(\theta) & u_0 & 0 \\ 0 & \frac{\beta}{\sin(\theta)} & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}$$

or:

In pixels →

$$\vec{p} = K \; {}^{C}\vec{p}$$

In camera-based coords

W. Freeman

Extrinsic parameters: translation and rotation of camera frame

$$^{C}\vec{p} = {}^{C}_{W}R \; {}^{W}\vec{p} + {}^{C}_{W}\vec{t}$$

Non-homogeneous coordinates

$$\begin{pmatrix} {}^{C}\vec{p} \\ \\ \end{pmatrix} = \begin{pmatrix} - & - & - & | \\ - & {}^{C}_{W}R & - & {}^{C}_{W}\vec{t} \\ - & - & - & | \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} {}^{W}\vec{p} \\ \\ \end{pmatrix}$$

Homogeneous coordinates

W. Freeman

Combining extrinsic and intrinsic calibration parameters, in homogeneous coordinates

pixels

Intrinsic

$$\vec{p} = K \; {}^{C}\vec{p}$$

World coordinates

Camera coordinates

$$\begin{pmatrix} {}^{C}\vec{p} \end{pmatrix} = \begin{pmatrix} {}^{C}_{W}R & {}^{C}_{W}\vec{t} \\ 0 \; 0 \; 0 & 1 \end{pmatrix} \begin{pmatrix} {}^{W}\vec{p} \end{pmatrix}$$

Extrinsic

$$\vec{p} = K \begin{pmatrix} {}^{C}_{W}R & {}^{C}_{W}\vec{t} \\ 0 \; 0 \; 0 & 1 \end{pmatrix} {}^{W}\vec{p}$$

$$\vec{p} = M \; {}^{W}\vec{p}$$

Forsyth&Ponce

W. Freeman

Other ways to write the same equation

pixel coordinates

world coordinates

$$\vec{p} = M \; {}^{W}\vec{p}$$

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} . & m_1^T & . & . \\ . & m_2^T & . & . \\ . & m_3^T & . & . \end{pmatrix} \begin{pmatrix} {}^{W}p_x \\ {}^{W}p_y \\ {}^{W}p_z \\ 1 \end{pmatrix}$$

Conversion back from homogeneous coordinates leads to:

$$\begin{cases} u = \dfrac{m_1 \cdot \vec{P}}{m_3 \cdot \vec{P}} \\[2ex] v = \dfrac{m_2 \cdot \vec{P}}{m_3 \cdot \vec{P}} \end{cases}$$

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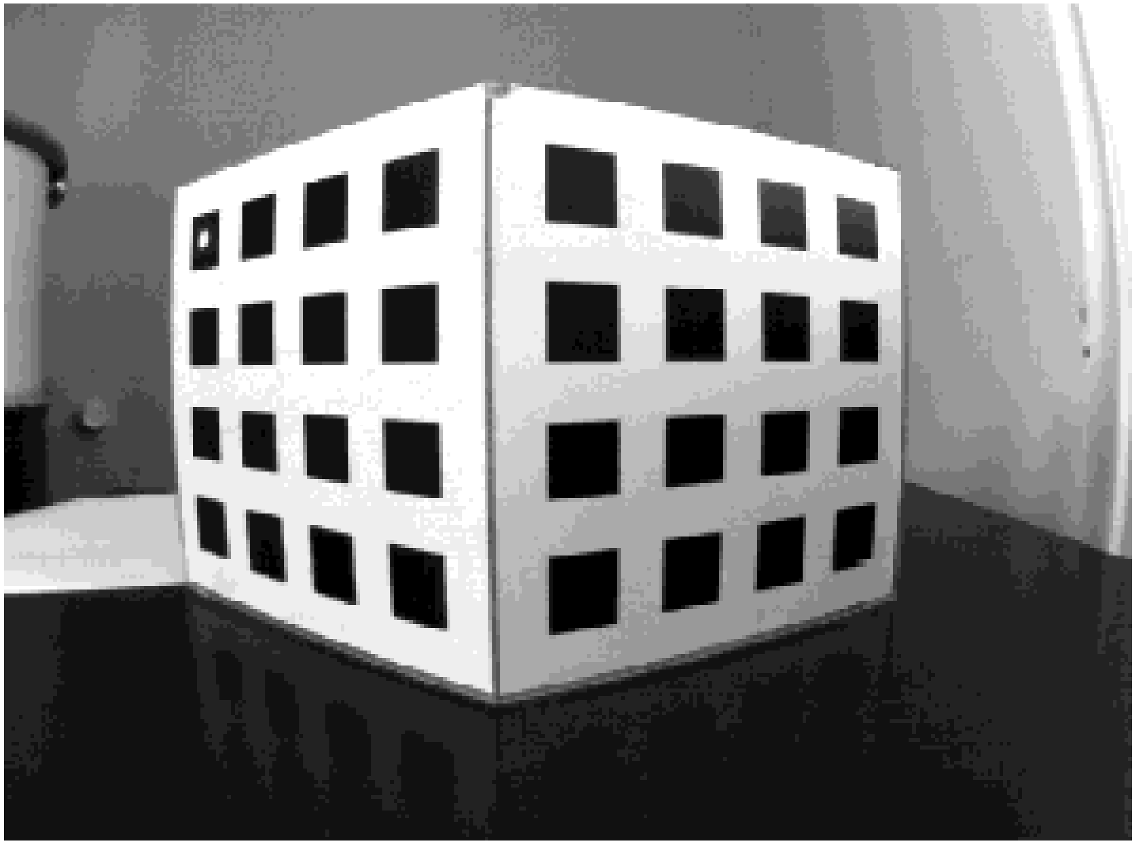
Calibration target



The Opti-CAL Calibration Target Image

Find the position, u_i and v_i, in pixels, of each calibration object feature point.

http://www.kinetic.bc.ca/CompVision/opti-CAL.html

Camera calibration

From before, we had these equations relating image positions,
u,v, to points at 3-d positions P (in homogeneous coordinates):

$$u = \frac{m_1 \cdot \vec{P}}{m_3 \cdot \vec{P}}$$

$$v = \frac{m_2 \cdot \vec{P}}{m_3 \cdot \vec{P}}$$

So for each feature point, i, we have:

$$(m_1 - u_i m_3) \cdot \vec{P}_i = 0$$
$$(m_2 - v_i m_3) \cdot \vec{P}_i = 0$$

W. Freeman

Camera calibration

Stack all these measurements of i=1…n points

$$(m_1 - u_i m_3) \cdot \vec{P}_i = 0$$
$$(m_2 - v_i m_3) \cdot \vec{P}_i = 0$$

into a big matrix:

$$\begin{pmatrix} P_1^T & 0^T & -u_1 P_1^T \\ 0^T & P_1^T & -v_1 P_1^T \\ \cdots & \cdots & \cdots \\ P_n^T & 0^T & -u_n P_n^T \\ 0^T & P_n^T & -v_n P_n^T \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix}$$

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Camera calibration

In vector form:

$$\begin{pmatrix} P_1^T & 0^T & -u_1 P_1^T \\ 0^T & P_1^T & -v_1 P_1^T \\ \cdots & \cdots & \cdots \\ P_n^T & 0^T & -u_n P_n^T \\ 0^T & P_n^T & -v_n P_n^T \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix}$$

Showing all the elements:

$$\begin{pmatrix} P_{1x} & P_{1y} & P_{1z} & 1 & 0 & 0 & 0 & 0 & -u_1 P_{1x} & -u_1 P_{1y} & -u_1 P_{1z} & -u_1 \\ 0 & 0 & 0 & 0 & P_{1x} & P_{1y} & P_{1z} & 1 & -v_1 P_{1x} & -v_1 P_{1y} & -v_1 P_{1z} & -v_1 \\ & & & & & & & \cdots & \cdots & \cdots & & \\ P_{nx} & P_{ny} & P_{nz} & 1 & 0 & 0 & 0 & 0 & -u_n P_{nx} & -u_n P_{ny} & -u_n P_{nz} & -u_n \\ 0 & 0 & 0 & 0 & P_{nx} & P_{ny} & P_{nz} & 1 & -v_n P_{nx} & -v_n P_{ny} & -v_n P_{nz} & -v_n \end{pmatrix} \begin{pmatrix} m_{11} \\ m_{12} \\ m_{13} \\ m_{14} \\ m_{21} \\ m_{22} \\ m_{23} \\ m_{24} \\ m_{31} \\ m_{32} \\ m_{33} \\ m_{34} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix}$$

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Camera calibration

$$\begin{pmatrix} P_{1x} & P_{1y} & P_{1z} & 1 & 0 & 0 & 0 & 0 & -u_1P_{1x} & -u_1P_{1y} & -u_1P_{1z} & -u_1 \\ 0 & 0 & 0 & 0 & P_{1x} & P_{1y} & P_{1z} & 1 & -v_1P_{1x} & -v_1P_{1y} & -v_1P_{1z} & -v_1 \\ & & & & & & \cdots & \cdots & \cdots & & & \\ P_{nx} & P_{ny} & P_{nz} & 1 & 0 & 0 & 0 & 0 & -u_nP_{nx} & -u_nP_{ny} & -u_nP_{nz} & -u_n \\ 0 & 0 & 0 & 0 & P_{nx} & P_{ny} & P_{nz} & 1 & -v_nP_{nx} & -v_nP_{ny} & -v_nP_{nz} & -v_n \end{pmatrix} \begin{pmatrix} m_{11} \\ m_{12} \\ m_{13} \\ m_{14} \\ m_{21} \\ m_{22} \\ m_{23} \\ m_{24} \\ m_{31} \\ m_{32} \\ m_{33} \\ m_{34} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix}$$

Q m = 0

We want to solve for the unit vector m (the stacked one) that minimizes

$$\left|Qm\right|^2$$

The minimum eigenvector of the matrix Q^TQ gives us that (see Forsyth&Ponce, 3.1), because it is the unit vector x that minimizes $x^T Q^TQ\ x$.

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Camera calibration

Once you have the M matrix, can recover the intrinsic and extrinsic parameters as in Forsyth&Ponce, sect. 3.2.2.

$$\mathcal{M} = \begin{pmatrix} \alpha \boldsymbol{r}_1^T - \alpha \cot\theta \boldsymbol{r}_2^T + u_0 \boldsymbol{r}_3^T & \alpha t_x - \alpha \cot\theta t_y + u_0 t_z \\ \dfrac{\beta}{\sin\theta} \boldsymbol{r}_2^T + v_0 \boldsymbol{r}_3^T & \dfrac{\beta}{\sin\theta} t_y + v_0 t_z \\ \boldsymbol{r}_3^T & t_z \end{pmatrix}$$

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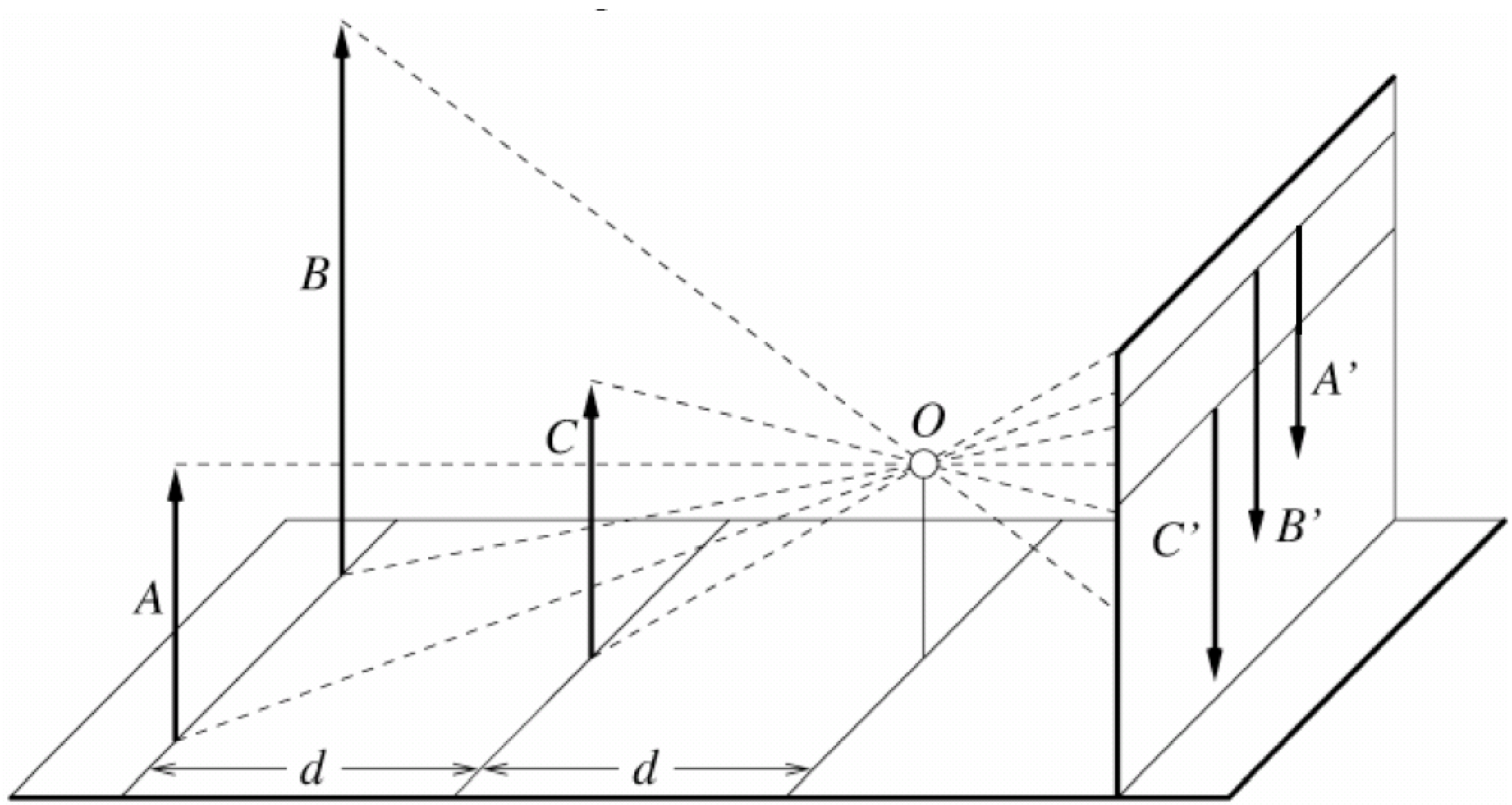
Recall, perspective effects…

