CS 6550

Unit 1: Image Formation

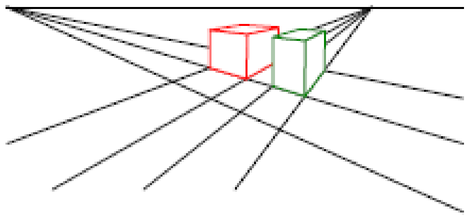
1. Geometry
2. Optics
3. Photometry
4. Sensor

Readings

- Szeliski: Chapter 2

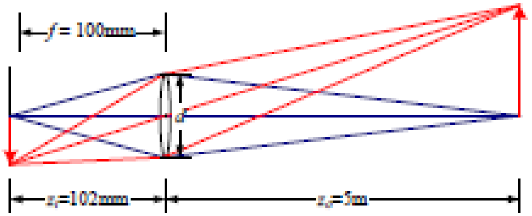
Physical parameters of image formation

Geometric



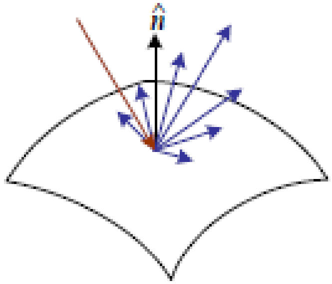
- Type of projection
- Camera pose

Optical



- Sensor’s lens type
- focal length, field of view, aperture

Photometric



- Type, direction, intensity of light reaching sensor
- Surfaces’ reflectance properties

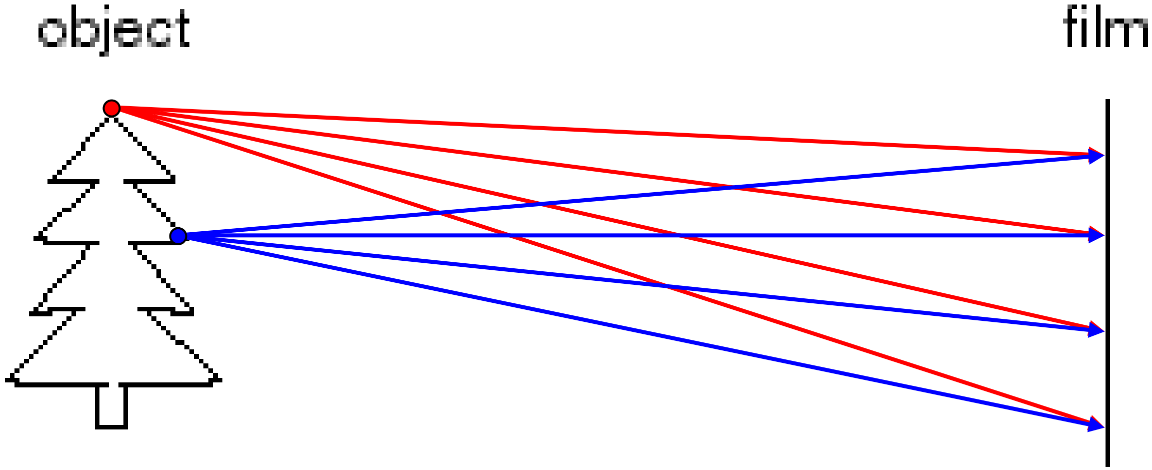
Sensor

- sampling, etc.

G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

Bayer color filter array

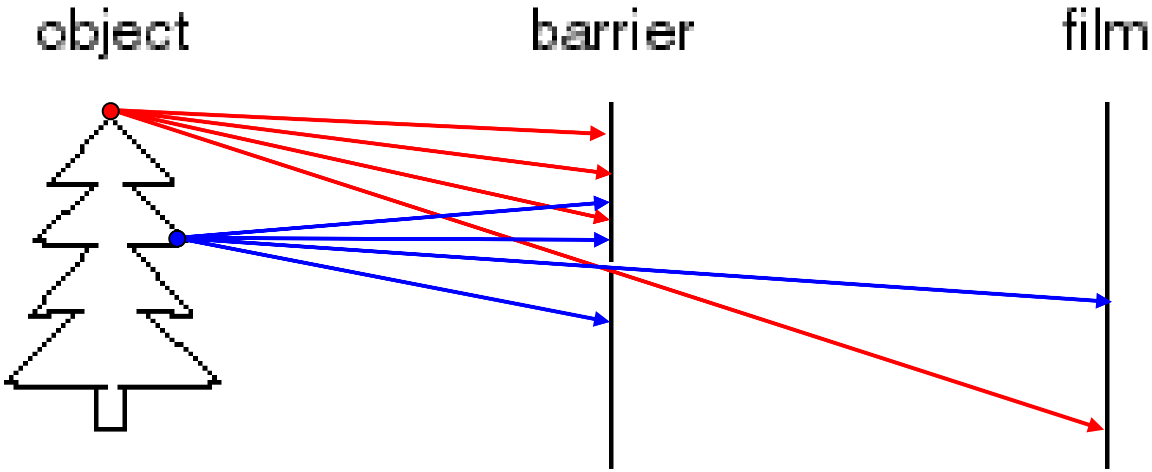
Image formation



Let's design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?

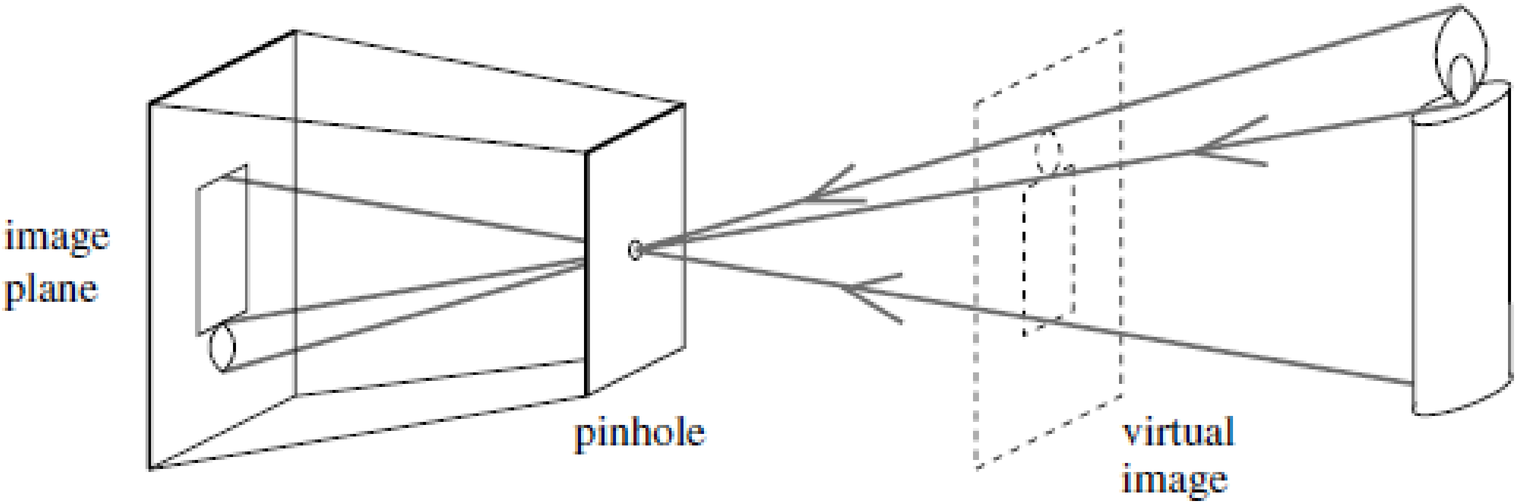
Pinhole camera



Add a barrier to block off most of the rays

- This reduces blurring
- The opening known as the **aperture**
- How does this transform the image?

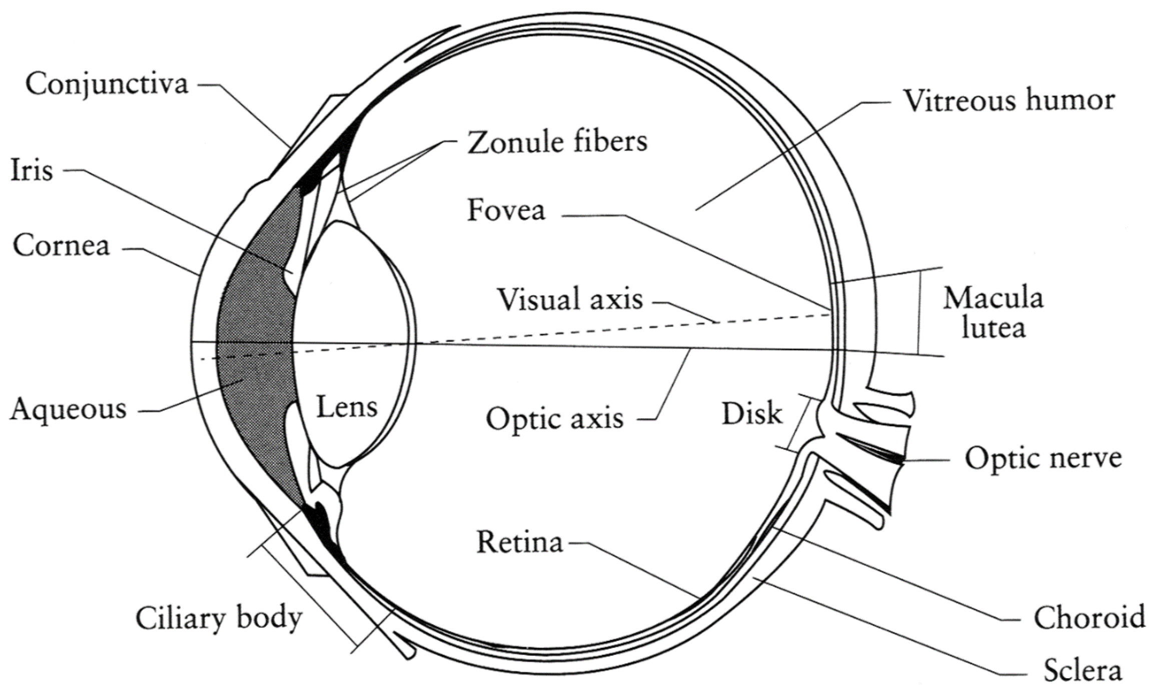
Pinhole Camera



If the pinhole were really reduced to a point, exactly one light ray would pass through each point in the image plane, the pinhole, and some scene point.

In reality, the pinhole has a finite size, and each point in the image plane collects light from a cone of rays subtending a finite solid angle.

The eye



The human eye is a camera

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What's the "film"?
  - photoreceptor cells (rods and cones) in the **retina**

Digital camera

A digital camera replaces film with a sensor array

- Each cell in the array is a **C**harge **C**oupled **D**evice
  - light-sensitive diode that converts photons to electrons
  - other variants exist: CMOS has become more popular
  - http://electronics.howstuffworks.com/digital-camera.htm

Issues with digital cameras

Noise
- big difference between consumer vs. SLR-style cameras
- low light is where you most notice noise

Compression
- creates artifacts except in uncompressed formats (tiff, raw)

Color
- color fringing artifacts from Bayer patterns

Blooming
- charge overflowing into neighboring pixels

In-camera processing
- oversharpening can produce halos

Interlaced vs. progressive scan video
- even/odd rows from different exposures

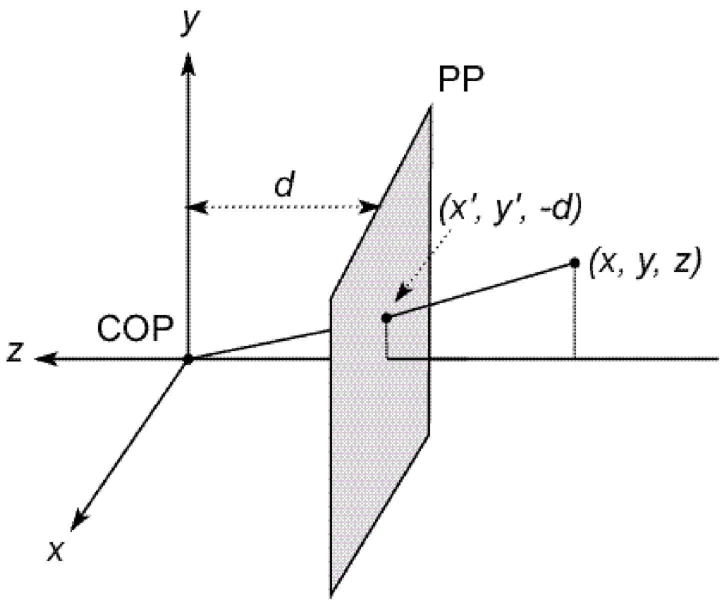
Are more megapixels better?
- requires higher quality lens
- noise issues

Stabilization
- compensate for camera shake (mechanical vs. electronic)

