SAIR

Spatial AI & Robotics Lab

CSE 473/573-A

L3: COLORING & WARPING

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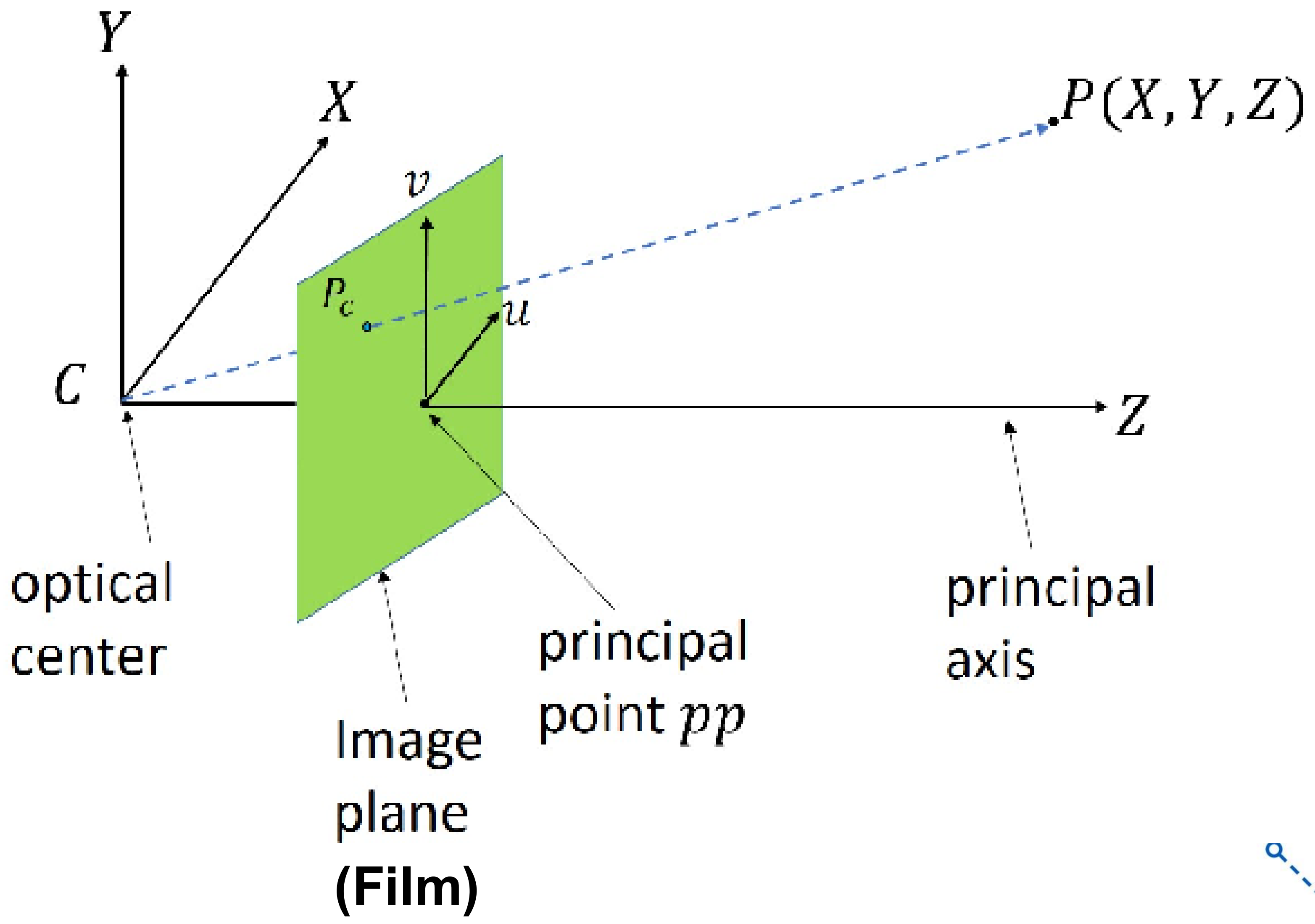
OPTICAL SENSOR