- Far away objects appear smaller



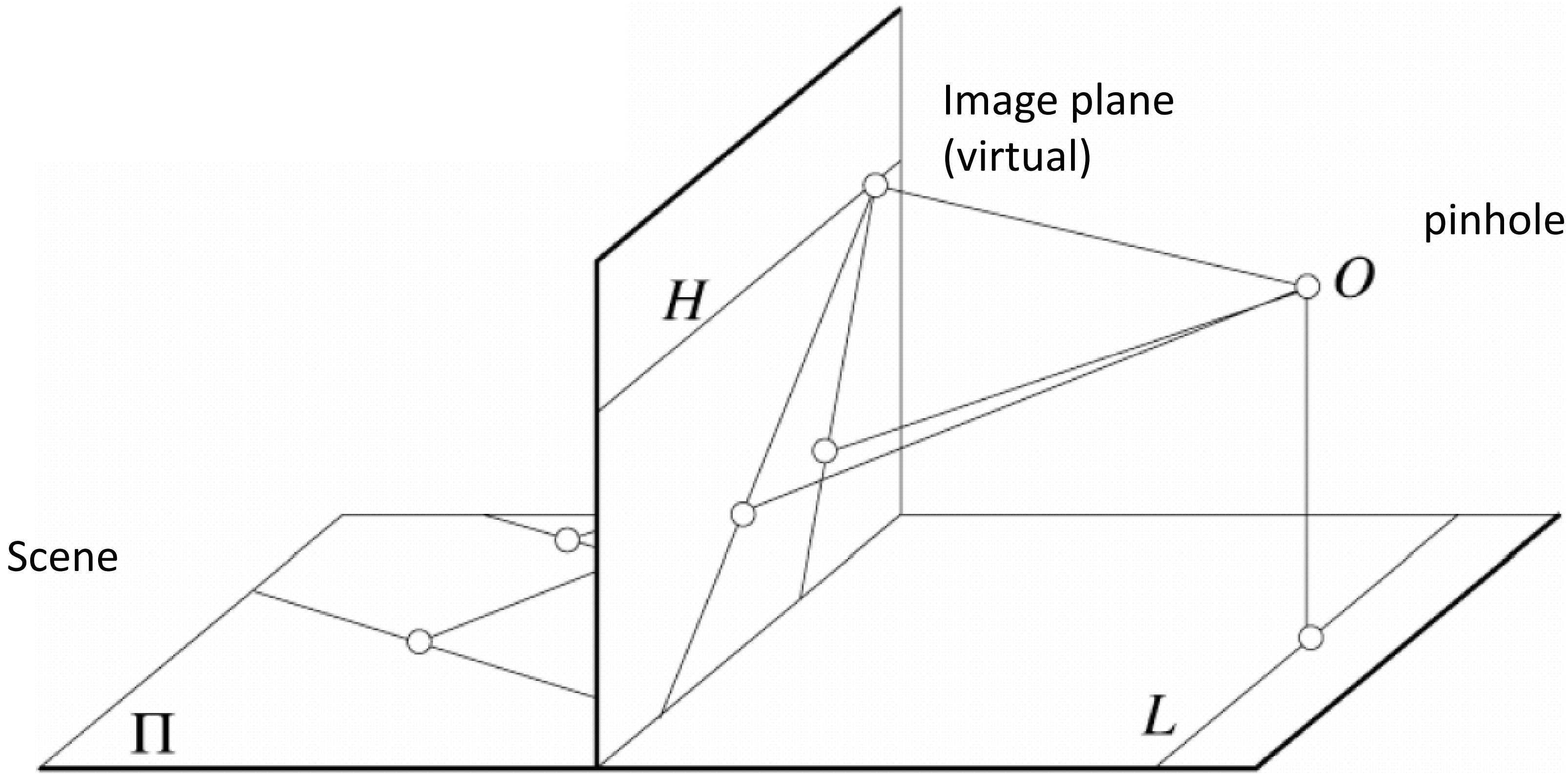
Forsyth and Ponce

Perspective effects

Perspective effects

Perspective effects

- Parallel lines in the scene intersect in the image
- Converge in image on horizon line



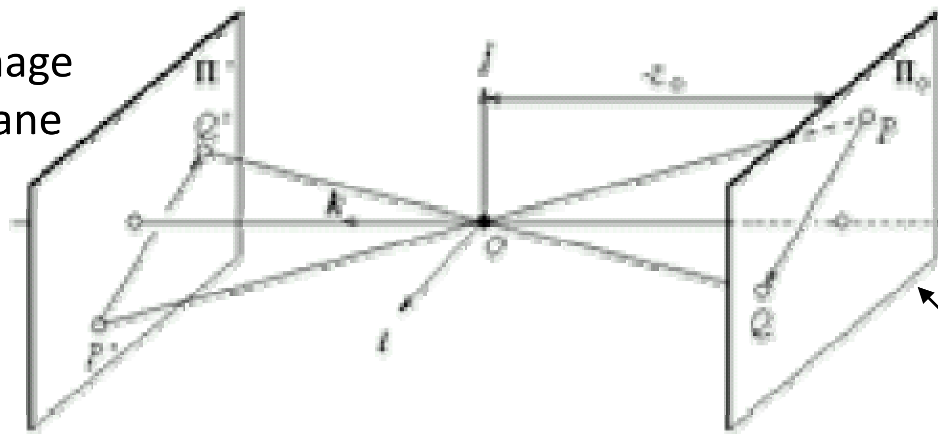
Projection properties

- Many-to-one: any points along same ray map to same point in image
- Points → ?
  - **points**
- Lines → ?
  - **lines** (collinearity preserved)
- Distances and angles are / are not **?** preserved
  - **are not**
- Degenerate cases:
  - Line through focal point projects to a point.
  - Plane through focal point projects to line
  - Plane perpendicular to image plane projects to part of the image.

Weak perspective

- Approximation: treat magnification as constant
- Assumes scene depth << average distance to camera

Image plane



World points:

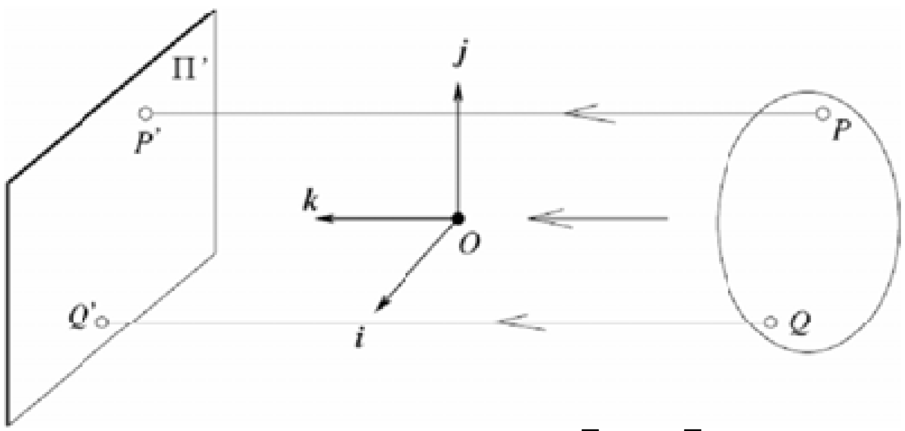
$z = z_0$

$$x' = f\frac{x}{z} \approx \frac{f}{z_0}x$$

$$y' = f\frac{y}{z} \approx \frac{f}{z_0}y$$

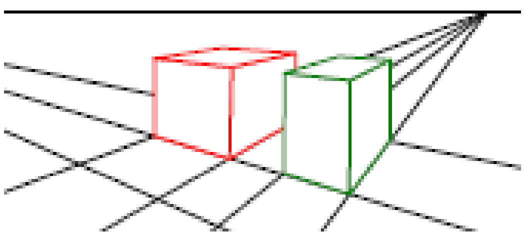
Orthographic projection

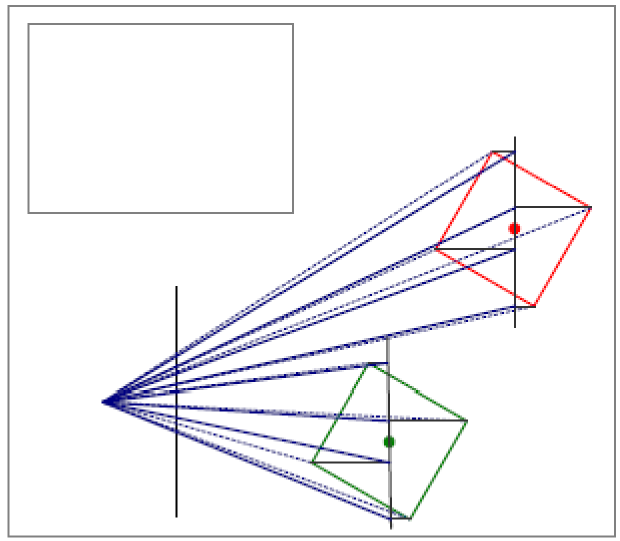
- Given camera at **constant** distance from scene
- World points projected along rays parallel to optical access



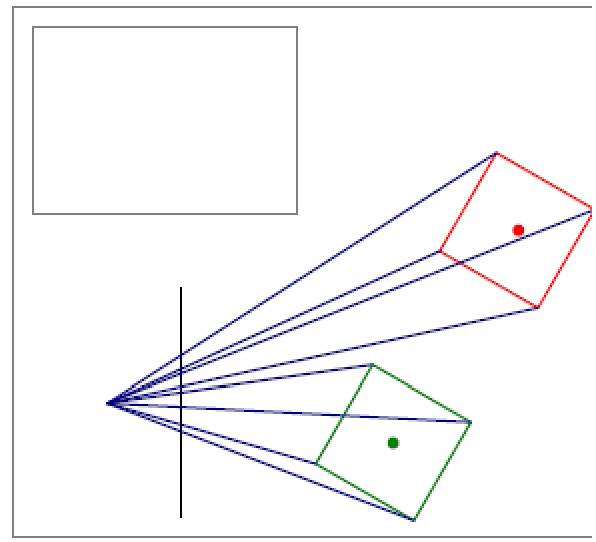
$$x' = x$$
$$y' = y$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$





(c) scaled orthography



(e) perspective

$$x = [sI_{2\times 2}|0]\ p.$$

$$x = \mathcal{P}_z(p) = \begin{bmatrix} x/z \\ y/z \\ 1 \end{bmatrix}.$$

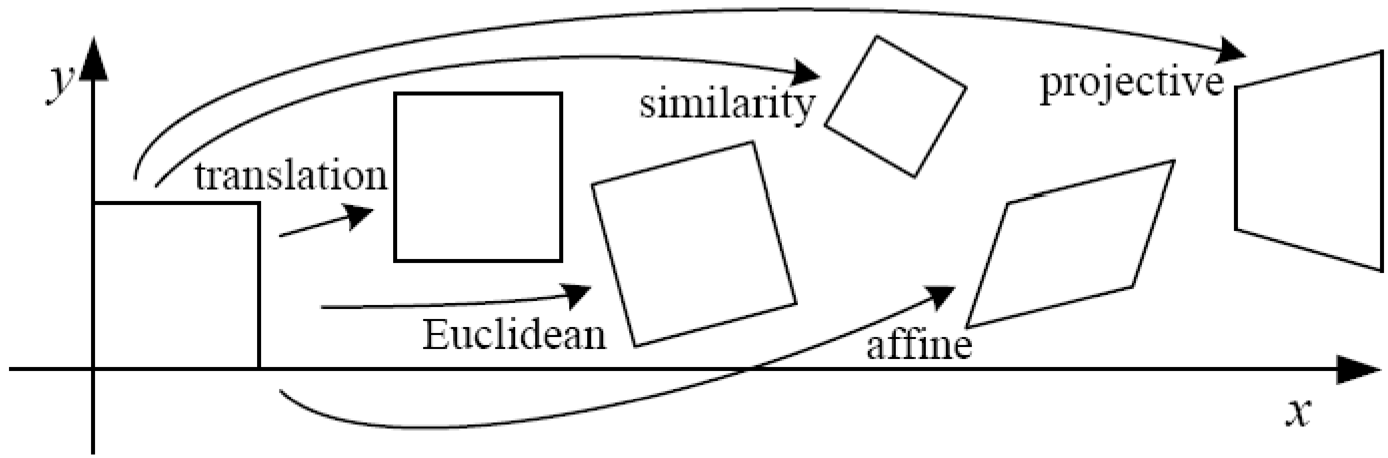
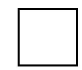
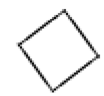
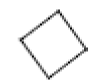
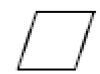
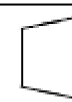
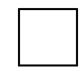
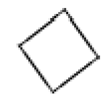
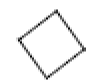
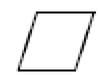
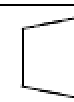


Figure 2.4: *Basic set of 2D planar transformations*

2D

Name	Matrix	# D.O.F.	Preserves:	Icon
translation	$\left[\begin{array}{c\|c} \boldsymbol{I} & \boldsymbol{t} \end{array}\right]_{2\times3}$	2	orientation $+\cdots$	
rigid (Euclidean)	$\left[\begin{array}{c\|c} \boldsymbol{R} & \boldsymbol{t} \end{array}\right]_{2\times3}$	3	lengths $+\cdots$	
similarity	$\left[\begin{array}{c\|c} s\boldsymbol{R} & \boldsymbol{t} \end{array}\right]_{2\times3}$	4	angles $+\cdots$	
affine	$\left[\begin{array}{c} \boldsymbol{A} \end{array}\right]_{2\times3}$	6	parallelism $+\cdots$	
projective	$\left[\begin{array}{c} \tilde{\boldsymbol{H}} \end{array}\right]_{3\times3}$	8	straight lines	

3D

Name	Matrix	# D.O.F.	Preserves:	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{3\times4}$	3	orientation $+\cdots$	
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{3\times4}$	6	lengths $+\cdots$	
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{3\times4}$	7	angles $+\cdots$	
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{3\times4}$	12	parallelism $+\cdots$	
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{4\times4}$	15	straight lines	

Other types of projection

- Lots of intriguing variants…
- (I'll just mention a few fun ones)