More info online, e.g.,

- http://electronics.howstuffworks.com/digital-camera.htm

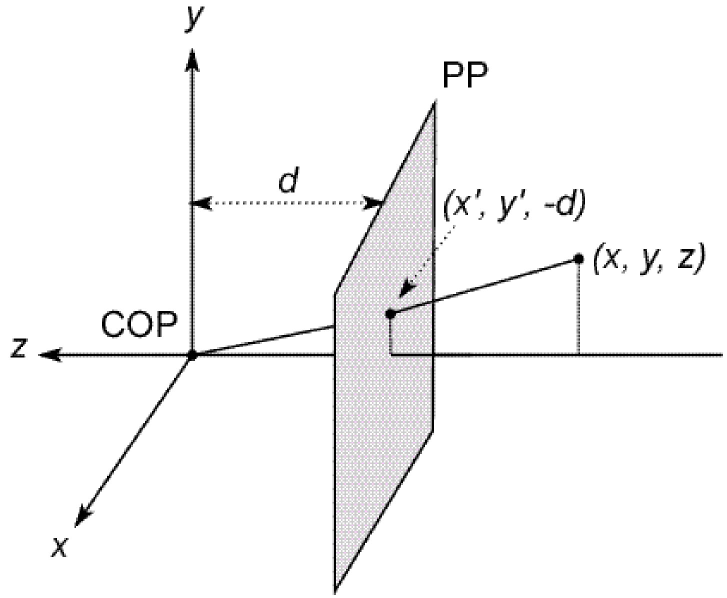
Geometric projection



The coordinate system

- We will use the pin-hole model as an approximation
- Put the optical center (**C**enter **O**f **P**rojection) at the origin
- Put the image plane (**P**rojection **P**lane) *in front* of the COP
  - Why?
- The camera looks down the *negative* z axis
  - we need this if we want right-handed-coordinates

Modeling projection



Projection equations

- Compute intersection with PP of ray from (x,y,z) to COP
- Derived using similar triangles (on board)

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z},\ -d)$$

- We get the projection by throwing out the last coordinate:

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z})$$

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

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

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

Homogeneous coordinates

Invariant to scaling

$$k\begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} kx \\ ky \\ kw \end{bmatrix} \Rightarrow \begin{bmatrix} \frac{kx}{kw} \\ \frac{ky}{kw} \end{bmatrix} = \begin{bmatrix} \frac{x}{w} \\ \frac{y}{w} \end{bmatrix}$$

Homogeneous Coordinates

Cartesian Coordinates

Point in Cartesian is ray in Homogeneous.

Basic geometry in homogeneous coordinates

Line equation: ax + by + c = 0

$$line_i = \begin{bmatrix} a_i \\ b_i \\ c_i \end{bmatrix}$$

Append 1 to pixel coordinate to get homogeneous coordinate

$$p_i = \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix}$$

Line given by cross product of two points

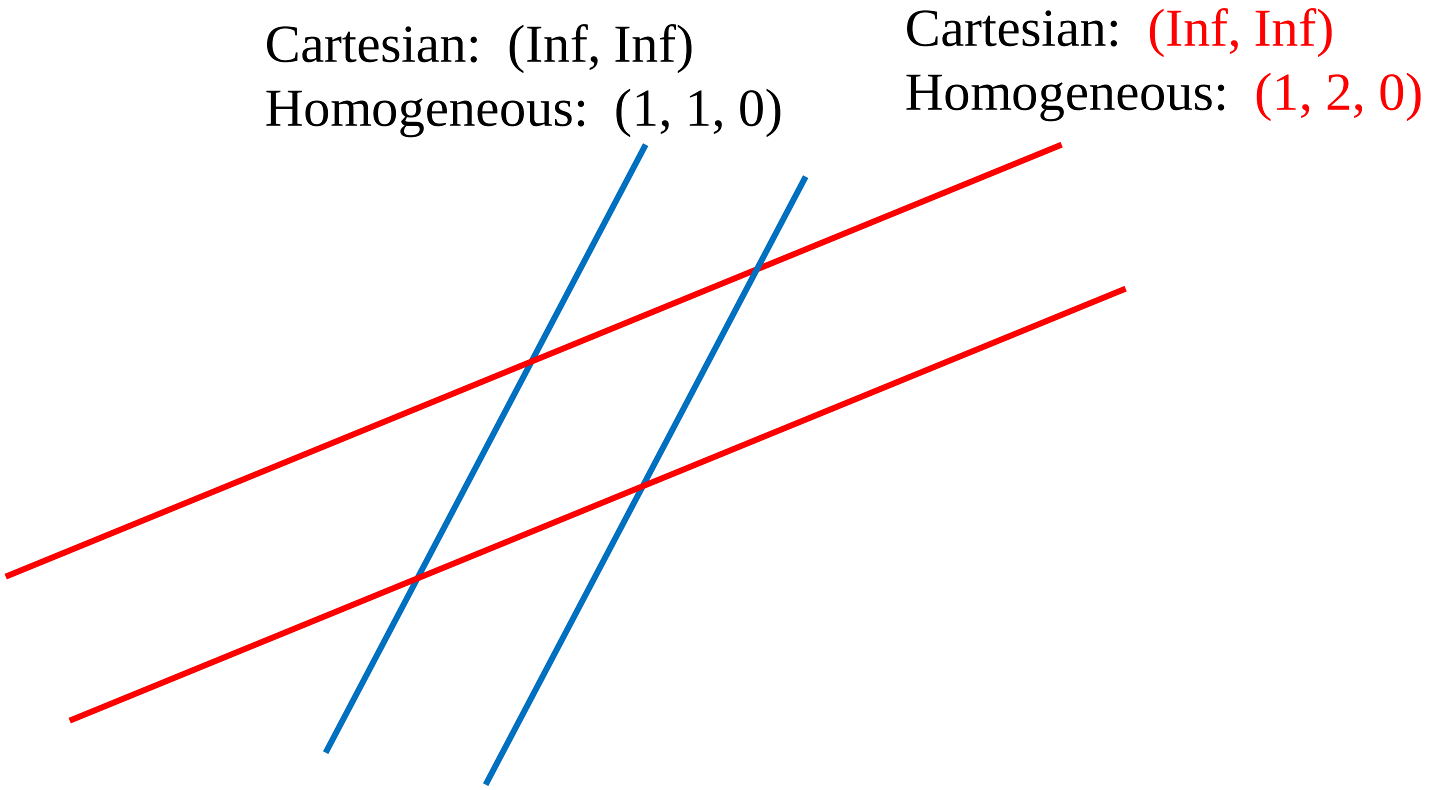
$$line_{ij} = p_i \times p_j$$

Intersection of two lines given by cross product of the lines

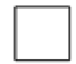
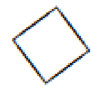
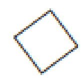
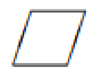
$$q_{ij} = line_i \times line_j$$

Another problem solved by homogeneous coordinates

Intersection of parallel lines



2D transformations

Transformation	Matrix	# DoF	Preserves	Icon
translation	$\begin{bmatrix} \mathbf{I} & \mathbf{t} \end{bmatrix}_{2\times 3}$	2	orientation	
rigid (Euclidean)	$\begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix}_{2\times 3}$	3	lengths	
similarity	$\begin{bmatrix} s\mathbf{R} & \mathbf{t} \end{bmatrix}_{2\times 3}$	4	angles	
affine	$\begin{bmatrix} \mathbf{A} \end{bmatrix}_{2\times 3}$	6	parallelism	
projective	$\begin{bmatrix} \tilde{\mathbf{H}} \end{bmatrix}_{3\times 3}$	8	straight lines	

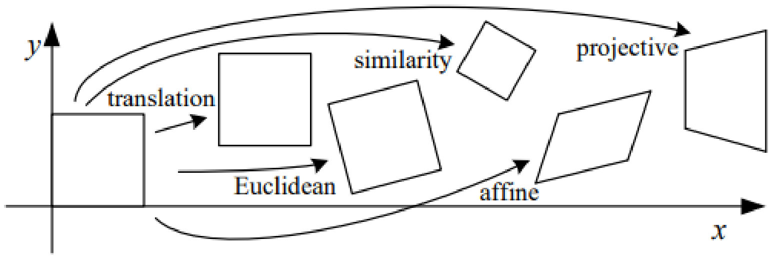
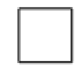
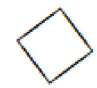
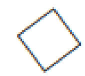
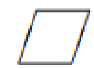
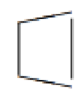


Figure 2.4 *Basic set of 2D planar transformations.*

Each transformation also preserves the properties listed in the rows below it, i.e., similarity preserves not only angles but also parallelism and straight lines.

The 2 × 3 matrices are extended with a third [0 0 1] row to form a full 3 × 3 matrix for homogeneous coordinate transformations

3D transformations

Transformation	Matrix	# DoF	Preserves	Icon
translation	$\begin{bmatrix} \mathbf{I} & \mathbf{t} \end{bmatrix}_{3\times 4}$	3	orientation	
rigid (Euclidean)	$\begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix}_{3\times 4}$	6	lengths	
similarity	$\begin{bmatrix} s\mathbf{R} & \mathbf{t} \end{bmatrix}_{3\times 4}$	7	angles	
affine	$\begin{bmatrix} \mathbf{A} \end{bmatrix}_{3\times 4}$	12	parallelism	
projective	$\begin{bmatrix} \tilde{\mathbf{H}} \end{bmatrix}_{4\times 4}$	15	straight lines	

Hierarchy of 3D coordinate transformations:

Each transformation also preserves the properties listed in the rows below it, i.e., similarity preserves not only angles but also parallelism and straight lines.

The 3×4 matrices are extended with a fourth [0 0 0 1] row to form a full 4×4 matrix for homogeneous coordinate transformations.

Perspective Projection

Projection is a matrix multiply using homogeneous coordinates:

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

divide by the third coordinate

This is known as **perspective projection**

- The matrix is the **projection matrix**

Perspective Projection

How does scaling the projection matrix change the transformation?

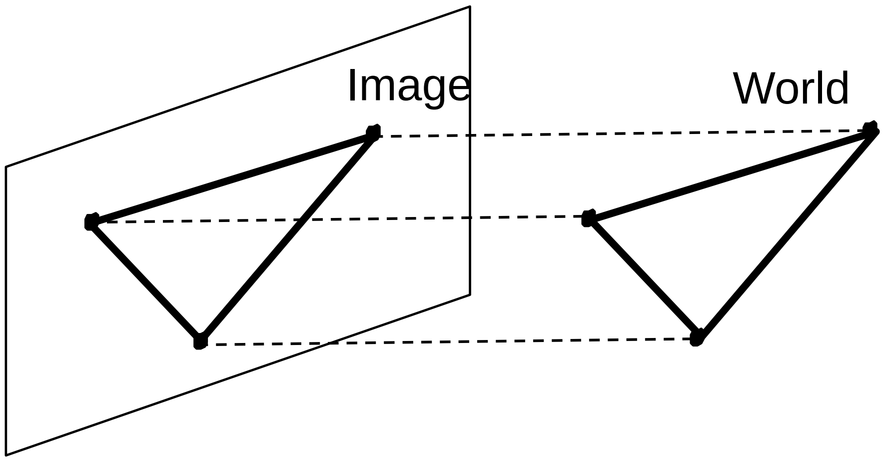
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ -z/d \end{bmatrix} \Rightarrow (-d\frac{x}{z}, \quad -d\frac{y}{z})$$

$$\begin{bmatrix} -d & 0 & 0 & 0 \\ 0 & -d & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} -dx \\ -dy \\ z \end{bmatrix} \Rightarrow (-d\frac{x}{z}, \quad -d\frac{y}{z})$$

Orthographic projection

Special case of perspective projection

- Distance from the COP to the PP is infinite

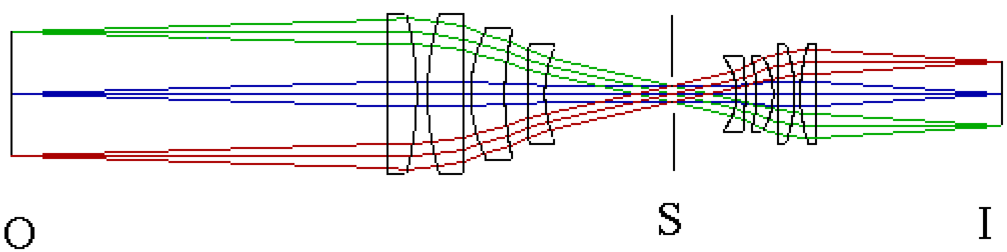


- Good approximation for telephoto optics
- Also called "parallel projection": $(x, y, z) \rightarrow (x, y)$
- What's the projection matrix?