Content

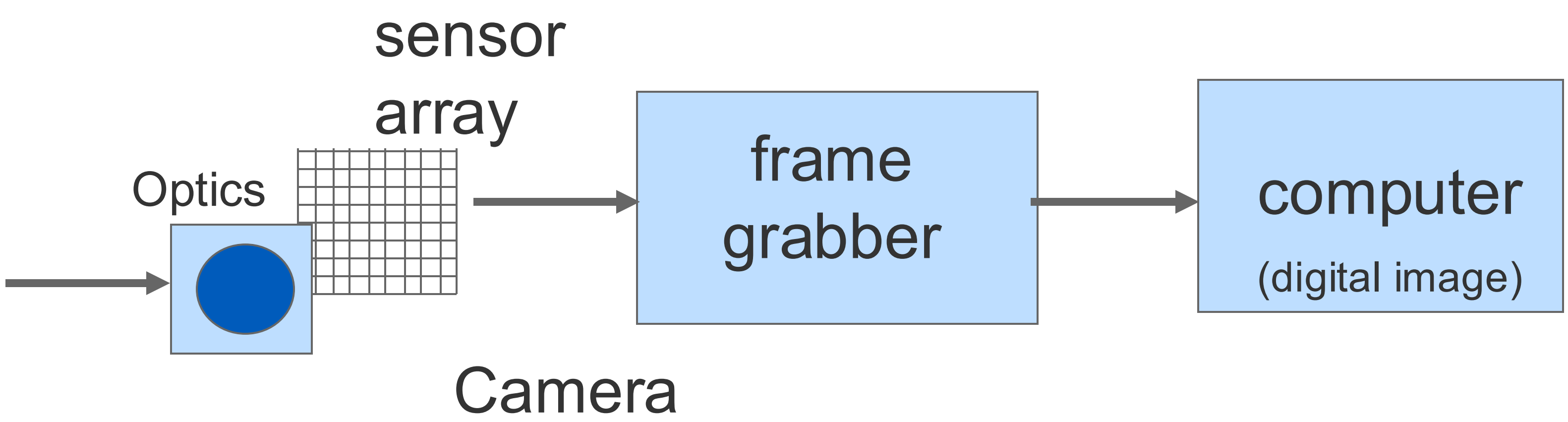
- Optical Sensor
  - Image representation, resolution, sampling & quantization
  - Digital Camera, CCD, CMOS
- Color Space
  - Electromagnetic Spectrum, Bayer pattern
  - RGB, HSV, L*a*b*, YCbCr

What is the film in a real camera?



Digital cameras

- Film is a sensor (detector) array
- Each position contains a light sensitive diode that converts **photons** (light energy) to **electrons.**



- Basic process:
  - photons hit a detector
  - the detector becomes charged
  - the charge is read out as brightness