S. Seitz

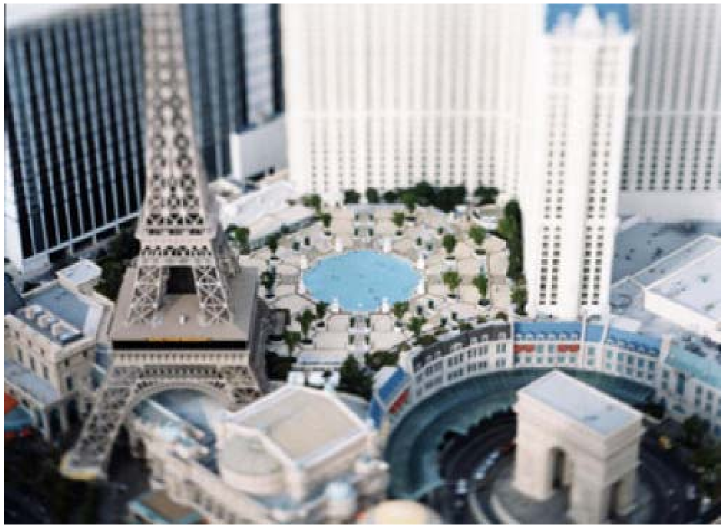
360 degree field of view…

- Basic approach
  - Take a photo of a parabolic mirror with an orthographic lens (Nayar)
  - Or buy one a lens from a variety of omnicam manufacturers…
    - See http://www.cis.upenn.edu/~kostas/omni.html

S. Seitz

Tilt-shift

http://www.northlight-images.co.uk/article_pages/tilt_and_shift_ts-e.html



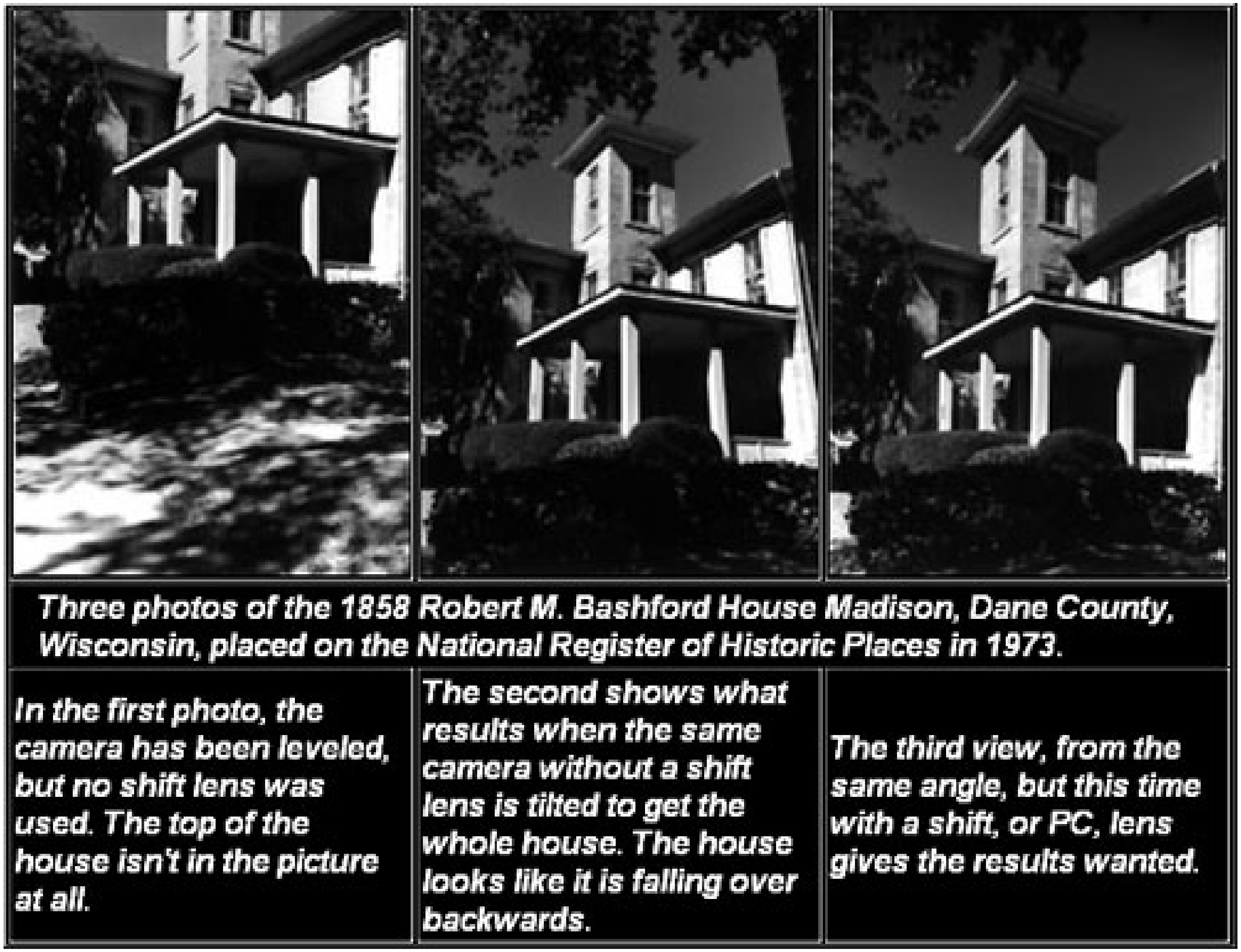
Titlt-shift images from Olivo Barbieri
and Photoshop imitations

S. Seitz

tilt, shift

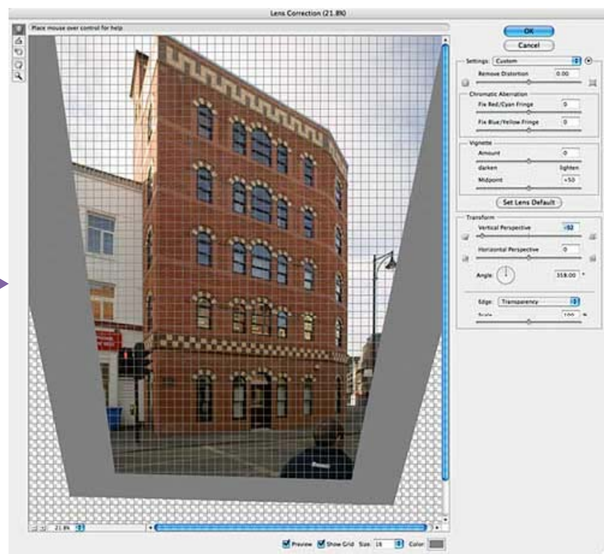
http://en.wikipedia.org/wiki/Tilt-shift_photography

Tilt-shift perspective correction



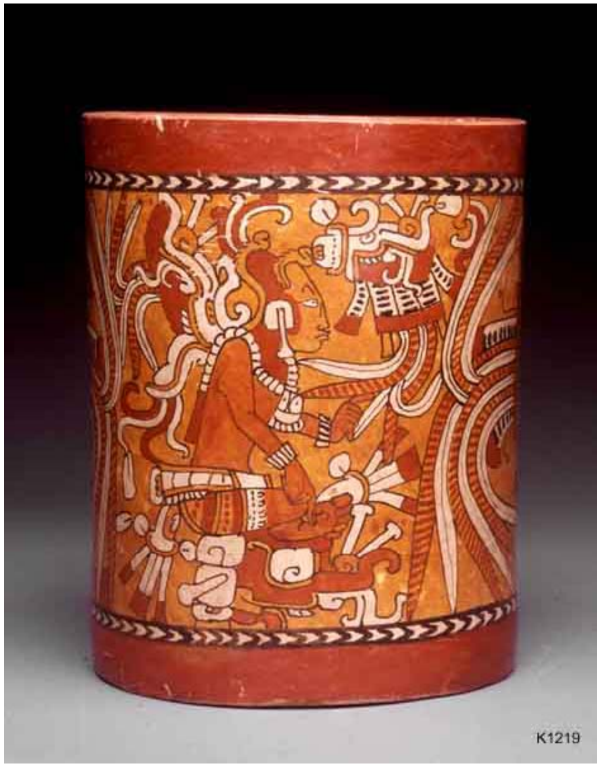
http://en.wikipedia.org/wiki/Tilt-shift_photography normal lens

tilt-shift lens



http://www.northlight-images.co.uk/article_pages/tilt_and_shift_ts-e.html

Rotating sensor (or object)

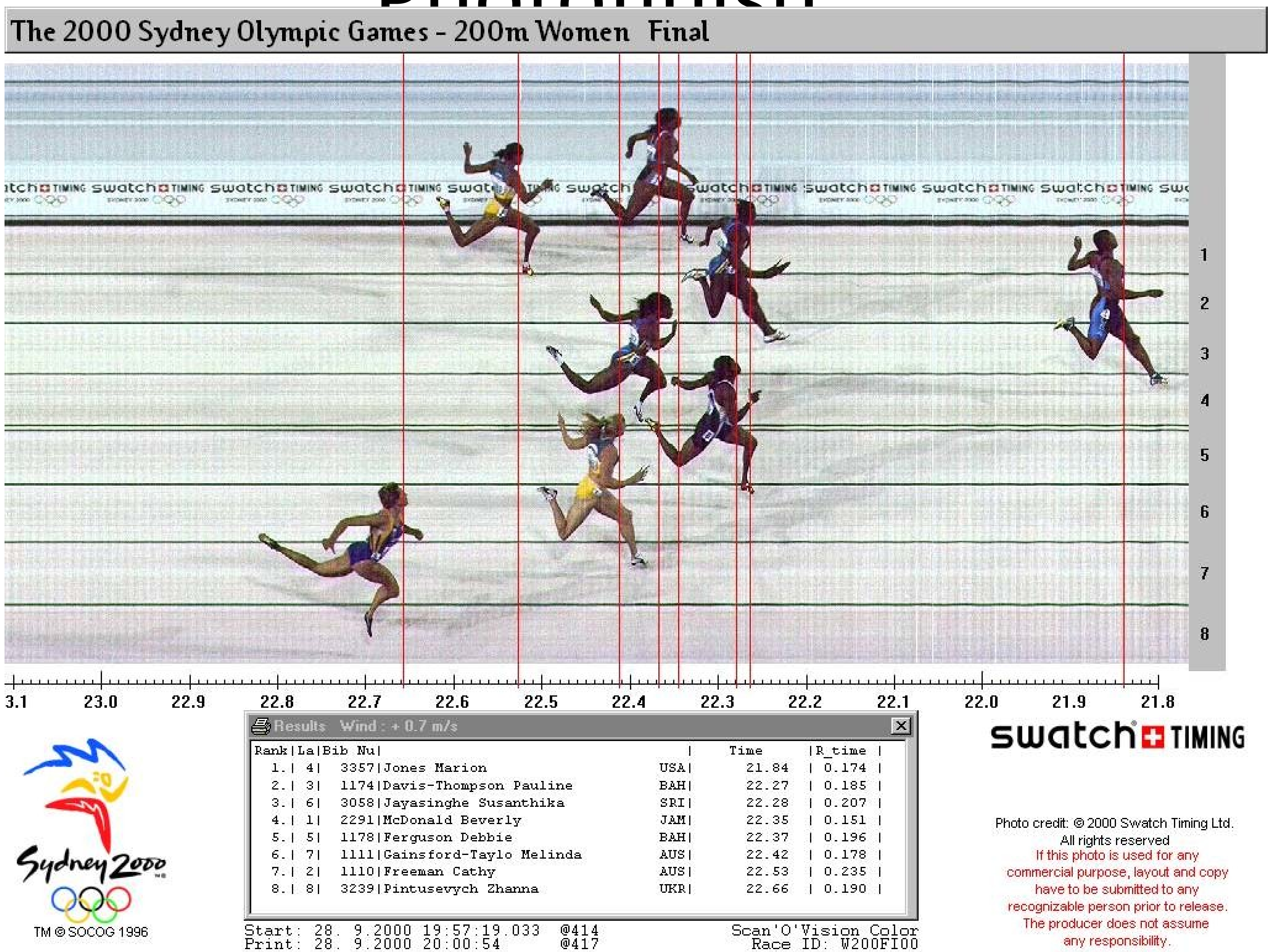


Rollout Photographs © Justin Kerr

http://research.famsi.org/kerrmaya.html

Also known as “cyclographs”, “peripheral images”

Photofinish



Physical parameters of image formation

- Geometric
  - Type of projection
  - Camera pose
- Optical
  - Sensor’s lens type
  - focal length, field of view, aperture
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  - Type, direction, intensity of light reaching sensor
  - Surfaces’ reflectance properties
- Sensor
  - sampling, etc.

Pinhole size / aperture

How does the size of the aperture affect the image we'd get?

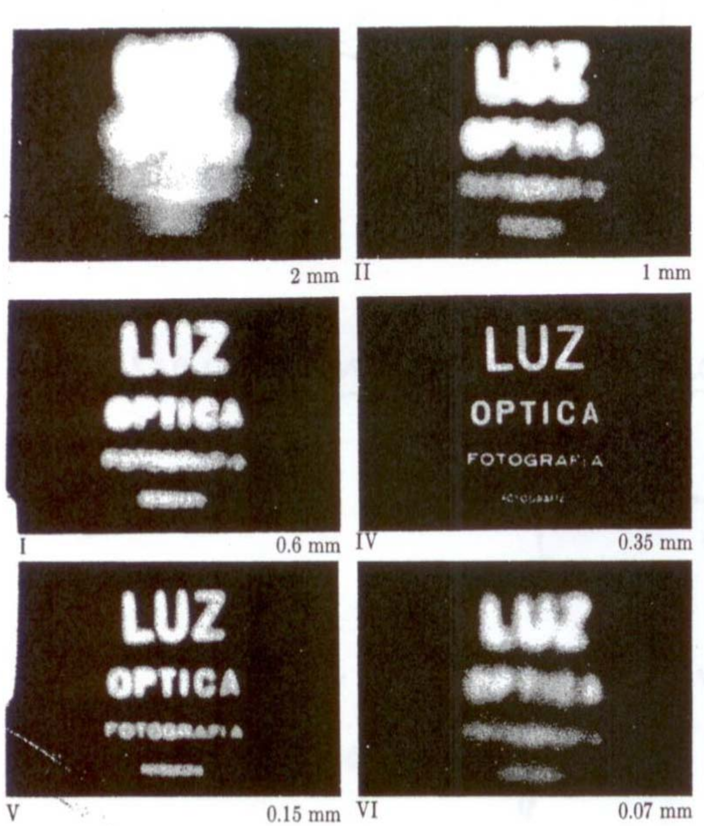
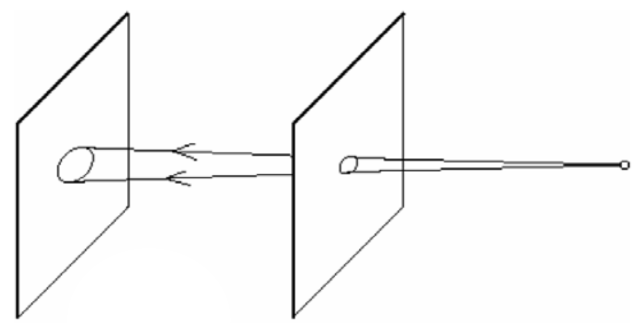


Fig. 5.96 The pinhole camera. Note the variation in image clarity as the hole diameter decreases. [Photos courtesy Dr. N. Joel, UNESCO.]