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

Orthographic (“telecentric”) lenses

[Navitar telecentric zoom lens](#)



http://www.lhup.edu/~dsimanek/3d/telecent.htm

Variants of orthographic projection

Scaled orthographic

- Also called “weak perspective”

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

Affine projection

- Also called “paraperspective”

$$\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

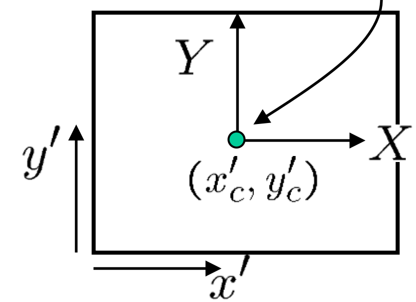
Camera parameters

A camera is described by several parameters

- Translation T of the optical center from the origin of world coords
- Rotation R of the image plane
- focal length f, principle point (c_x, c_y), pixel size (s_x, s_y)
- blue parameters are called "extrinsics," red are "intrinsics"

Projection equation

$$\mathbf{x} = \begin{bmatrix} sx \\ sy \\ s \end{bmatrix} = \begin{bmatrix} * & * & * & * \\ * & * & * & * \\ * & * & * & * \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \mathbf{\Pi X}$$



- The projection matrix models the cumulative effect of all parameters
- Useful to decompose into a series of operations

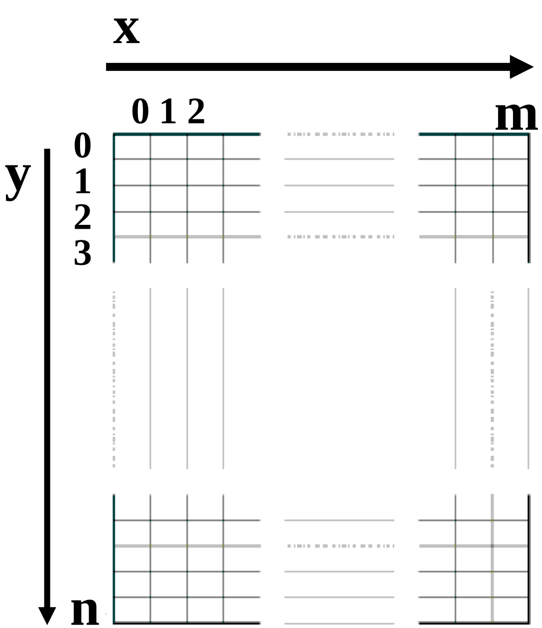
identity matrix

$$\mathbf{\Pi} = \underbrace{\begin{bmatrix} fs_x & 0 & c_x \\ 0 & fs_y & c_y \\ 0 & 0 & 1 \end{bmatrix}}_{\text{intrinsics}} \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\text{projection}} \underbrace{\begin{bmatrix} \mathbf{R}_{3x3} & \mathbf{0}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{bmatrix}}_{\text{rotation}} \underbrace{\begin{bmatrix} \mathbf{I}_{3x3} & \mathbf{T}_{3x1} \\ \mathbf{0}_{1x3} & 1 \end{bmatrix}}_{\text{translation}}$$

- The definitions of these parameters are **not** completely standardized
  - especially intrinsics—varies from one book to another

Camera Calibration Matrix

Image coordinates are to be expressed as *pixel coordinates*



$$\begin{cases} x = f_x u + s\, v + c_x \\ y = f_y v + c_y \end{cases}$$

→ (c_x, c_y): the pixel coordinates of the principal point

→ f_x : the number of pixels per unit length horizontally

→ f_y : the number of pixels per unit length vertically

→ s indicates the skew ; typically $s = 0$

f_y/f_x is called the *aspect ratio*

f_x, f_y, s, c_x and c_y are called *internal camera parameters*

3D-to-2D Camera Projection

Camera calibration matrix K is a 3X3 upper-triangular matrix

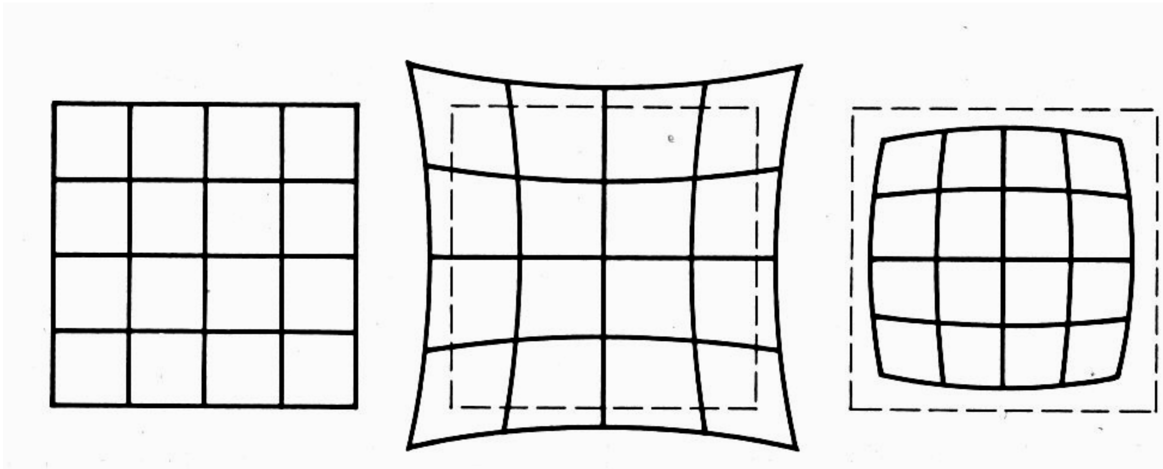
$$K = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

The camera projection matrix P (3X4) which maps the 3D point coordinate (in world coordinate) to the corresponding 2D image coordinate is given by

$$\boldsymbol{P} = \boldsymbol{K}[\boldsymbol{R}|\boldsymbol{t}]$$

R & t: the camera extrinsic parameters

Lens Distortion

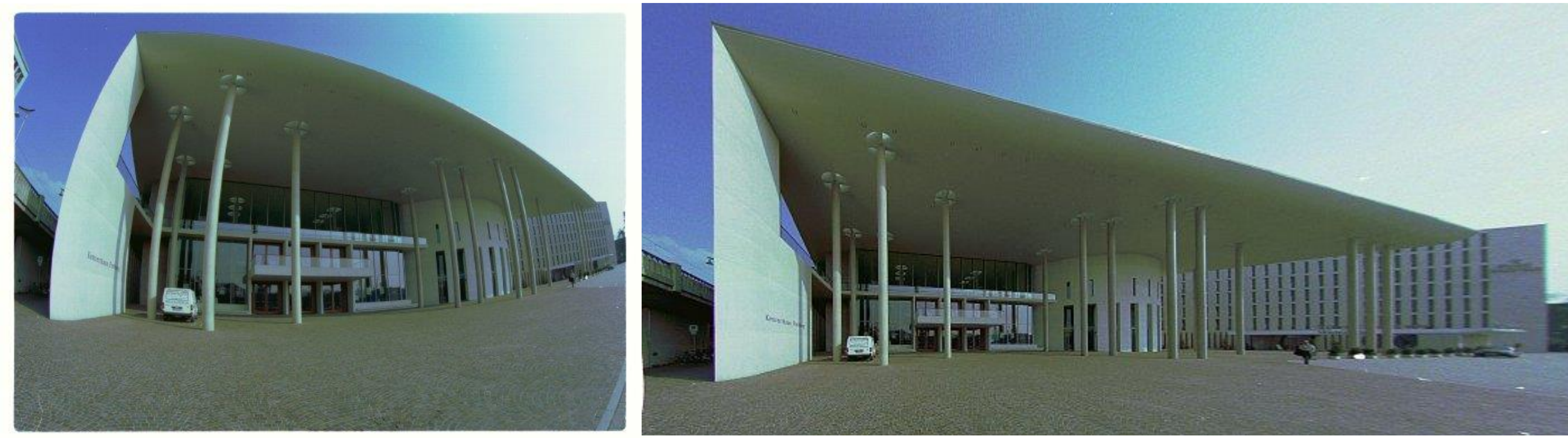


No distortion Pin cushion Barrel

Radial distortion of the image

- Caused by imperfect lenses
- Deviations are most noticeable for rays that pass through the edge of the lens
- The radial distortion model says that coordinates in the observed images are displaced away (barrel) or towards (pincushion) the image center by an amount proportional to their radial distance.

Correcting radial distortion



from Helmut Dersch

Radial Distortion Model

Let (x_c, y_c) be the pixel coordinates obtained after perspective division but before scaling by focal length *f* and shifting by the optical center (c_x, c_y), i.e.,

$$x_c = \frac{\boldsymbol{r}_x \cdot \boldsymbol{p} + t_x}{\boldsymbol{r}_z \cdot \boldsymbol{p} + t_z}$$

$$y_c = \frac{\boldsymbol{r}_y \cdot \boldsymbol{p} + t_y}{\boldsymbol{r}_z \cdot \boldsymbol{p} + t_z}$$

The simplest radial distortion models use low-order polynomials, e.g.

$$\hat{x}_c = x_c(1 + \kappa_1 r_c^2 + \kappa_2 r_c^4)$$

$$\hat{y}_c = y_c(1 + \kappa_1 r_c^2 + \kappa_2 r_c^4)$$

$$r_c^2 = x_c^2 + y_c^2$$

The final pixel coordinates can be computed using

$$x_s = f x'_c + c_x$$

$$y_s = f y'_c + c_y.$$

Modeling distortion

Project $(\widehat{x}, \widehat{y}, \widehat{z})$
to "normalized"
image coordinates

$$x'_n = \widehat{x}/\widehat{z}$$
$$y'_n = \widehat{y}/\widehat{z}$$

Apply radial distortion

$$r^2 = {x'_n}^2 + {y'_n}^2$$
$$x'_d = x'_n(1 + \kappa_1 r^2 + \kappa_2 r^4)$$
$$y'_d = y'_n(1 + \kappa_1 r^2 + \kappa_2 r^4)$$

Apply focal length
translate image center

$$x' = f x'_d + x_c$$
$$y' = f y'_d + y_c$$

To model lens distortion

- Use above projection operation instead of standard projection matrix multiplication

Example of Radial Distortion Correction

Pinhole size / aperture

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

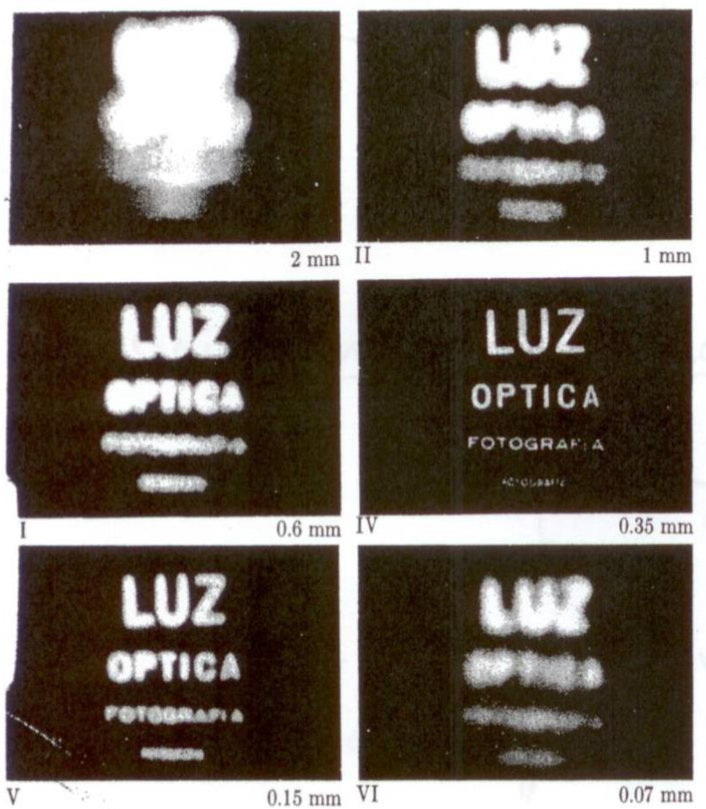
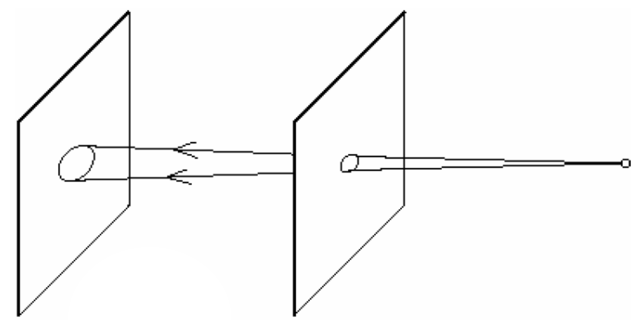