Larger

Smaller



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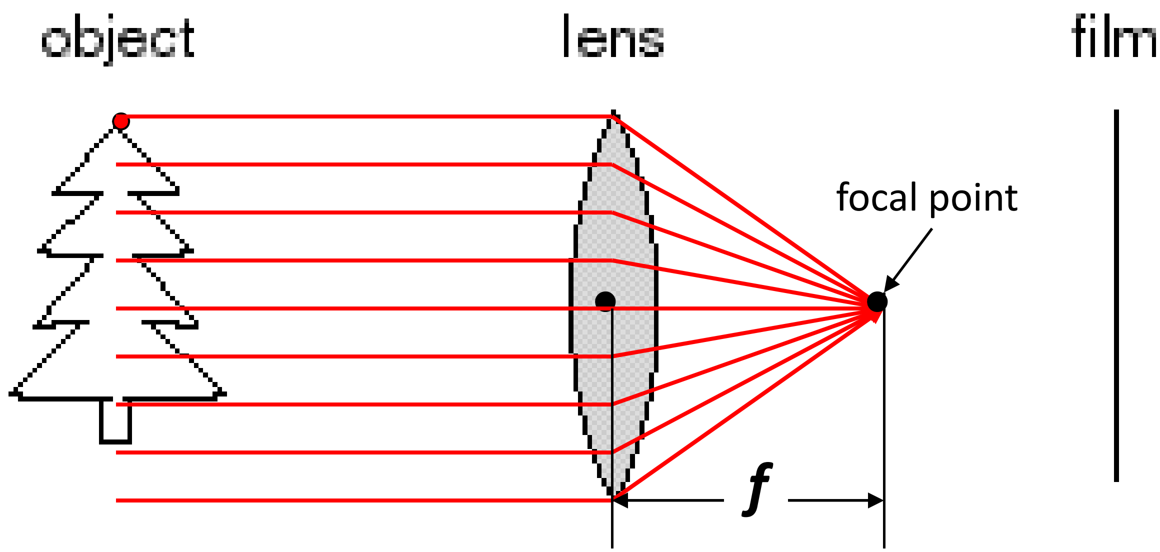
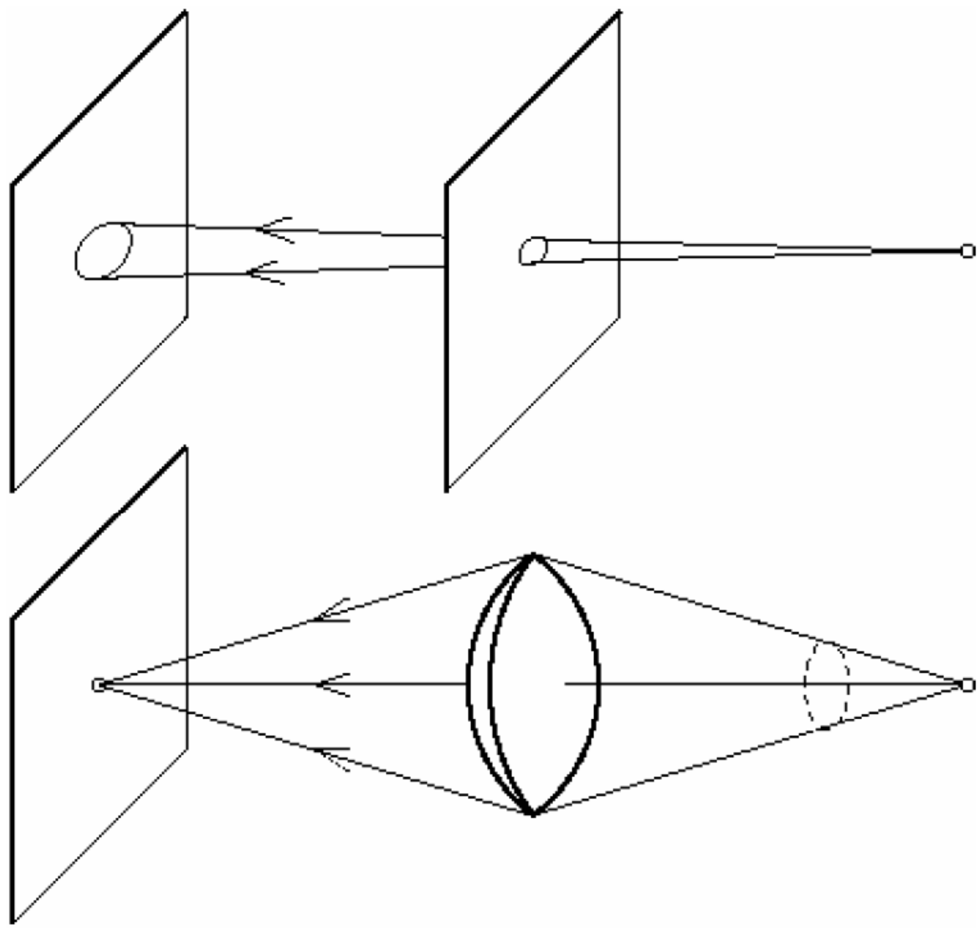
Adding a lens



- A lens focuses light onto the film
  - Rays passing through the center are not deviated
  - All parallel rays converge to one point on a plane located at the *focal length f*

Slide by Steve Seitz

Pinhole vs. lens



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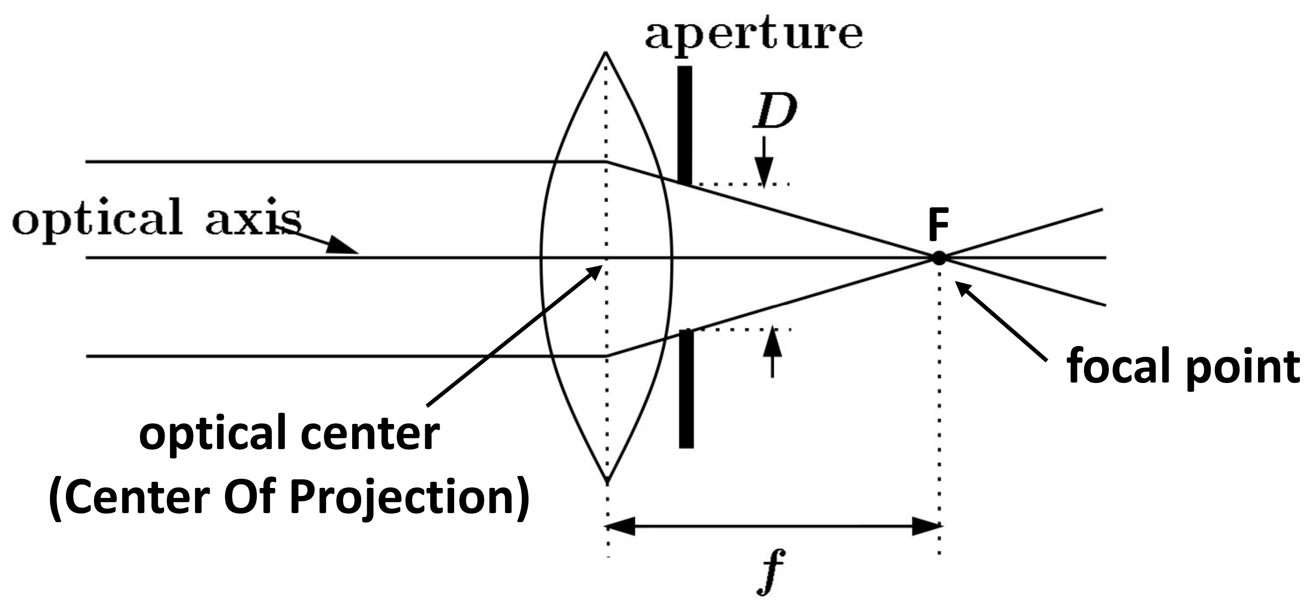
Cameras with lenses



- A lens focuses parallel rays onto a single focal point
- Gather more light, while keeping focus; make pinhole perspective projection practical

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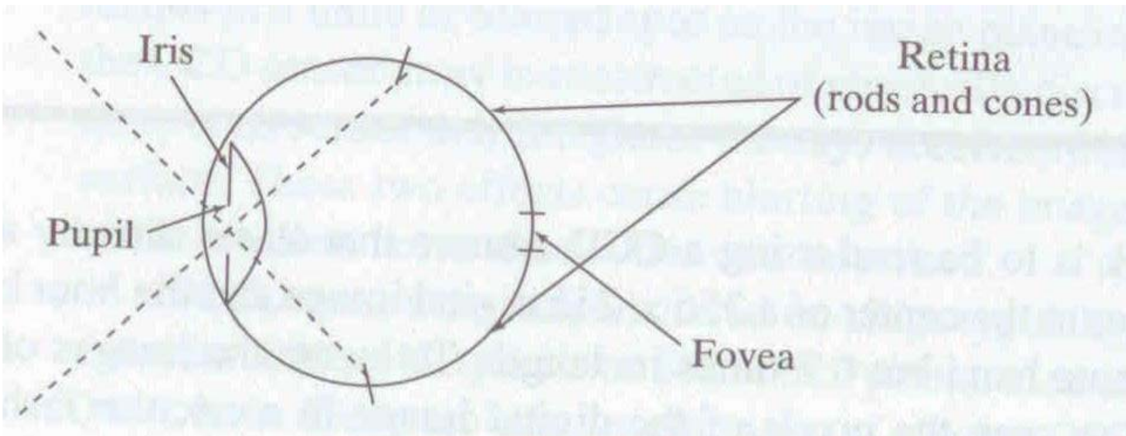
Human eye

Rough analogy with human visual system:



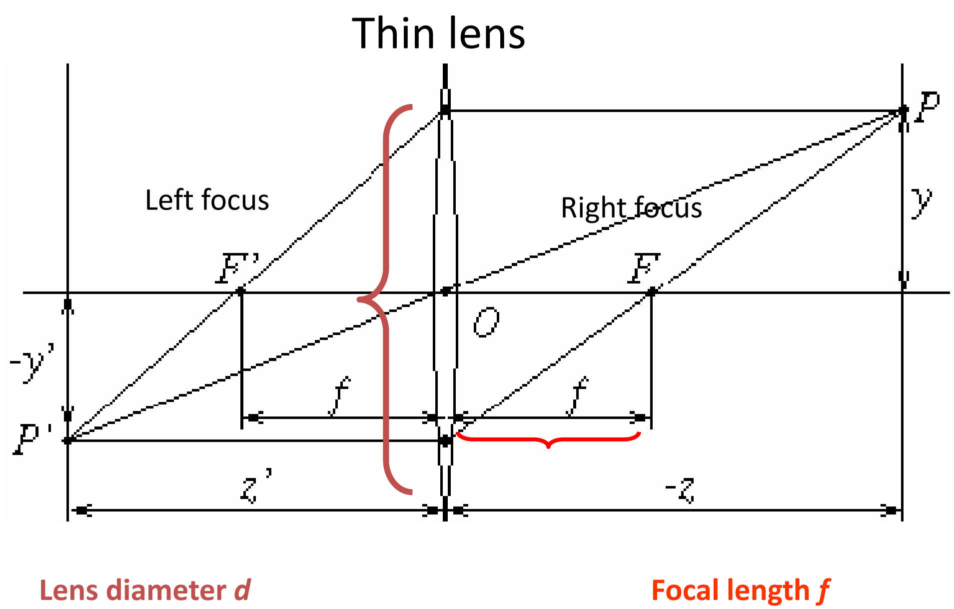
Pupil/Iris – control amount of light passing through lens

Retina - contains sensor cells, where image is formed

Fovea – highest concentration of cones

Fig from Shapiro and Stockman

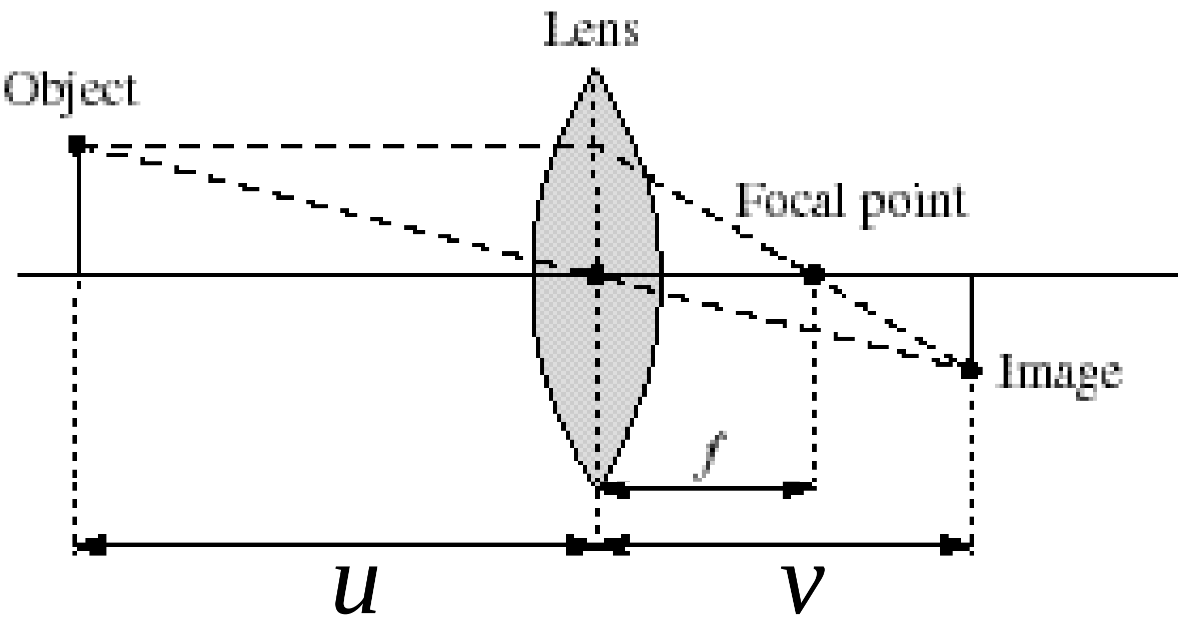
Thin lens



Rays entering parallel on one side go through focus on other, and vice versa.

In ideal case – all rays from P imaged at P'.

Thin lens equation



$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

- Any object point satisfying this equation is in focus

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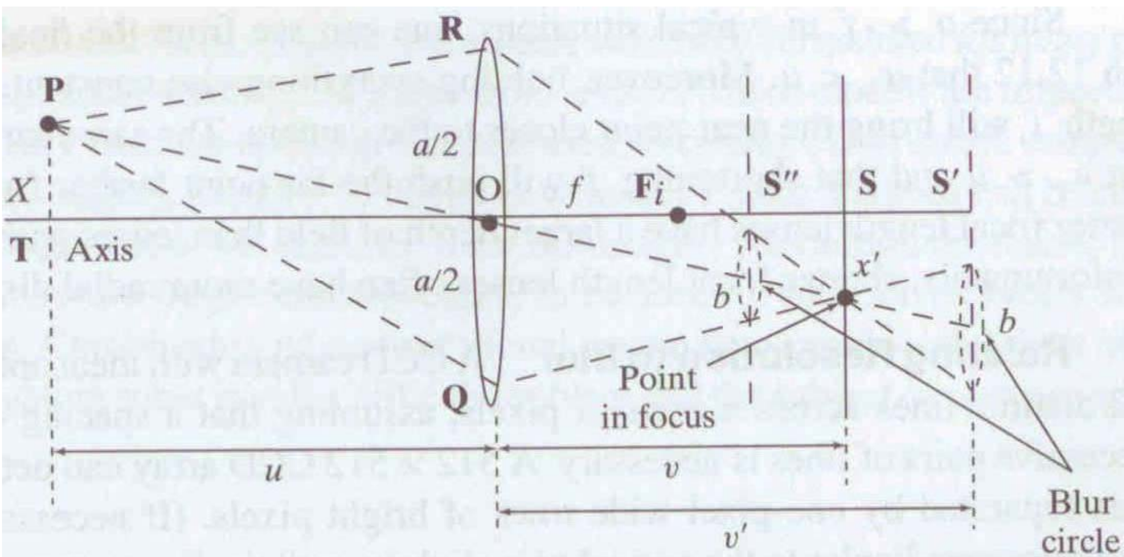
Focus and depth of field

Image credit: cambridgeincolour.com

Focus and depth of field

- Depth of field: distance between image planes where blur is tolerable



← "circles of confusion" →

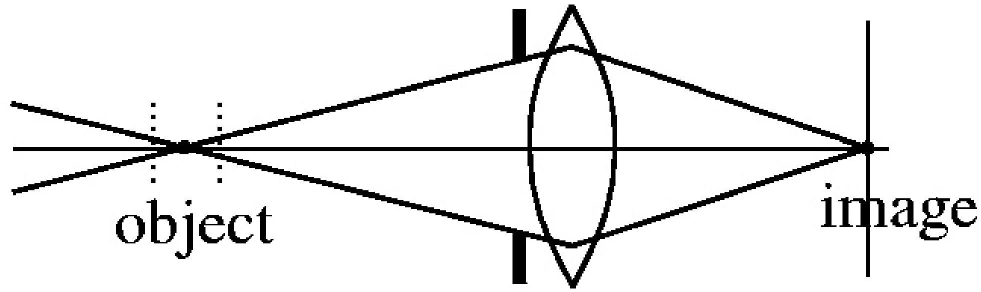
Thin lens: scene points at distinct depths come in focus at different image planes.

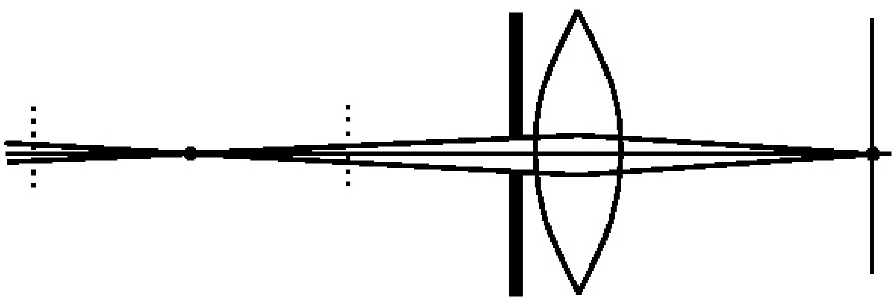
(Real camera lens systems have greater depth of field.)

Shapiro and Stockman

Focus and depth of field

- How does the aperture affect the depth of field?



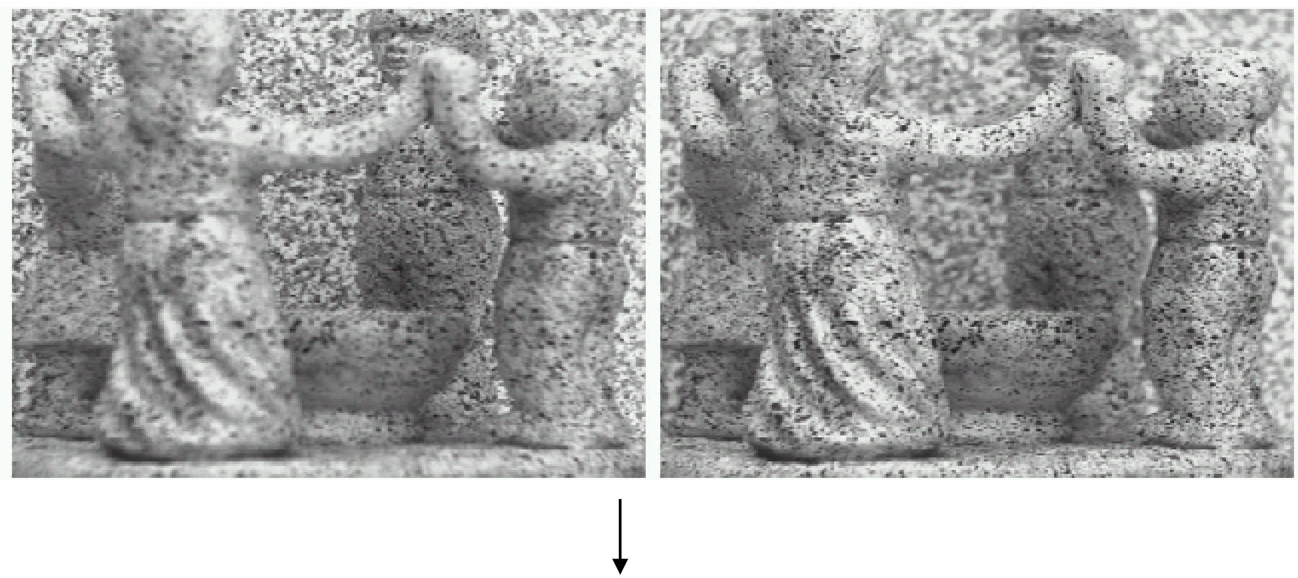


- A smaller aperture increases the range in which the object is approximately in focus

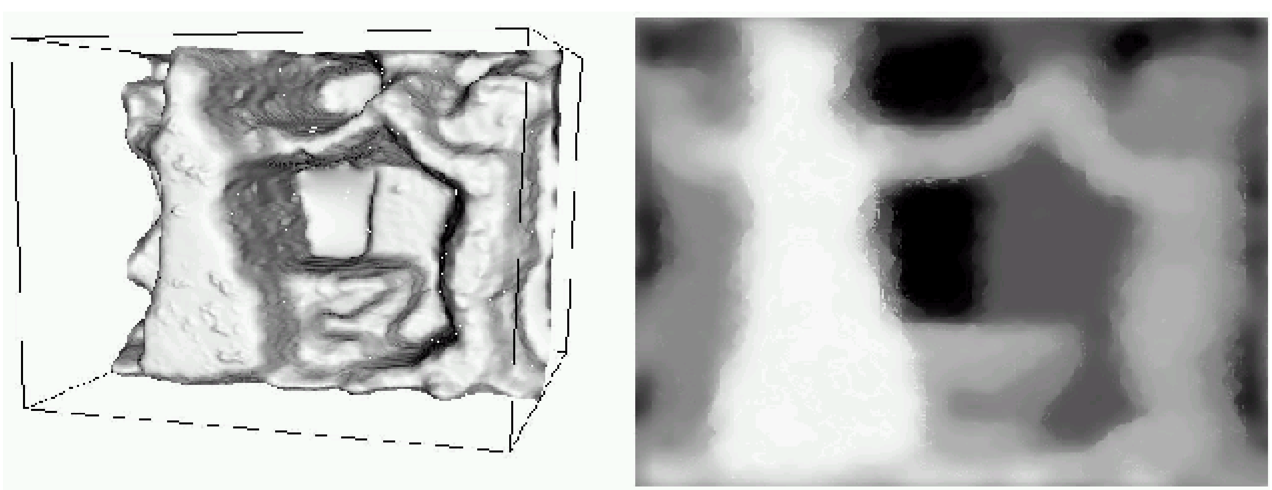
Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field

Slide from S. Seitz

Depth from focus



Images from same point of view, different camera parameters



3d shape / depth estimates

[figs from H. Jin and P. Favaro, 2002]

Field of view

- Angular measure of portion of 3d space seen by the camera

28 mm lens, 65.5° × 46.4°

50 mm lens, 39.6° × 27.0°

70 mm lens, 28.9° × 19.5°

210 mm lens, 9.8° × 6.5°

Images from http://en.wikipedia.org/wiki/Angle_of_view

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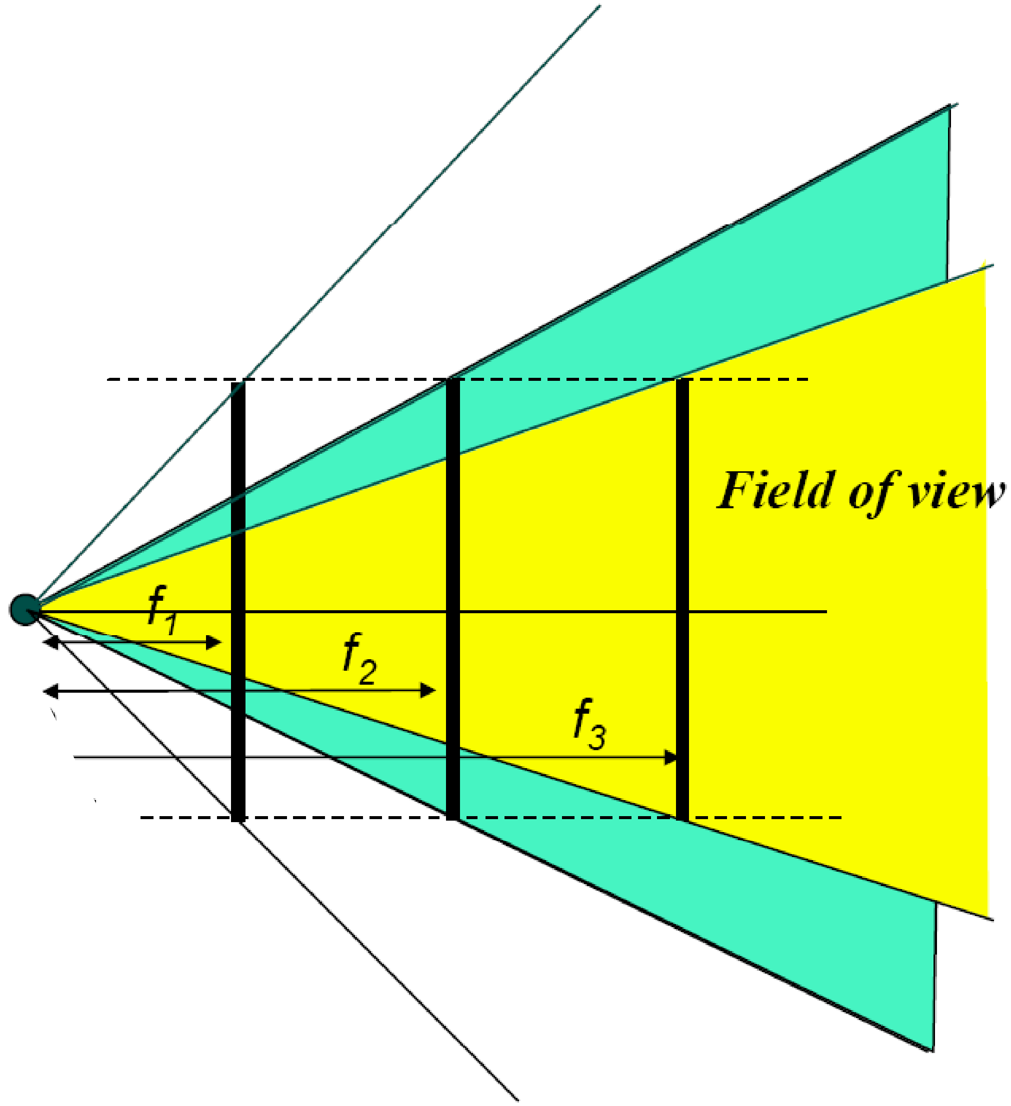
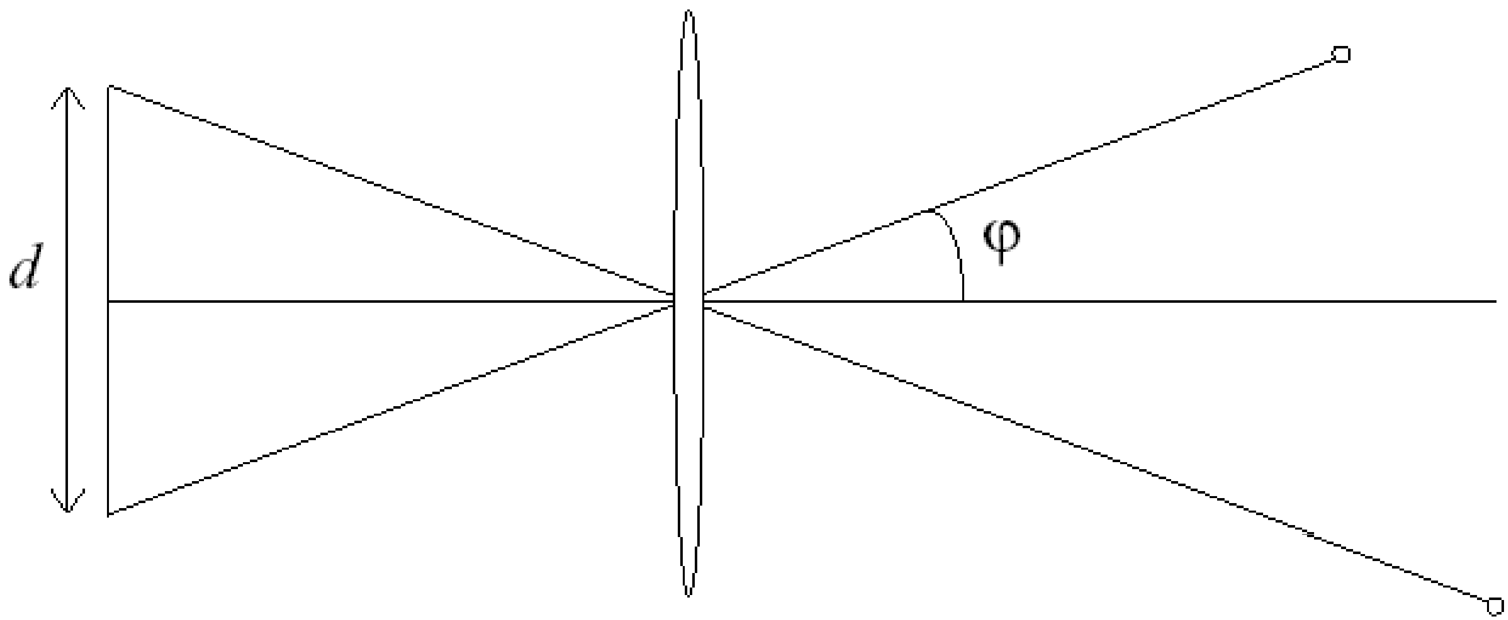
Field of view depends on focal length