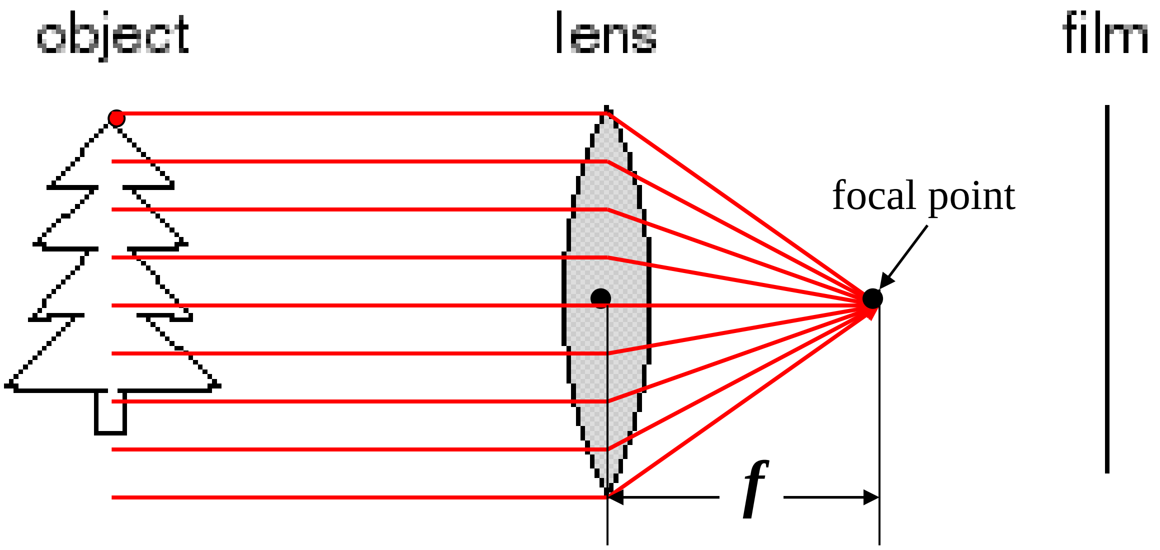
Fig. 5.96 The pinhole camera. Note the variation in image clarity as the hole diameter decreases. [Photos courtesy Dr. N. Joel, UNESCO.]

Larger

Smaller



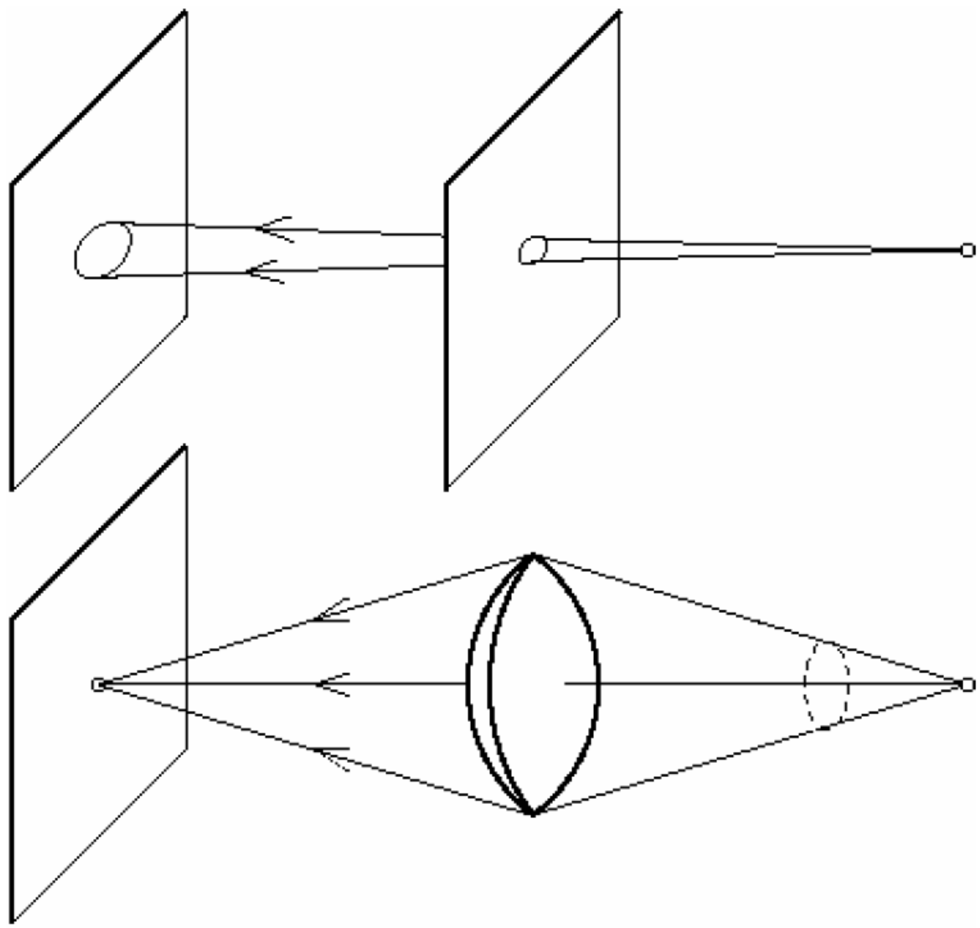
Adding a lens



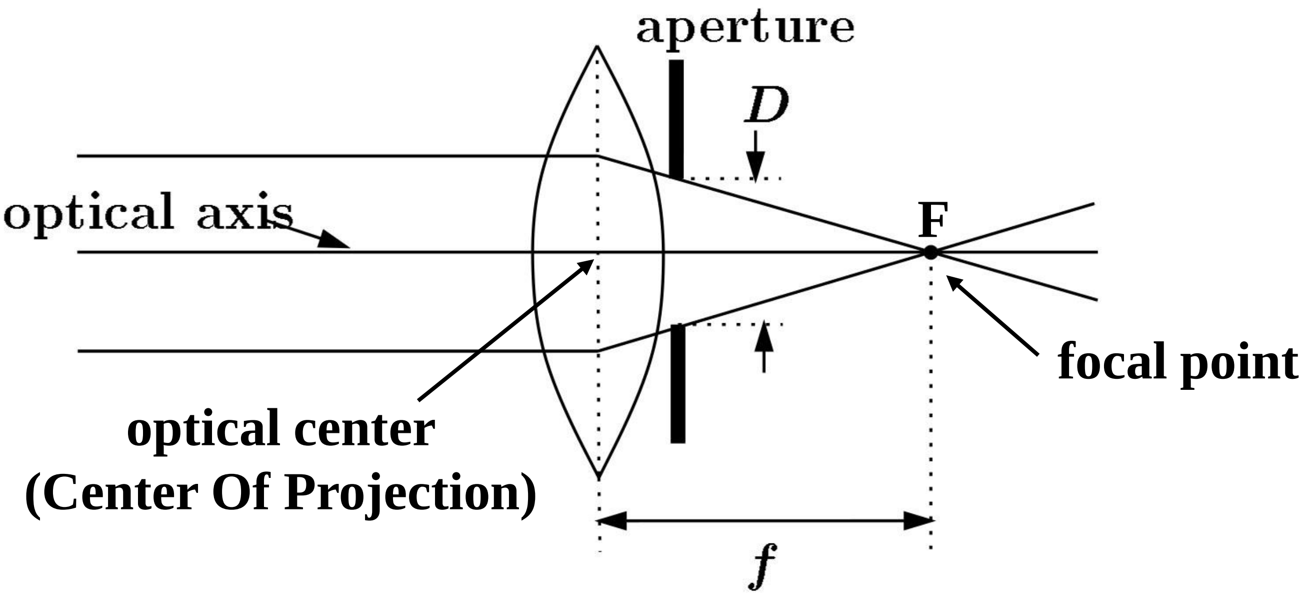
- A lens focuses light onto the film
  - Rays passing through the center are not deviated
  - All parallel rays converge to one point on a plane located at the *focal length* *f*

Slide by Steve Seitz

Pinhole vs. lens



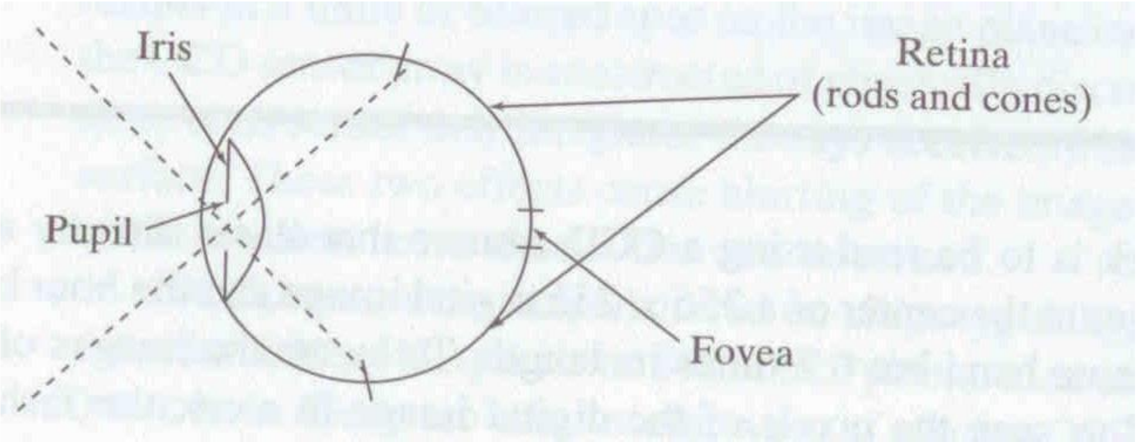
Cameras with lenses



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

Human eye

Rough analogy with human visual system:



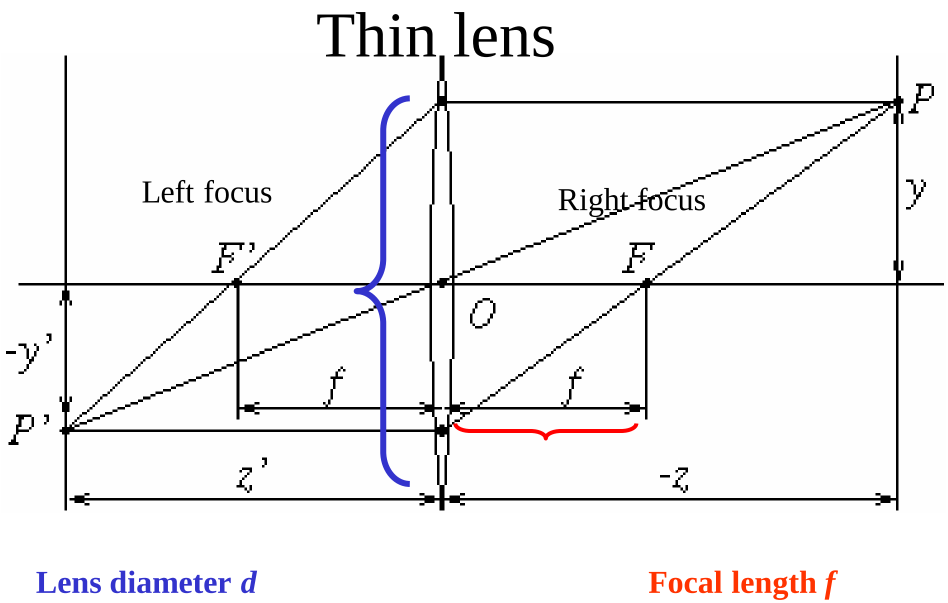
Pupil/Iris – control amount of light passing through lens

Retina - contains sensor cells, where image is formed

Fovea – highest concentration of cones

Fig from Shapiro and Stockman

Thin lens

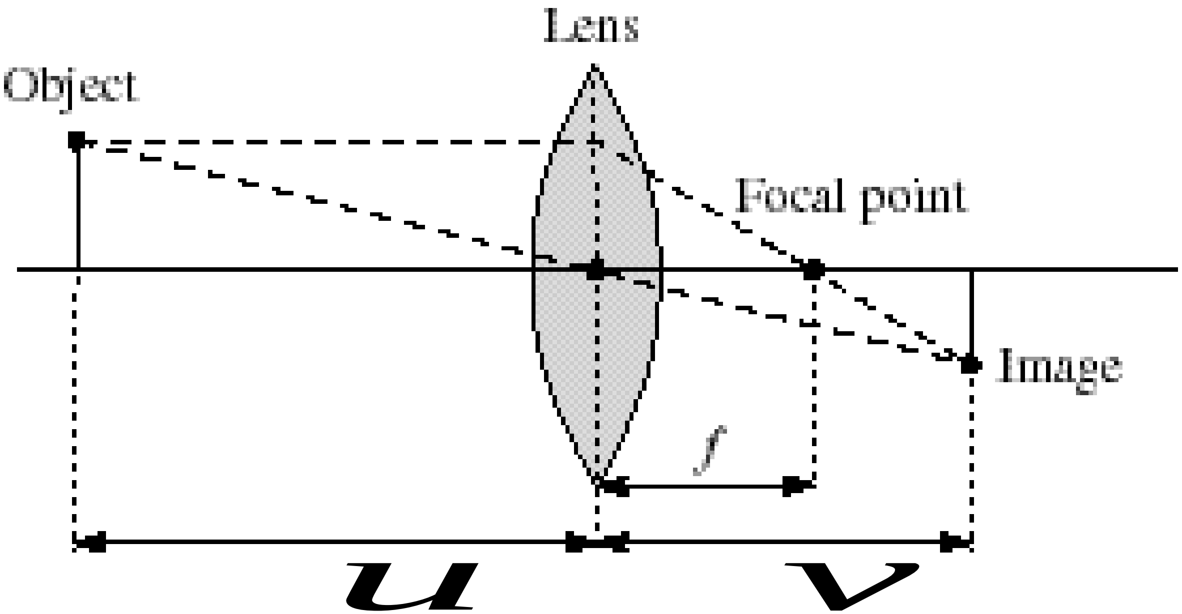


Rays entering parallel on one side go through focus on other, and vice versa.

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

Slide from K. Grauman

Thin lens equation



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

- Any object point satisfying this equation is in focus

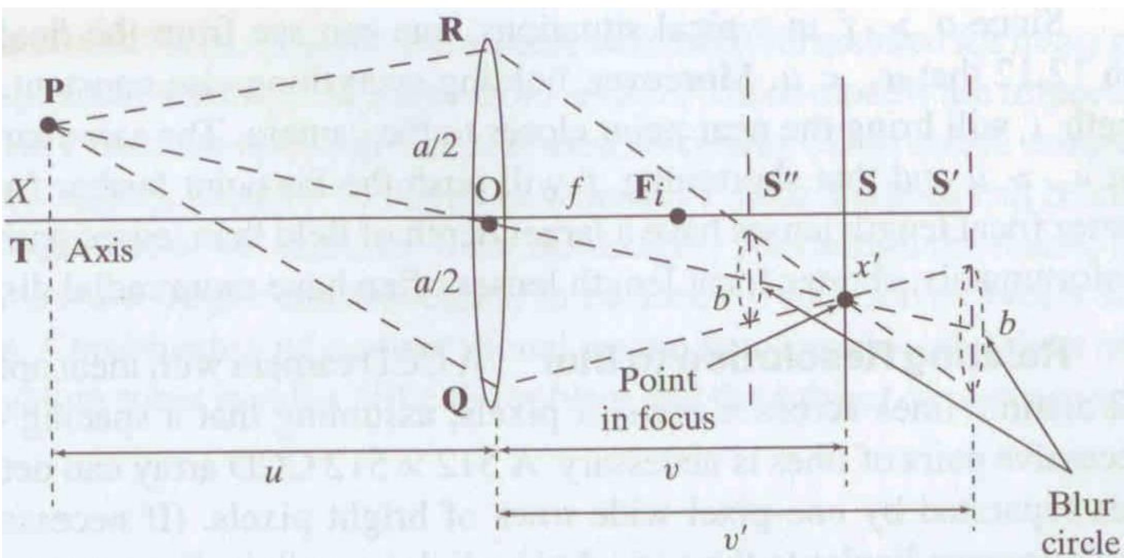
Slide from K. Grauman

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



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

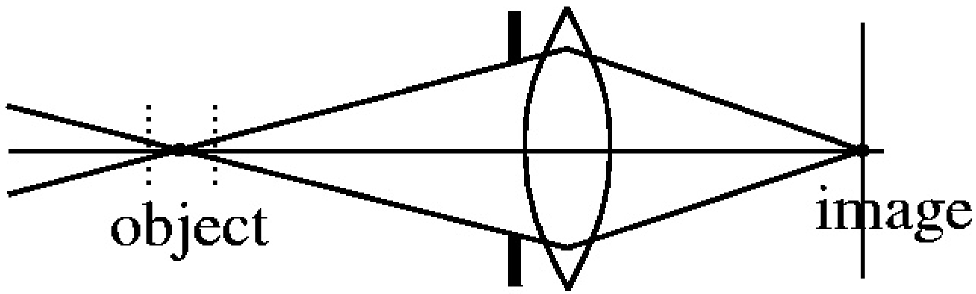
(Real camera lens systems have greater depth of field.)

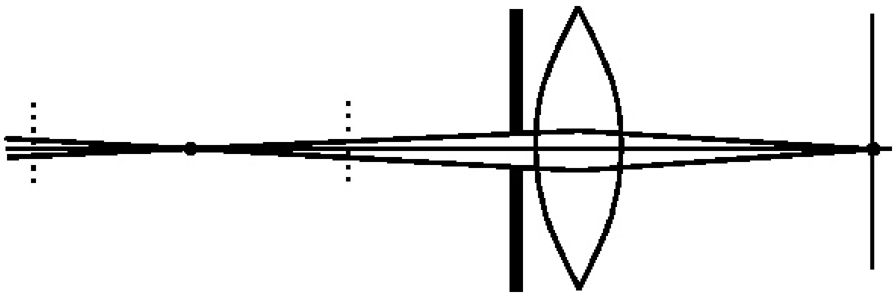
← "circles of confusion" →

Fig from Shapiro and Stockman

Focus and depth of field

How does the aperture affect the depth of field?



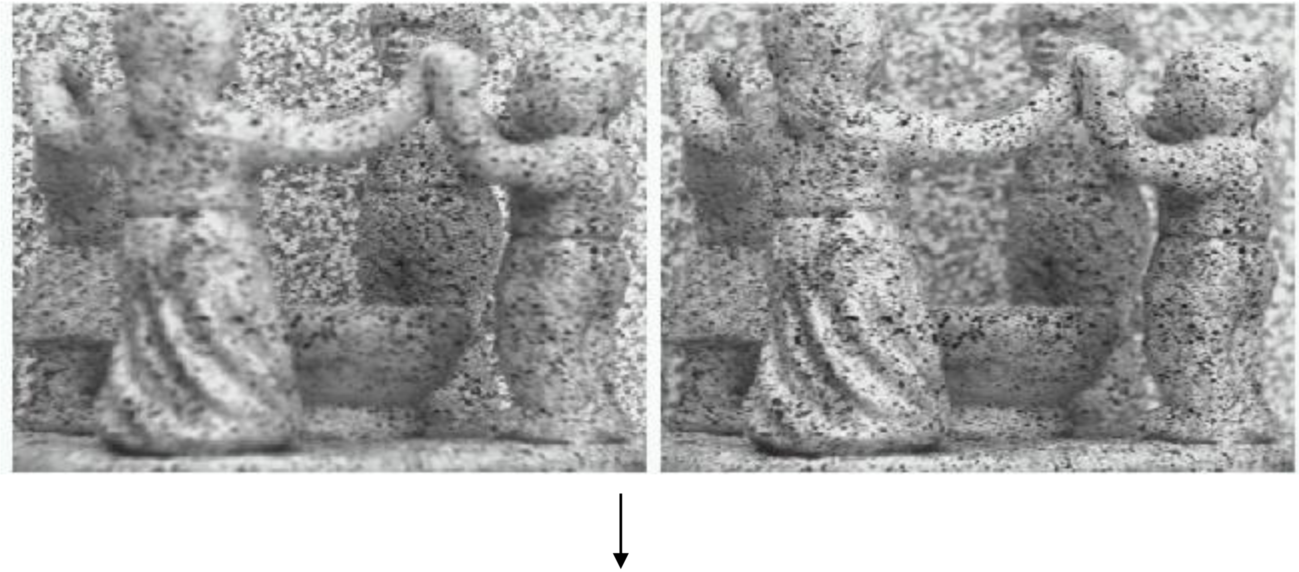


- A smaller aperture increases the range in which the object is approximately in focus

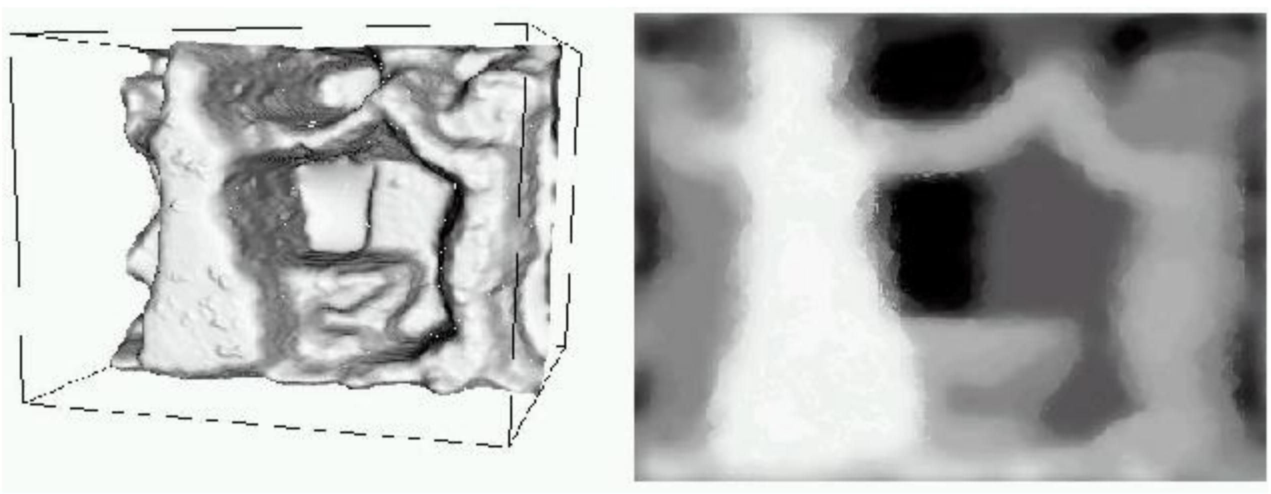
 Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field Slide from S. Seitz