- As ***f*** gets smaller, image becomes more *wide angle*
  - more world points project onto the finite image plane
- As ***f*** gets larger, image becomes more *telescopic*
  - smaller part of the world projects onto the finite image plane



from R. Duraiswami

Field of view depends on focal length



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

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

Smaller FOV = larger Focal Length

Slide by A. Efros

Vignetting

http://www.ptgui.com/examples/vigntutorial.html

http://www.tlucretius.net/Photo/eHolga.html

Vignetting

- "natural":

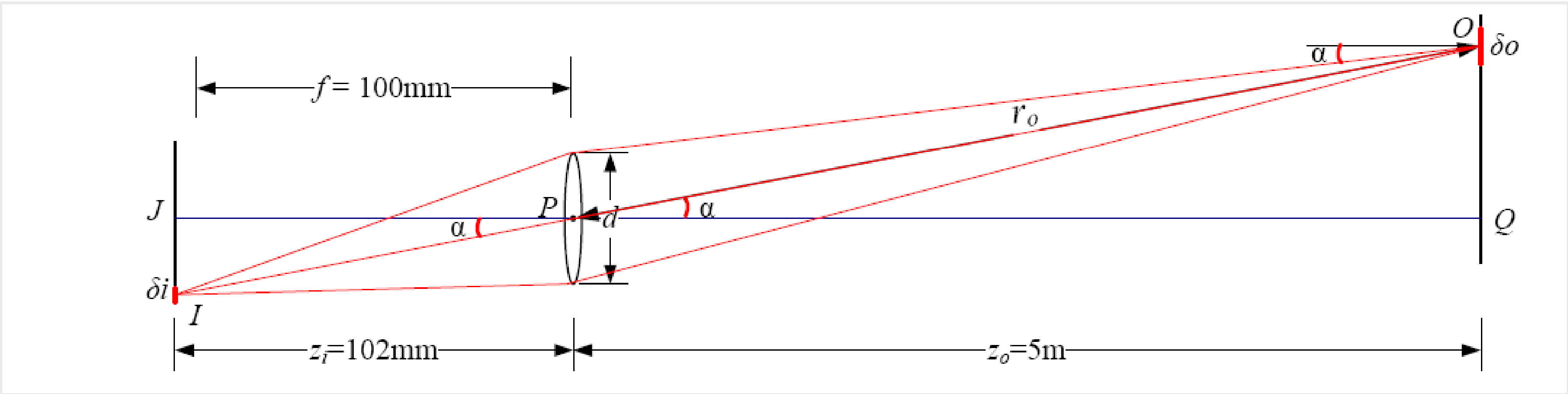
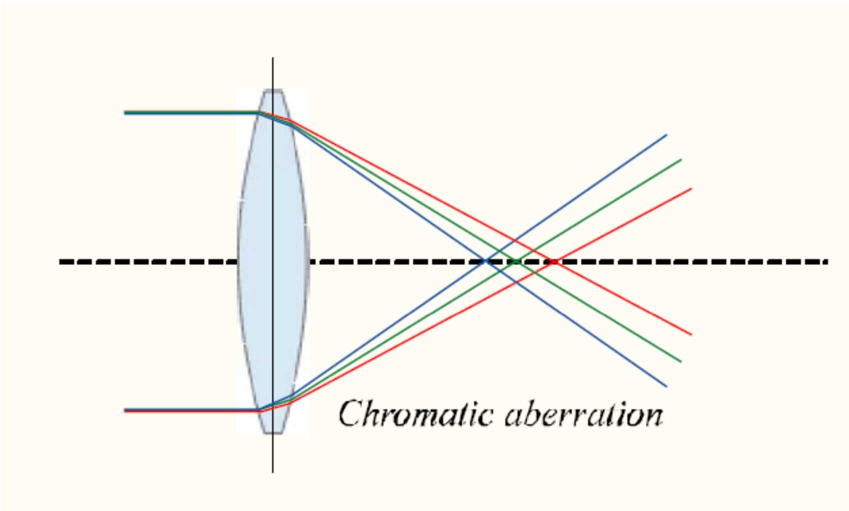


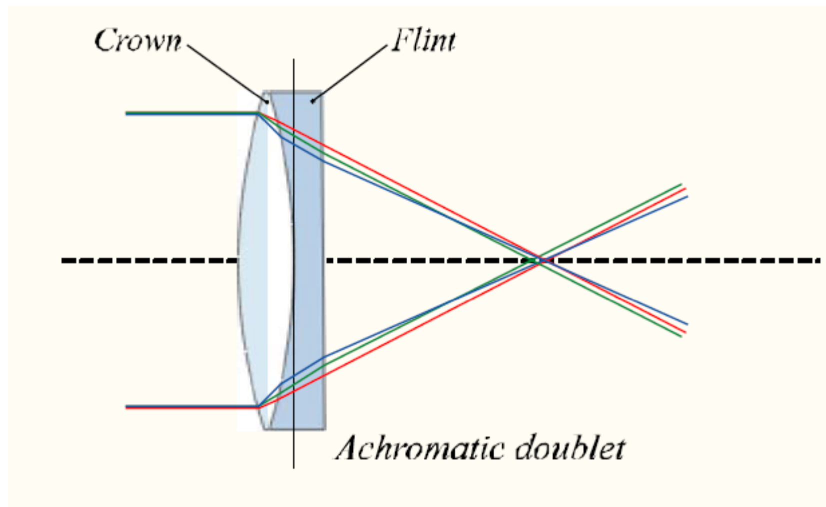
Figure 2.23: *The amount of light hitting a pixel of surface area δi depends on the square of the ratio of the aperture diameter d to the focal length f, as well as the fourth power of the off-axis angle α cosine, $\cos^4 \alpha$.*

- "mechanical": intrusion on optical path

Chromatic aberration

Chromatic aberration





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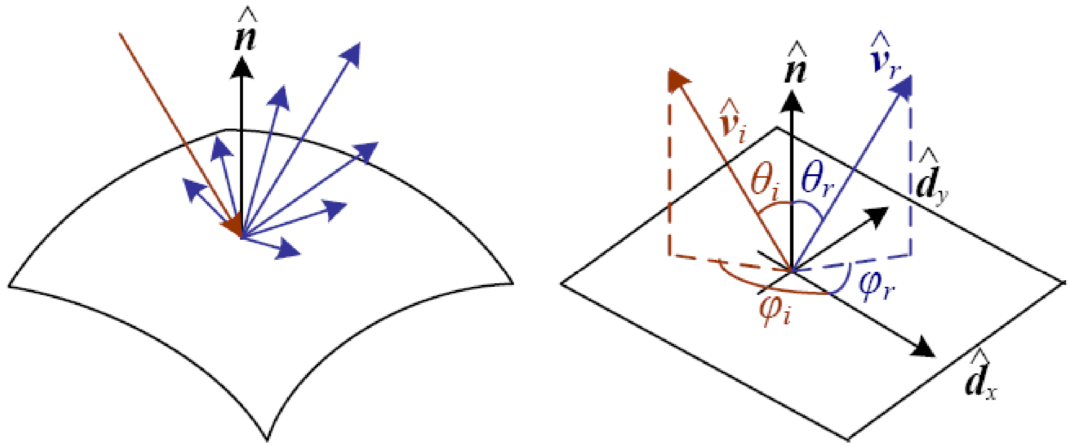
Environment map

$$L(\hat{\boldsymbol{v}}; \lambda),$$

http://www.sparse.org/3d.html

BDRF



(a) (b)

Figure 2.15: *(a) Light scattering when hitting a surface. (b) The bidirectional reflectance distribution function (BRDF)* $f(\theta_i, \phi_i, \theta_r, \phi_r)$ *is parameterized by the angles the incident* $\hat{\boldsymbol{v}}_i$ *and reflected* $\hat{\boldsymbol{v}}_r$ *light ray directions make with the local surface coordinate frame* $(\hat{\mathbf{d}}_x, \hat{\mathbf{d}}_y, \hat{\mathbf{n}})$.

For an isotropic material, we can simplify the BRDF to

$$f_r(\theta_i, \theta_r, |\phi_r - \phi_i|; \lambda) \;\text{ or }\; f_r(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{v}}_r, \hat{\boldsymbol{n}}; \lambda),$$

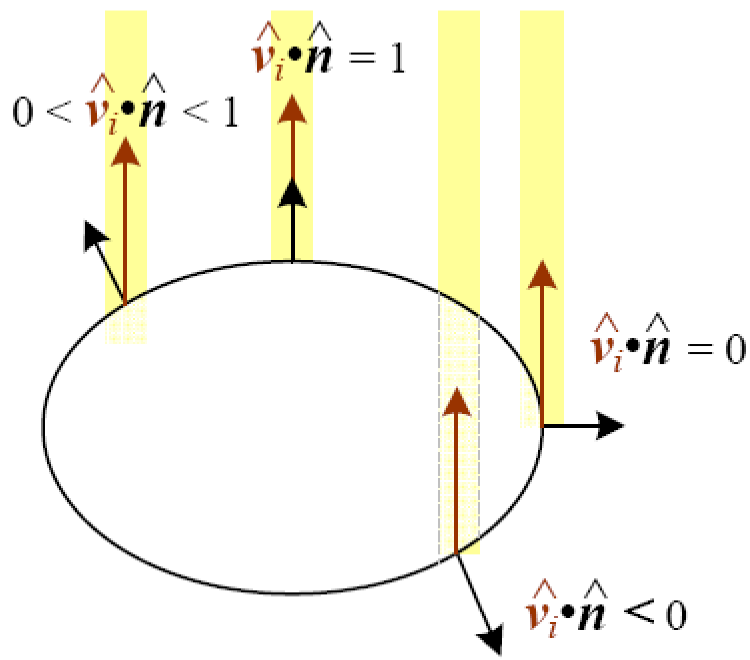
Diffuse / Lambertian

Figure 2.16: *This close-up of a statue shows both diffuse (smooth shading) and specular (shiny highlight) reflection, as well as the darkening in the grooves and creases due to reduced light visibility and interreflections. (Photo courtesy of Alyosha Efros.)*

While light is scattered uniformly in all directions, i.e., the BRDF is constant,

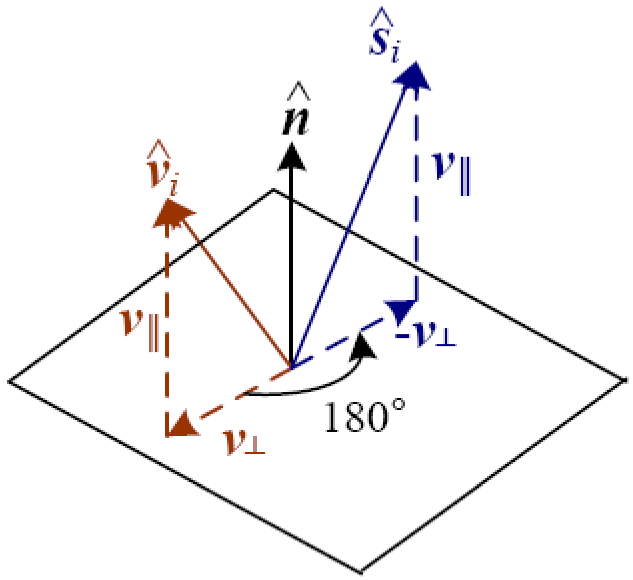
$$f_d(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{v}}_r, \hat{\boldsymbol{n}}; \lambda) = f_d(\lambda),$$

Foreshortening



The diminution of returned light caused by foreshortening *depends on $\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}$, the cosine of the angle between the incident light direction $\hat{\boldsymbol{v}}_i$ and the surface normal $\hat{\boldsymbol{n}}$.*

Specular reflection



Phong

- Diffuse+specular+ambient:

$$f_d(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{v}}_r, \hat{\boldsymbol{n}}; \lambda) = f_d(\lambda),$$

$$f_s(\theta_s; \lambda) = k_s(\lambda) \cos^{k_e} \theta_s,$$

$$f_a(\lambda) = k_a(\lambda) L_a(\lambda).$$

$$L_r(\hat{\boldsymbol{v}}_r; \lambda) = k_a(\lambda) L_a(\lambda) + k_d(\lambda) \sum_i L_i(\lambda) [\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+ + k_s(\lambda) \sum_i L_i(\lambda) (\hat{\boldsymbol{v}}_r \cdot \hat{\boldsymbol{s}}_i)^{k_e}.$$

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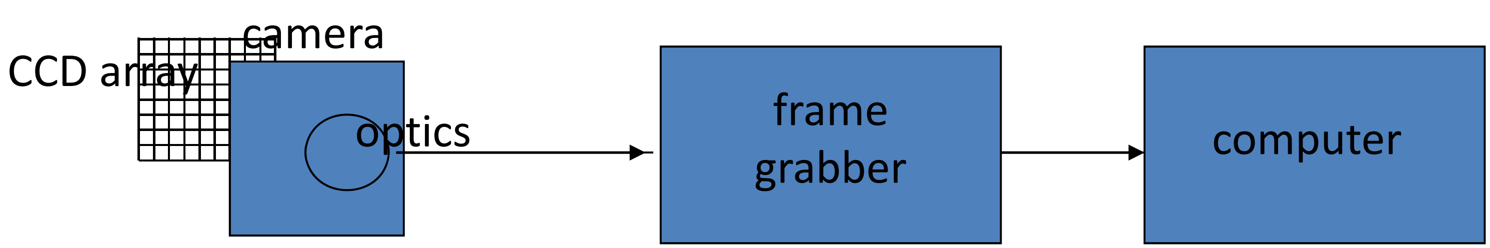
Digital cameras

- Film → sensor array
- Often an array of charge coupled devices
- Each CCD is light sensitive diode that converts photons (light energy) to electrons



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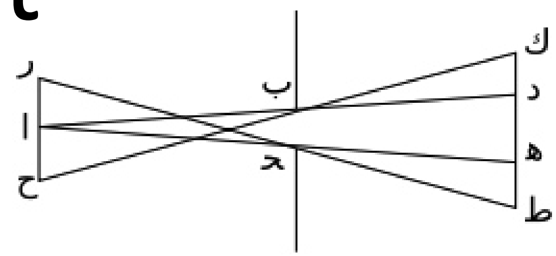
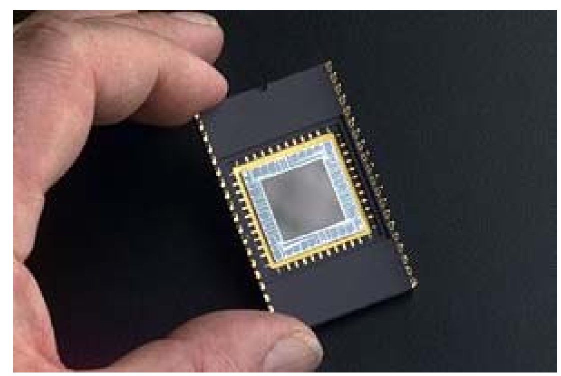
Historical context

- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD**: Sony Mavica (1981)
- **First fully digital camera:** Kodak DCS100 (1990)



Alhacen's notes

Niepce, "La Table Servie," 1822



CCD chip

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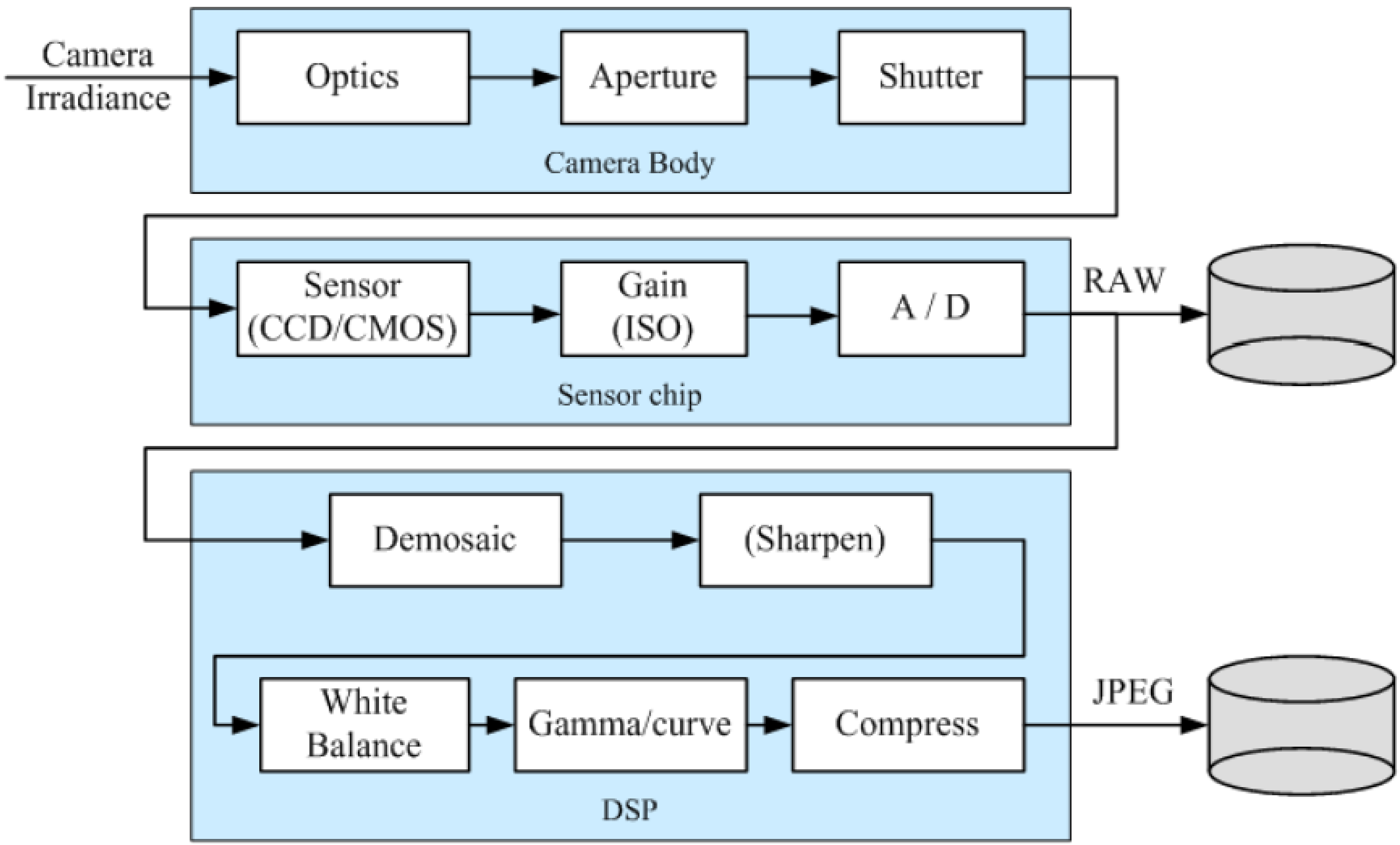
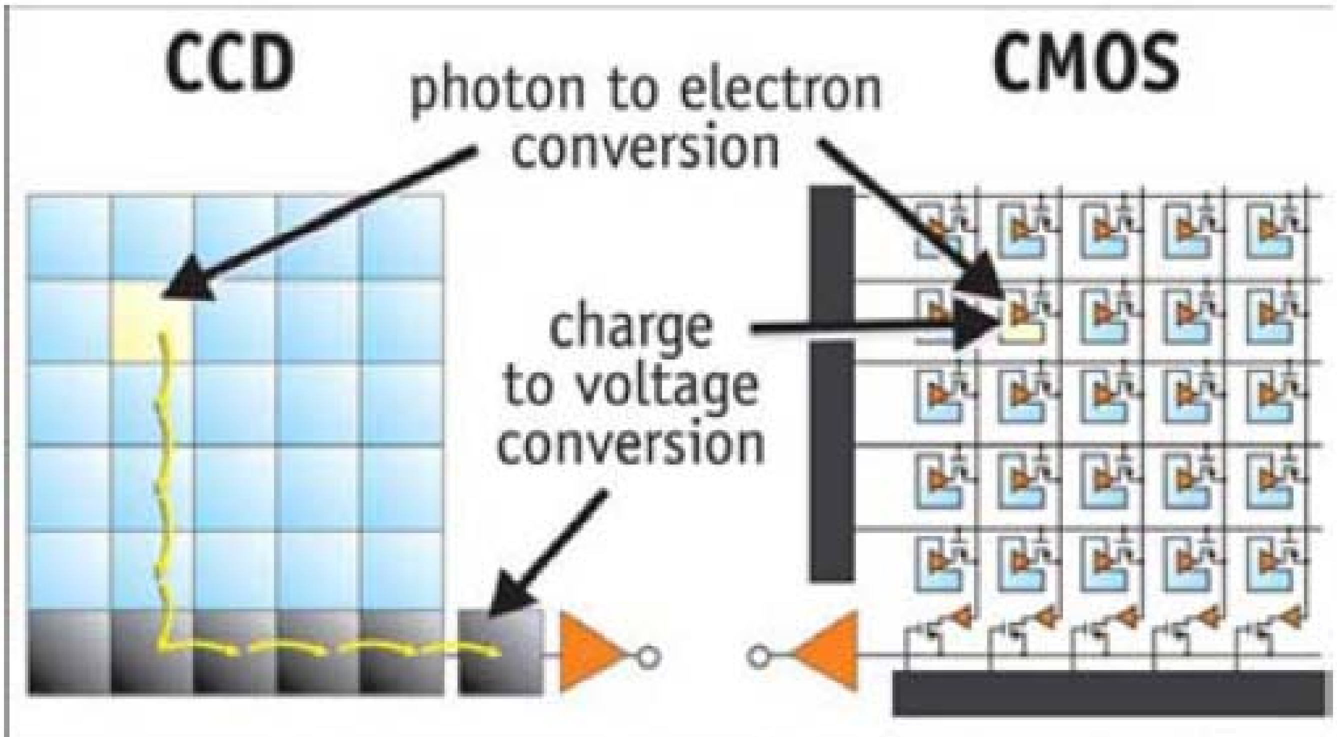
Slide credit: L. Lazebnik


Camera Irradiance
Optics
Aperture
Shutter
Camera Body
Sensor (CCD/CMOS)
Gain (ISO)
A / D
RAW
Sensor chip
Demosaic
(Sharpen)
White Balance
Gamma/curve
Compress
JPEG
DSP

Digital Sensors



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

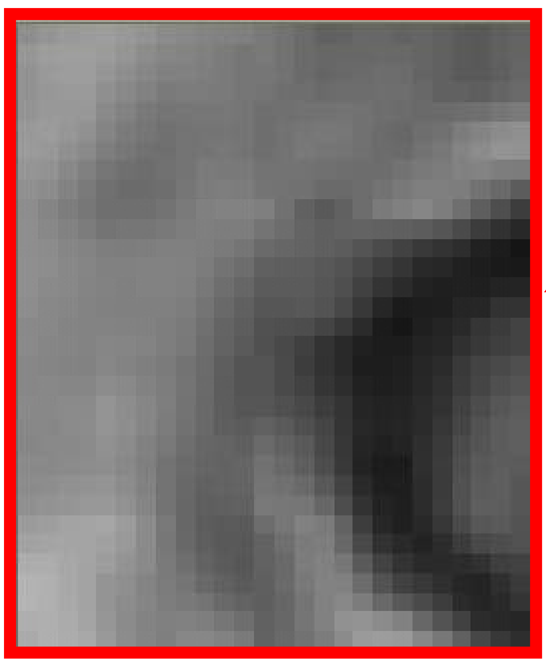
Resolution

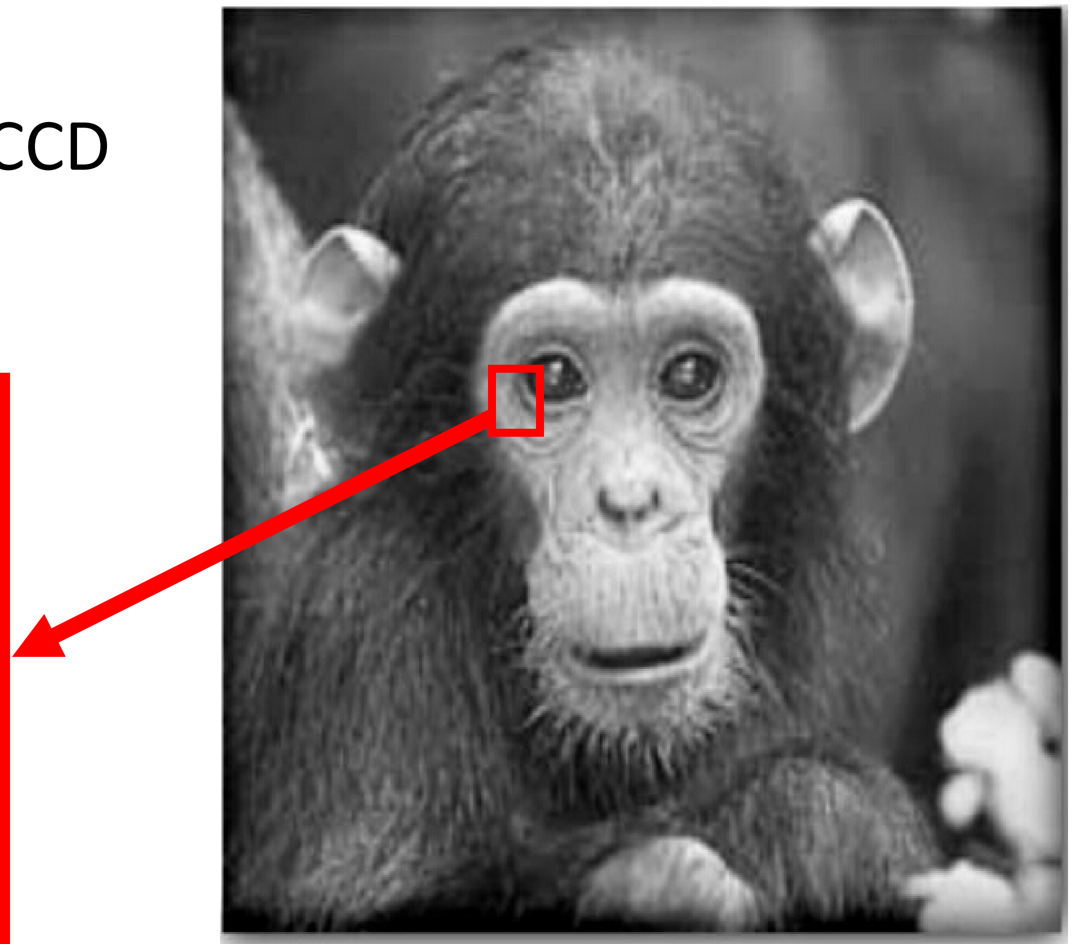
- sensor: size of real world scene element a that images to a single pixel
- image: number of pixels
- Influences what analysis is feasible, affects best representation choice.