Synthesis of bokeh effect

Depth from focus



Images from same point of view, different camera parameters



Depth map estimation

[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 K. Grauman

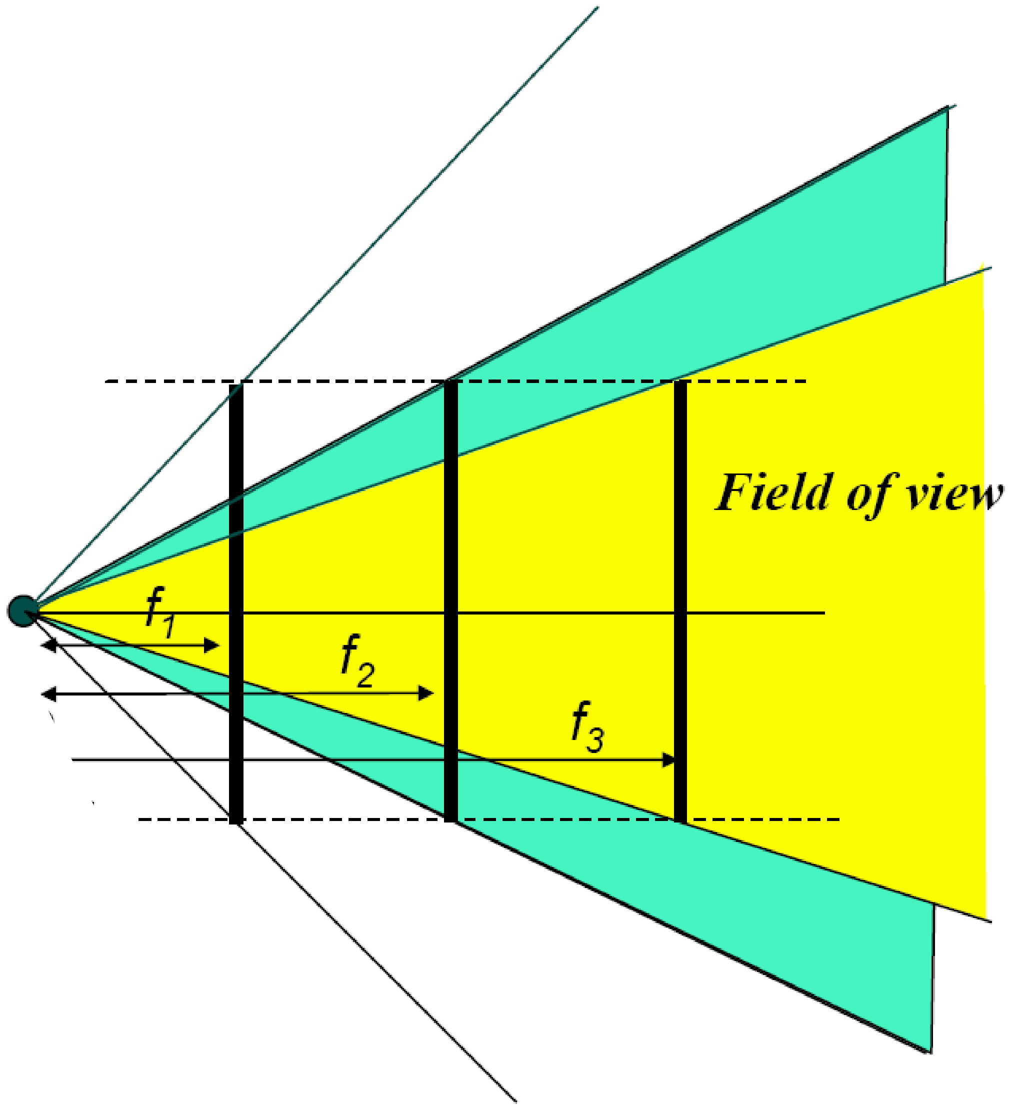
Field of view depends on focal length

As ***f*** gets smaller, image becomes more *wide angle*

- more world points project onto the finite image plane

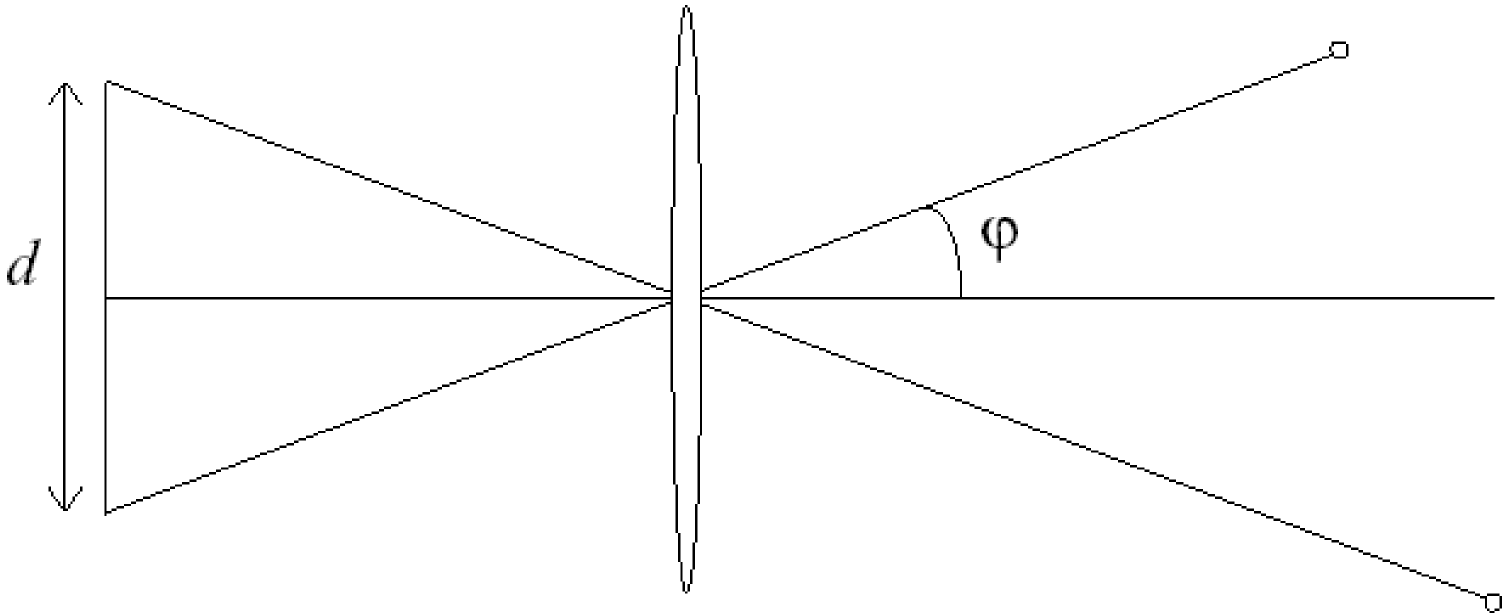
As ***f*** gets larger, image becomes more *telescopic*

- 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

Physical parameters of image formation

Geometric

- Type of projection
- Camera pose

Optical

- Sensor’s lens type
- focal length, field of view, aperture

Photometric

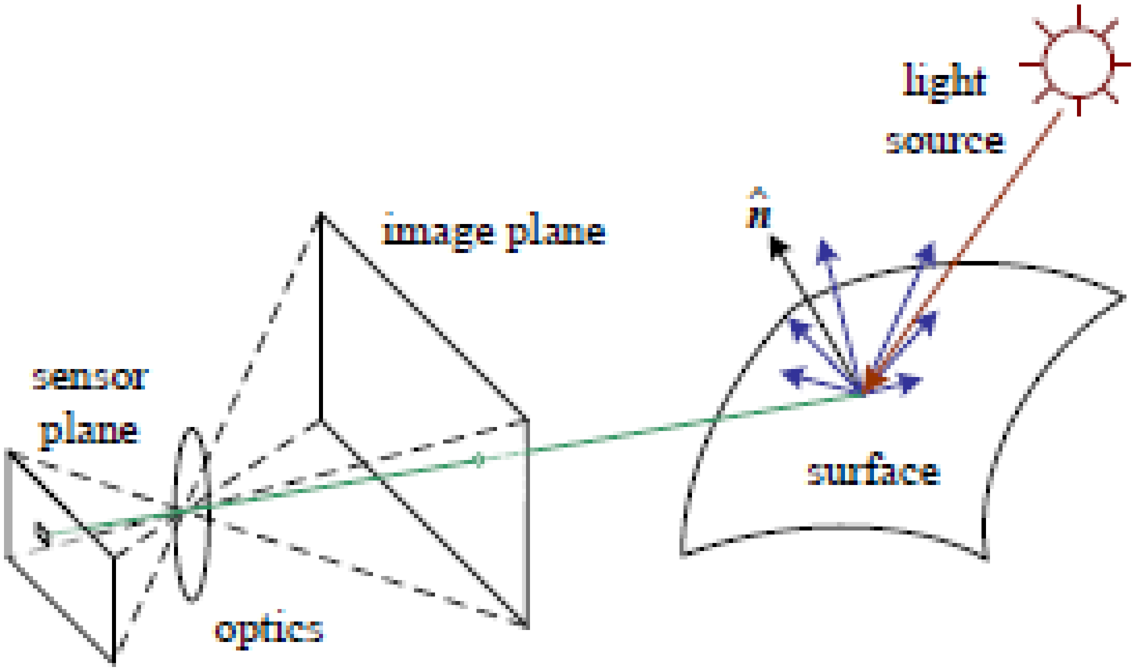
- Type, direction, intensity of light reaching sensor
- Surfaces’ reflectance properties

Sensor

- sampling, etc.

Photometric Image Formation

A simplified model of photometric image formation. Light is emitted by one or more light sources and is then reflected from an object’s surface. A portion of this light is directed towards the camera. This simplified model ignores multiple reflections, which often occur in real-world scenes.



BRDF (Bidirectional Reflectance Distribution Function)

$$f_r(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)$$

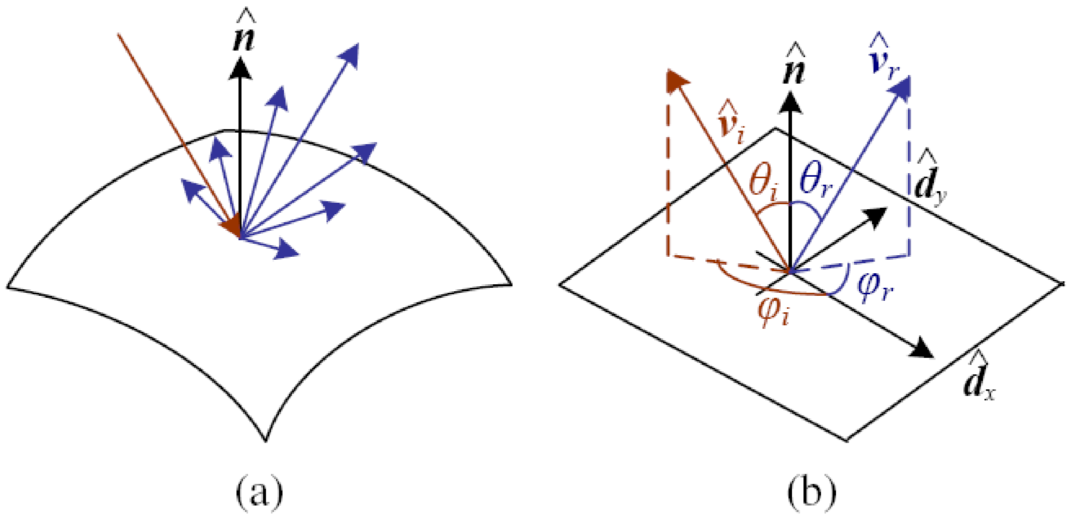
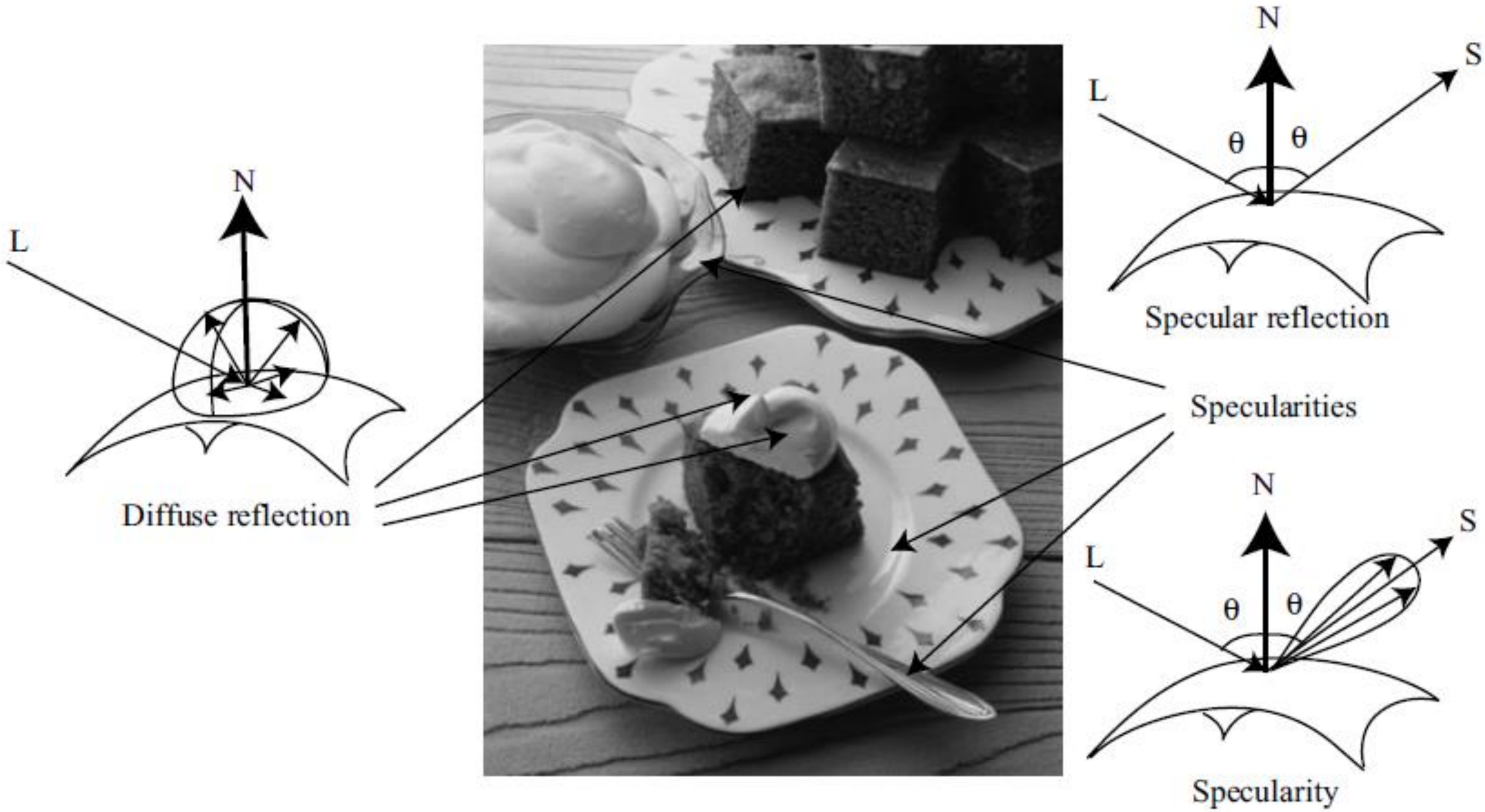


Figure 2.15: *(a) Light scattering when hitting a surface. (b) The bidirectional reflectance distribution function (BRDF) $f(\theta_i, \phi_i, \theta_r, \phi_r)$ is parameterized by the angles the incident $\hat{\boldsymbol{v}}_i$ and reflected $\hat{\boldsymbol{v}}_r$ light ray directions make with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

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 and Specular Reflection



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,

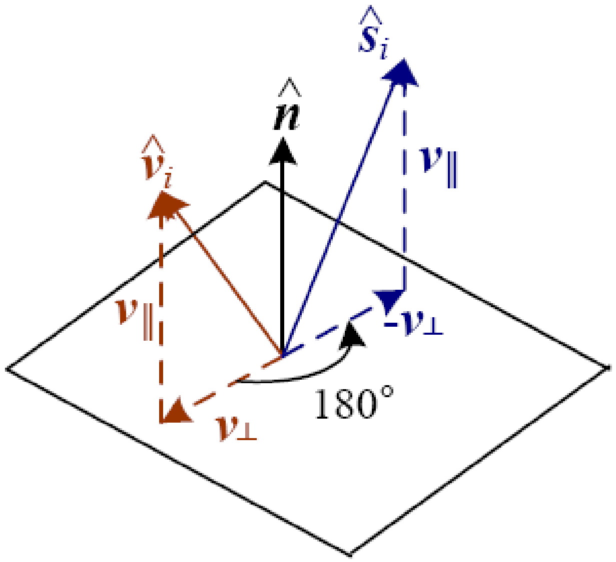
$$f_d(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{v}}_r, \hat{\boldsymbol{n}}; \lambda) = f_d(\lambda),$$

Shading equation for diffuse reflection :

$$L_d(\hat{\boldsymbol{v}}_r; \lambda) = \sum_i L_i(\lambda) f_d(\lambda) \cos^+ \theta_i = \sum_i L_i(\lambda) f_d(\lambda) [\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+,$$

$$[\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+ = \max(0, \hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}})$$

Specular reflection



The amount of light reflected in a given direction $\hat{v}_r$ thus depends on the angle $\theta_s = \cos^{-1}(\hat{v}_r \cdot \hat{s}_i)$ between the view direction $\hat{v}_r$ and the specular direction $\hat{s}_i$. For example, the Phong (1975) model uses a power of the cosine of the angle,

$$f_s(\theta_s; \lambda) = k_s(\lambda) \cos^{k_e} \theta_s, \tag{2.90}$$

while the Torrance and Sparrow (1967) micro-facet model uses a Gaussian,

$$f_s(\theta_s; \lambda) = k_s(\lambda) \exp(-c_s^2 \theta_s^2). \tag{2.91}$$

Phong Model

Diffuse+specular+ambient:

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

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

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

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

Physical parameters of image formation

Geometric

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- Surfaces’ reflectance properties

Sensor

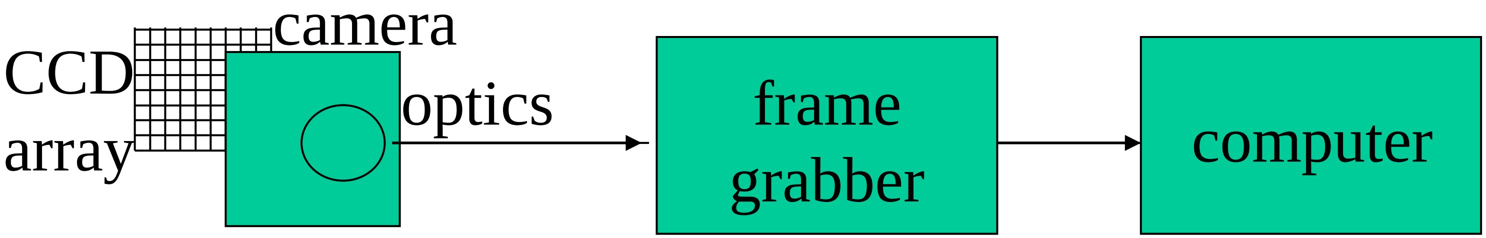
- sampling, etc.

Digital cameras

Film → sensor array

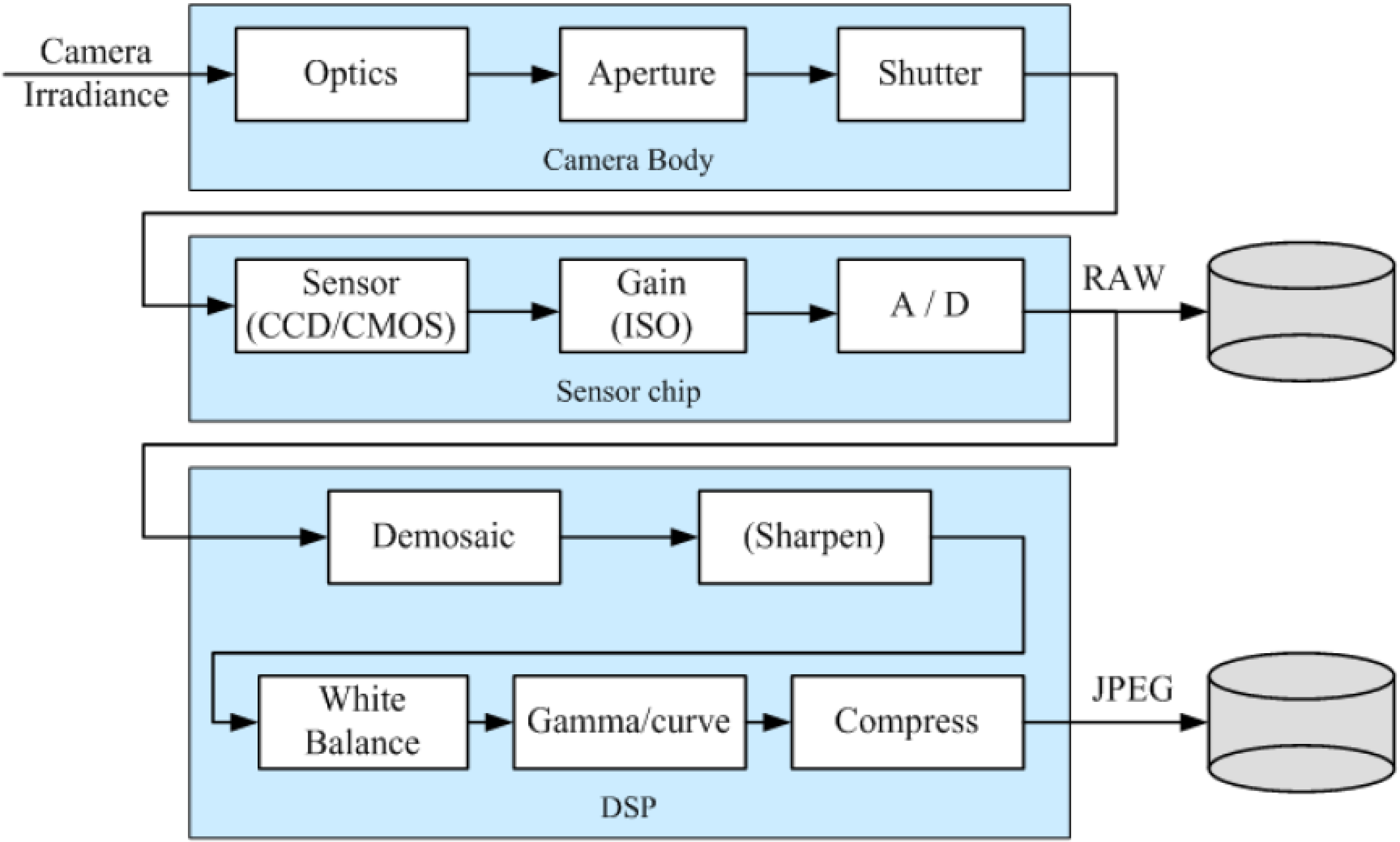
Often an array of charge coupled devices

Each CCD is light sensitive diode that converts photons (light energy) to electrons

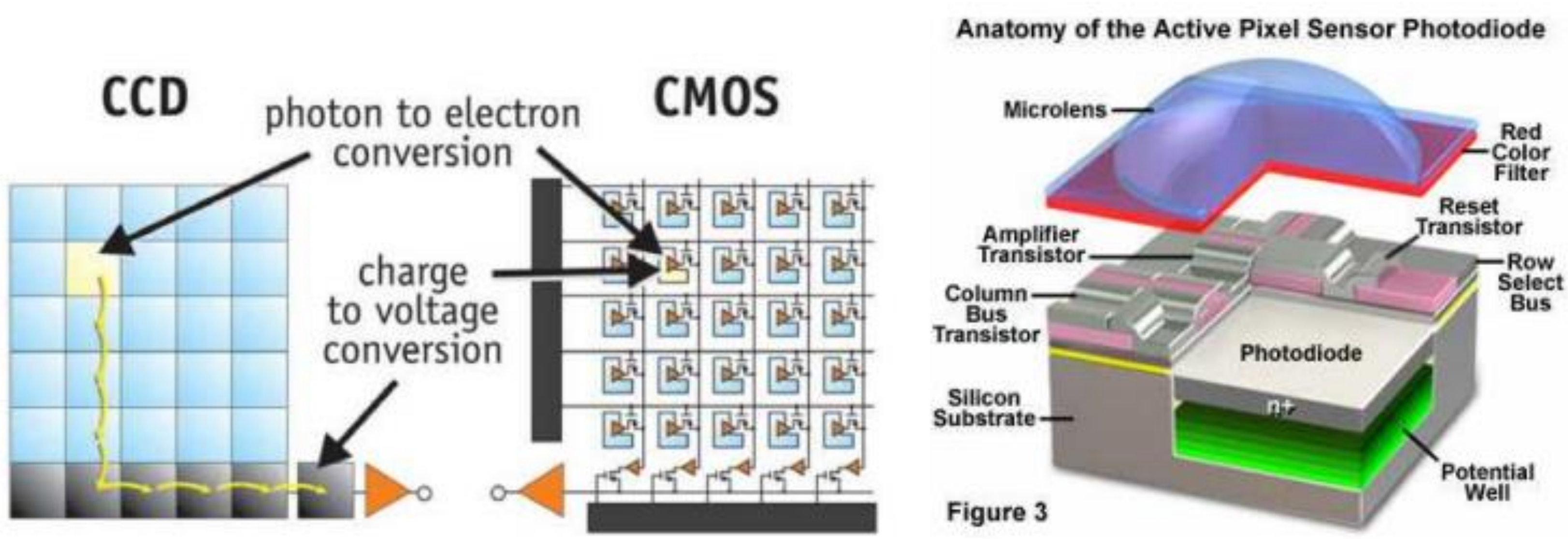


Slide form K. Grauman

Image sensing pipeline



Digital Sensors



(a) (b)

Figure 2.24 *Digital imaging sensors: (a) CCDs move photogenerated charge from pixel to pixel and convert it to voltage at the output node; CMOS imagers convert charge to voltage inside each pixel (Litwiller 2005) © 2005 Photonics Spectra; (b) cutaway diagram of a CMOS pixel sensor, from https://micro.magnet.fsu.edu/primer/digitalimaging/cmosimagesensors.html.*