[fig from Mori et al]

Digital images

Think of images as matrices taken from CCD array.





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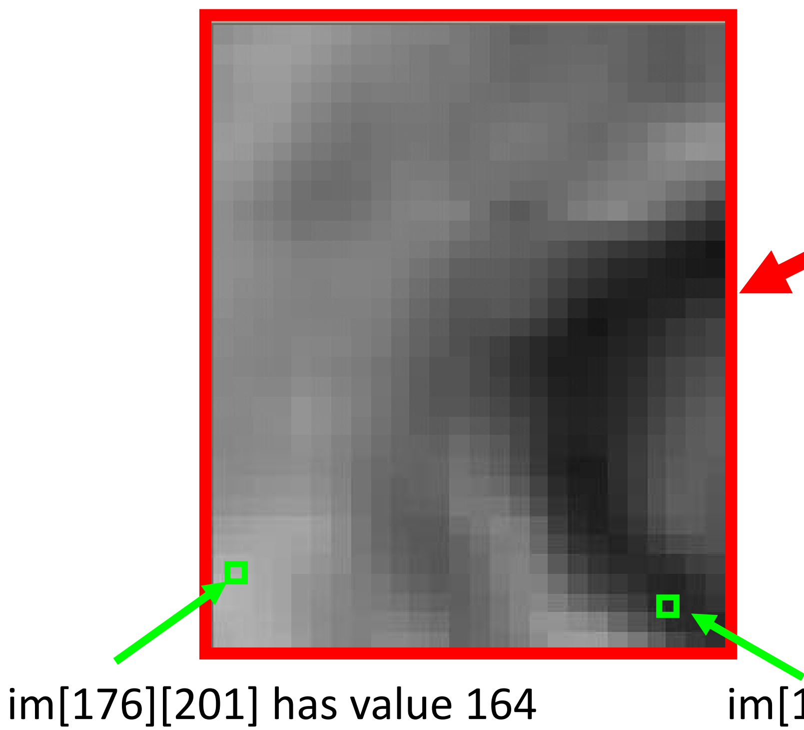
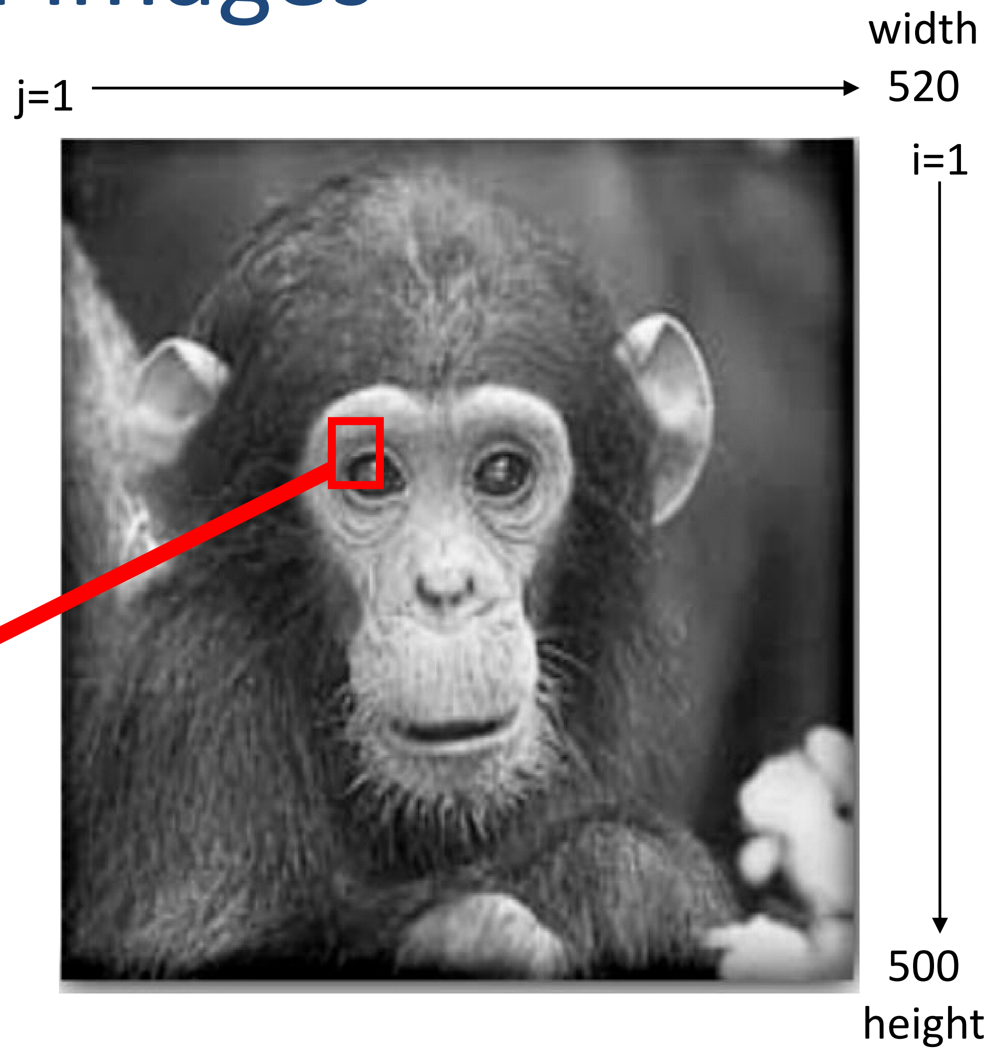
Digital images

Intensity : [0,255]





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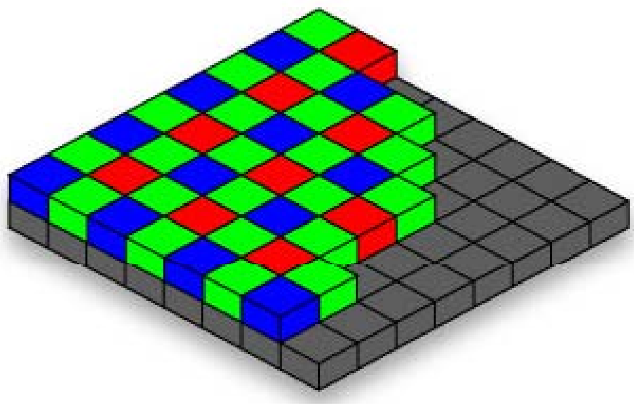
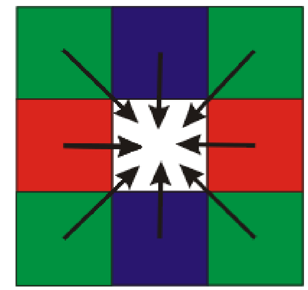
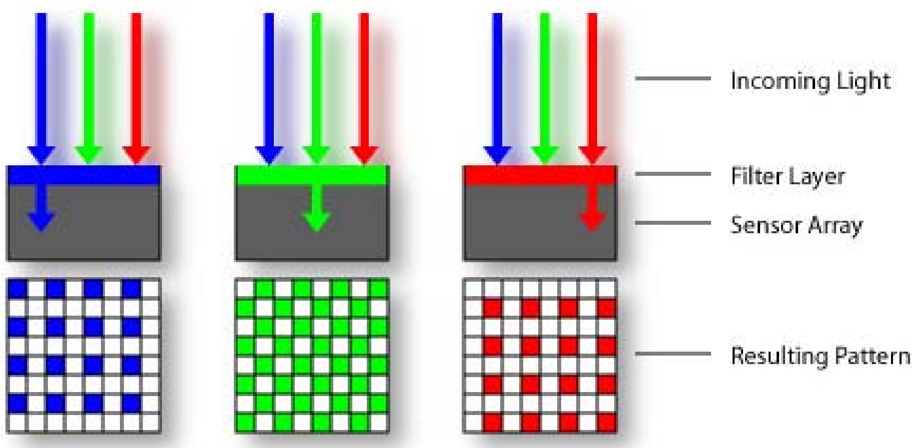
Color sensing in digital cameras

Bayer grid



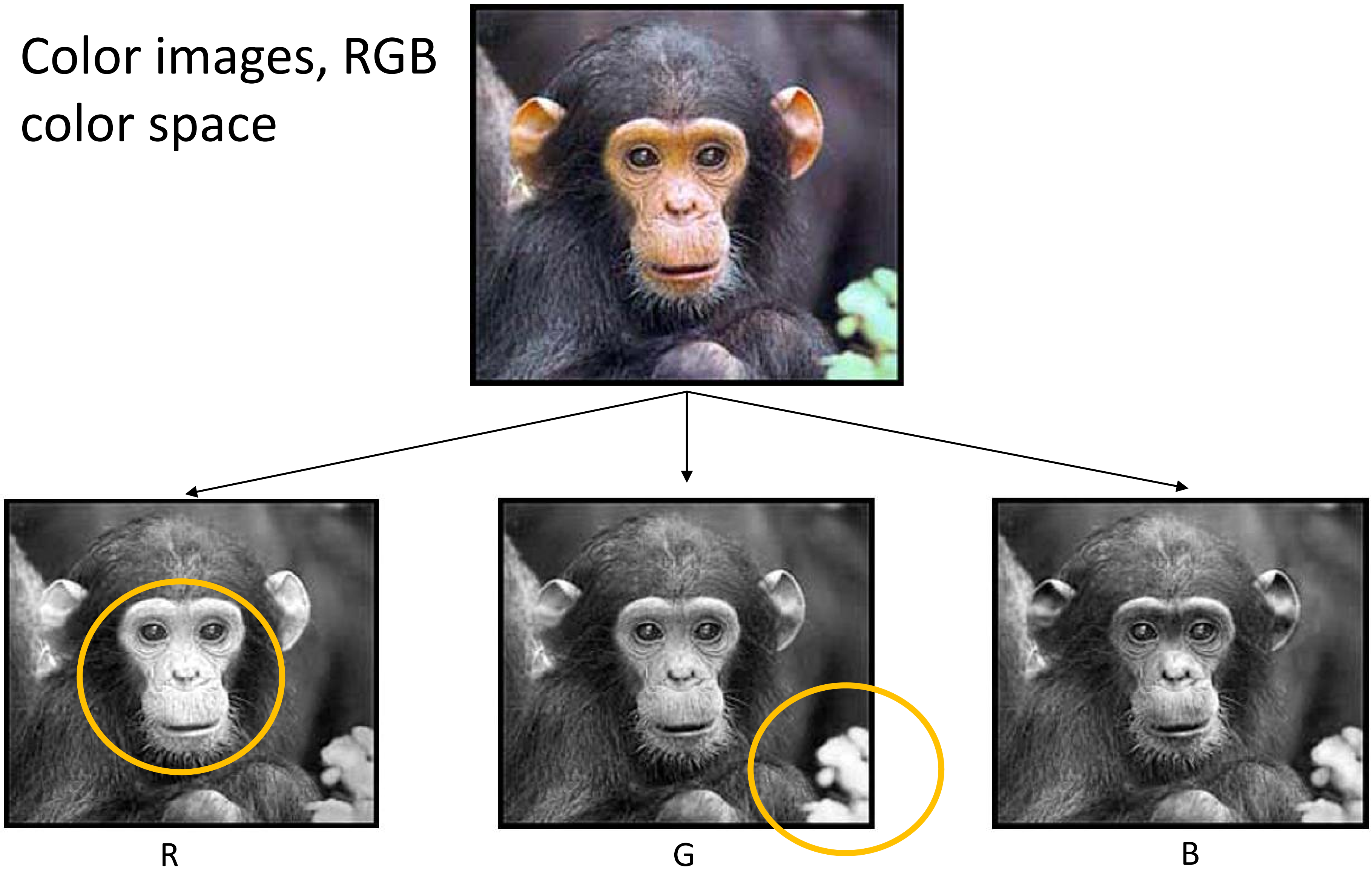
Estimate missing components from neighboring values (demosaicing)





Source: Steve Seitz

Color images, RGB color space



Much more on color in next lecture…

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  - sampling, etc.

Summary

- Image formation affected by geometry, photometry, and optics.
- Projection equations express how world points mapped to 2d image.
- Homogenous coordinates allow linear system for projection equations.
- Lenses make pinhole model practical
- Photometry models: Lambertian, BRDF
- Digital imagers, Bayer demosaicing

Parameters (focal length, aperture, lens diameter, sensor sampling…) strongly affect image obtained.

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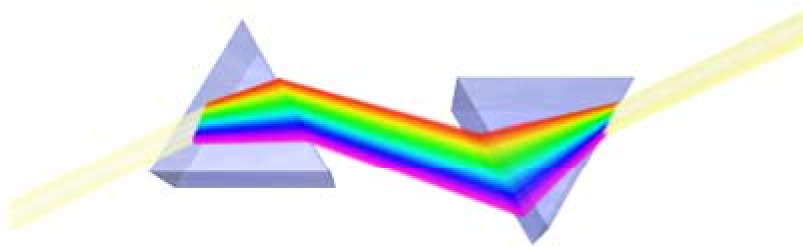
Slide Credits

- Bill Freeman
- Steve Seitz
- Kristen Grauman
- Forsyth and Ponce
- Rick Szeliski
- and others, as marked…

Next time



Color

Readings:

- Forsyth and Ponce, Chapter 6
- Szeliski, 2.3.2