Resolution

sensor: size of real world scene element a that images to a single pixel

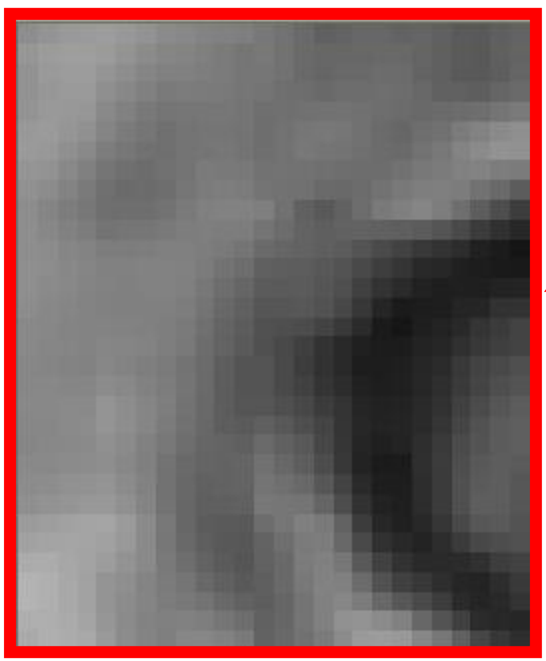
image: number of pixels

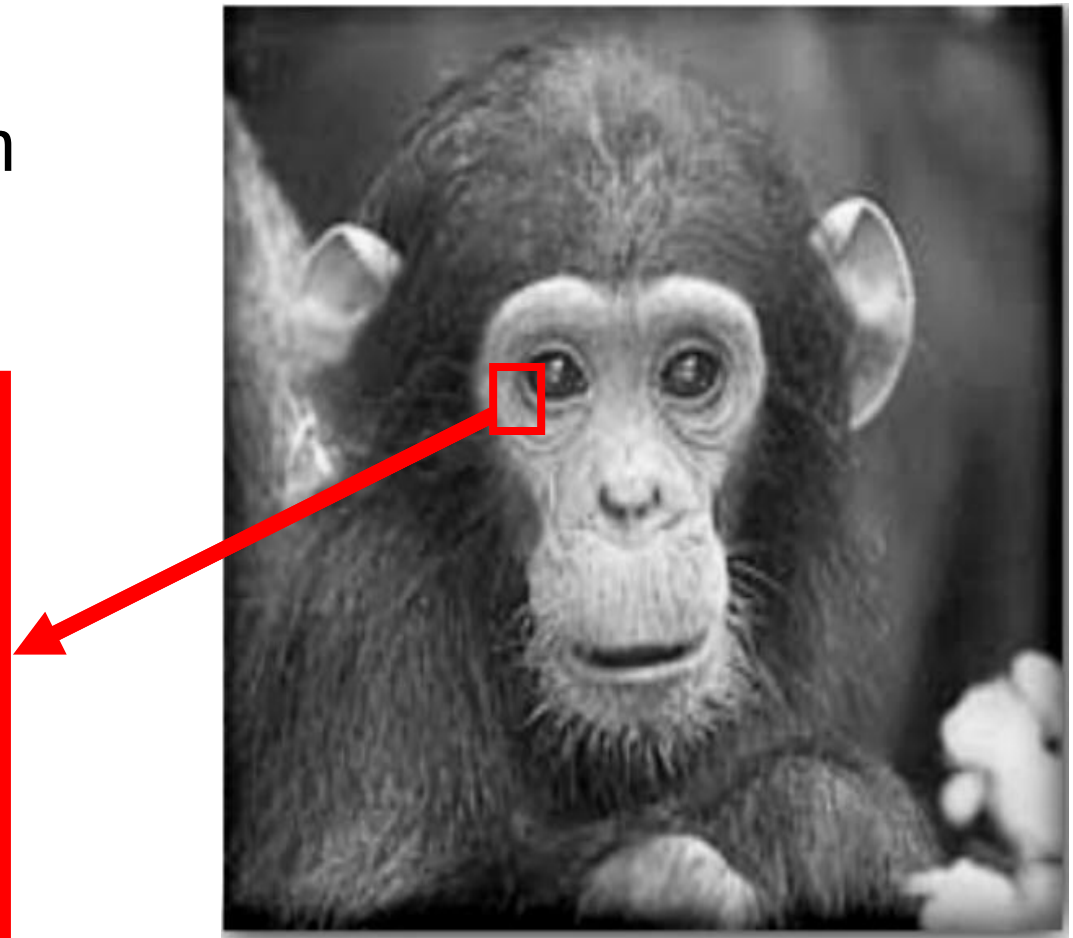
Influences what analysis is feasible, affects best representation choice.

[fig from Mori et al]

Digital images

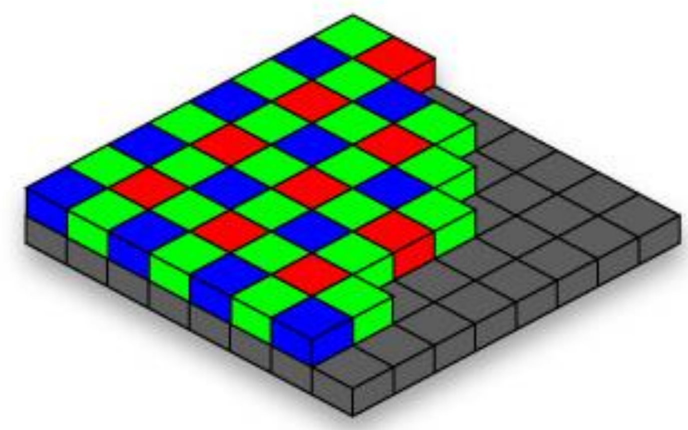
Think of images as matrices taken from CCD array.

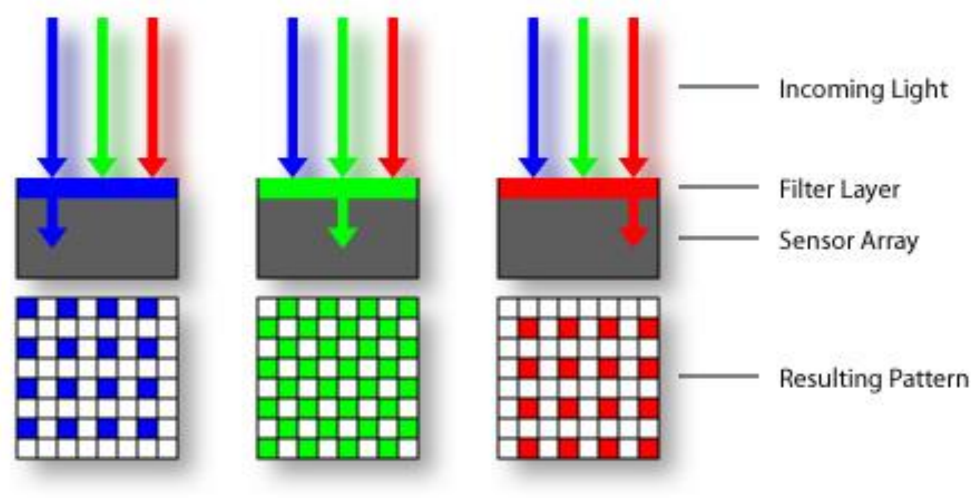




Color sensing in digital cameras

Bayer grid





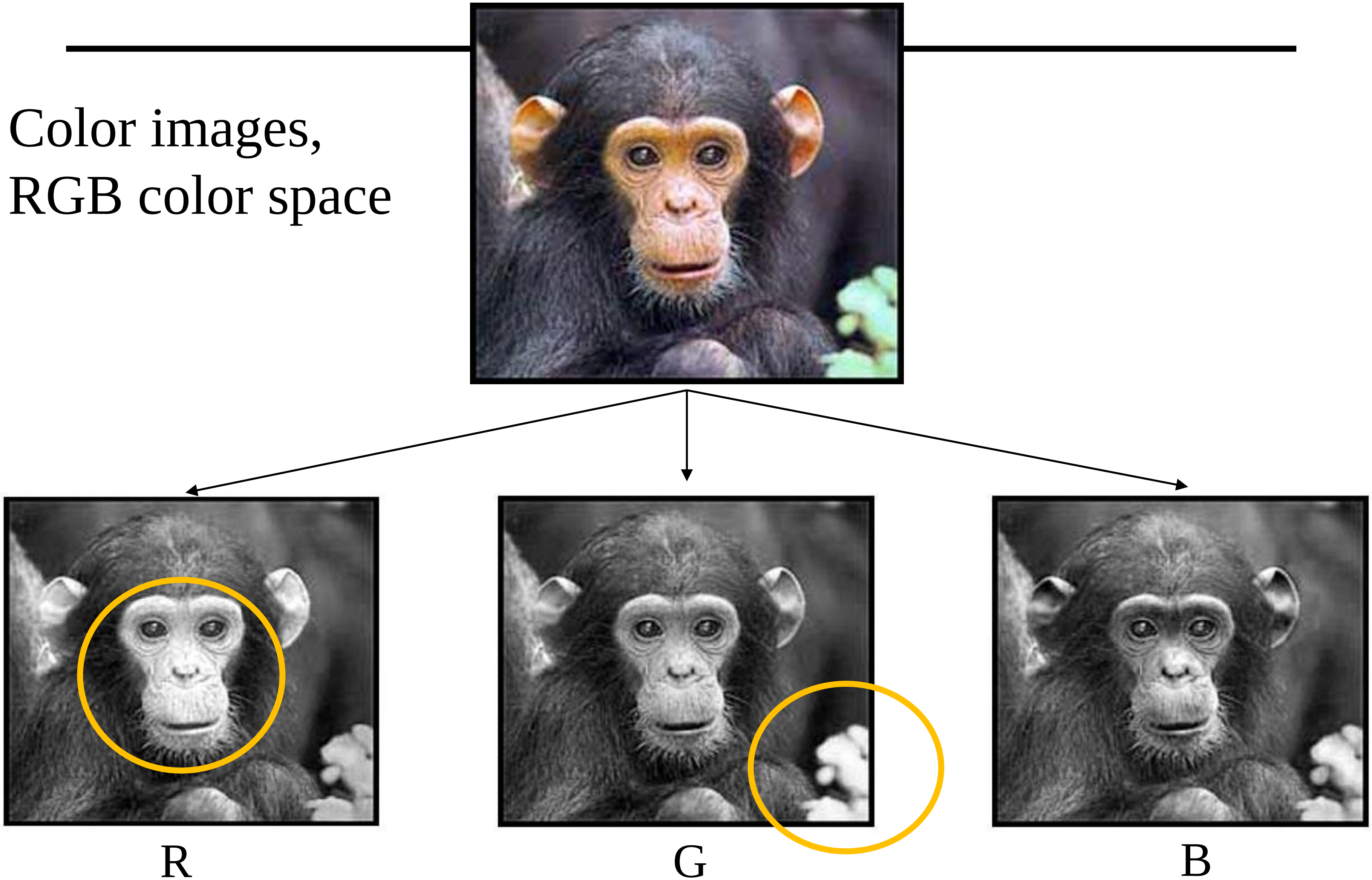
Demosaicing

(color interpolation):

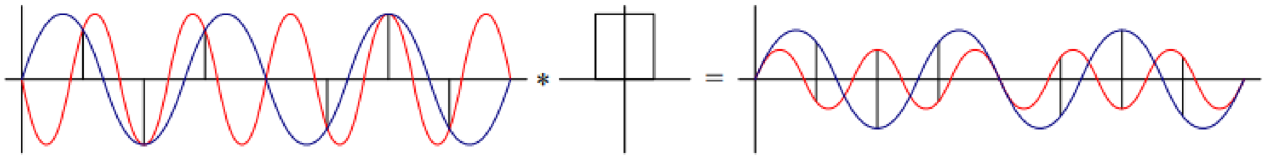
Estimate missing color components from neighboring values.

Source: Steve Seitz

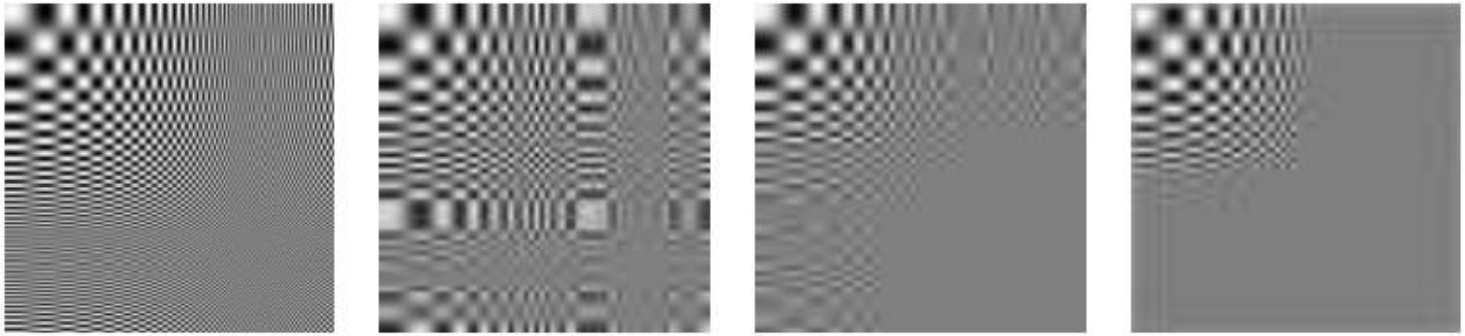
Color images, RGB color space



Aliasing



Aliasing of a one-dimensional signal: The blue sine wave at f = 3/4 and the red sine wave at f = 5/4 have the same digital samples, when sampled at f = 2. Even after convolution with a 100% fill factor box filter, the two signals, while no longer of the same magnitude, are still aliased.



(a) (b) (c) (d)

Figure 2.26 *Aliasing of a two-dimensional signal: (a) original full-resolution image; (b) downsampled 4 × with a 25% fill factor box filter; (c) downsampled 4 × with a 100% fill factor box filter; (d) downsampled 4 × with a high-quality 9-tap filter. Notice how the higher frequencies are aliased into visible frequencies with the lower quality filters, while the 9-tap filter completely removes these higher frequencies.*

Image Super-resolution

- Image upsampling, image scaling, digital zoom
- Increase the spatial resolution of an image

(a). Bicubic (b). Shan et al. (c). Freedman et al. (d). Proposed

Summary

- Geometric projection models
- Optical issues
- Photometric models
- Image sensing in digital camera