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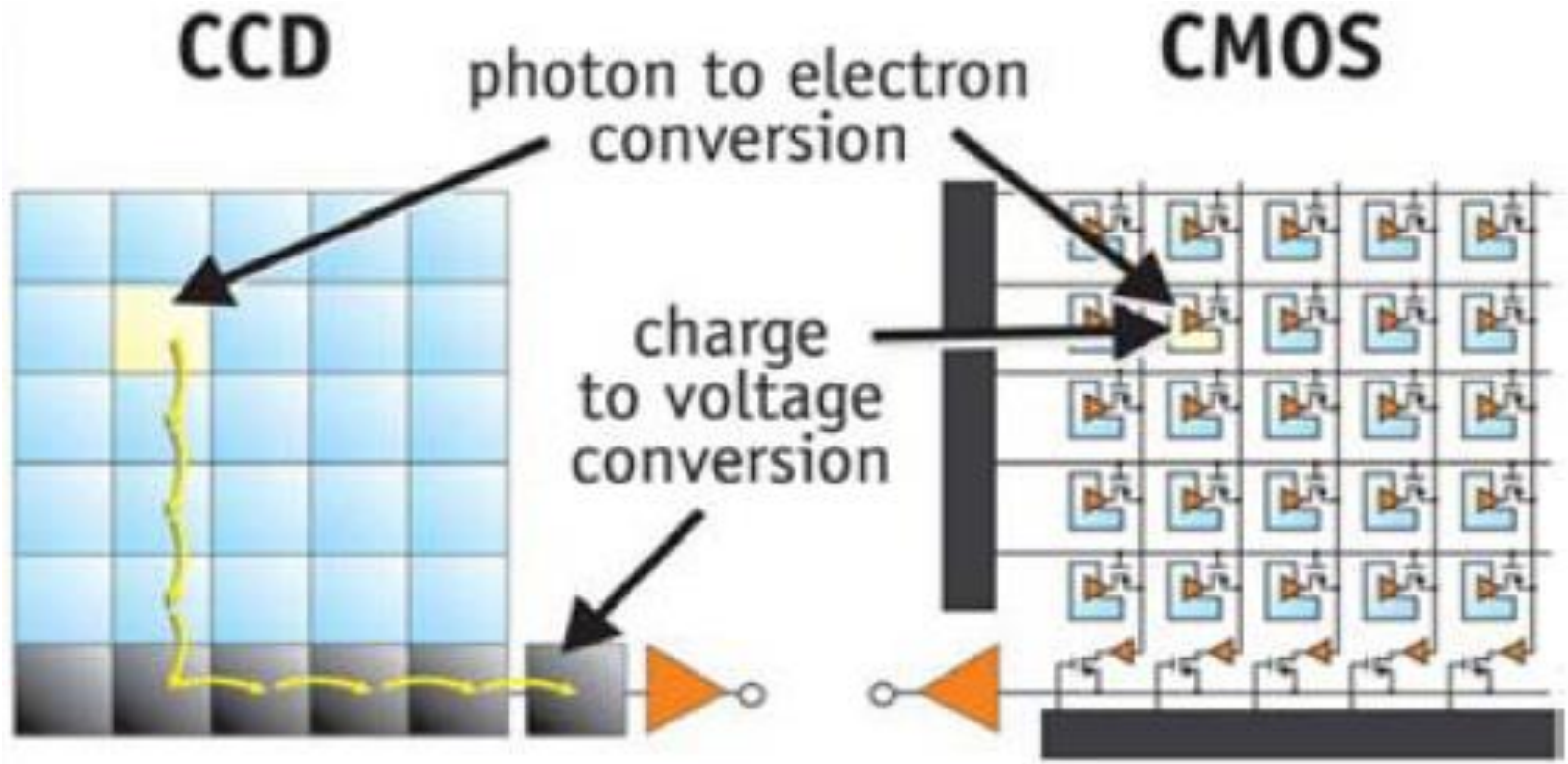
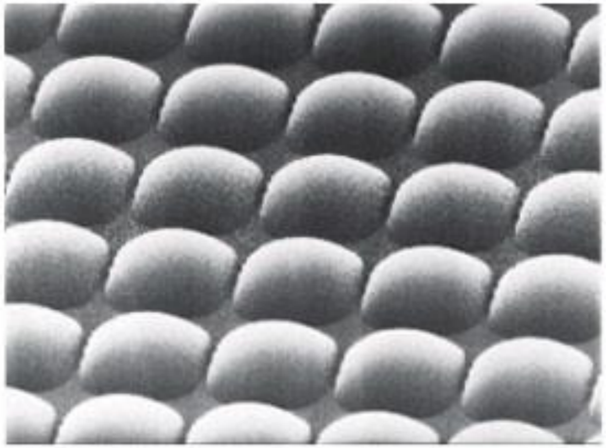
Digital Sensors

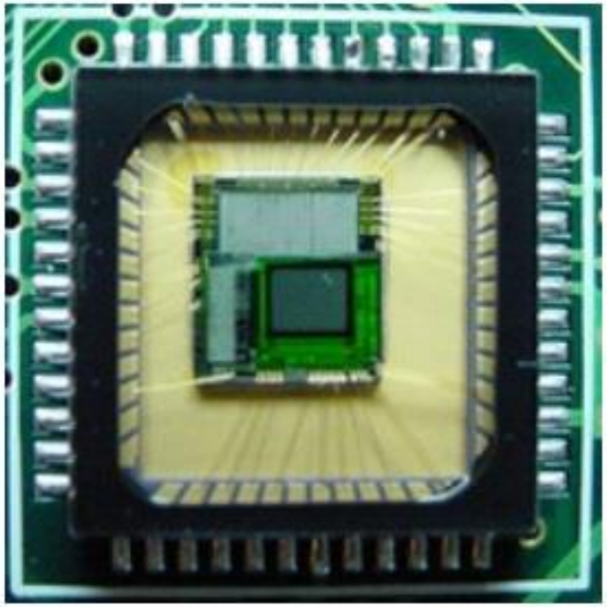
- CCD (charge couple devices): moves photogenerated charge from pixel to pixel and convert it to voltage at an output node.
- CMOS (complementary metal oxide semiconductor): convert charge to voltage inside each pixel.



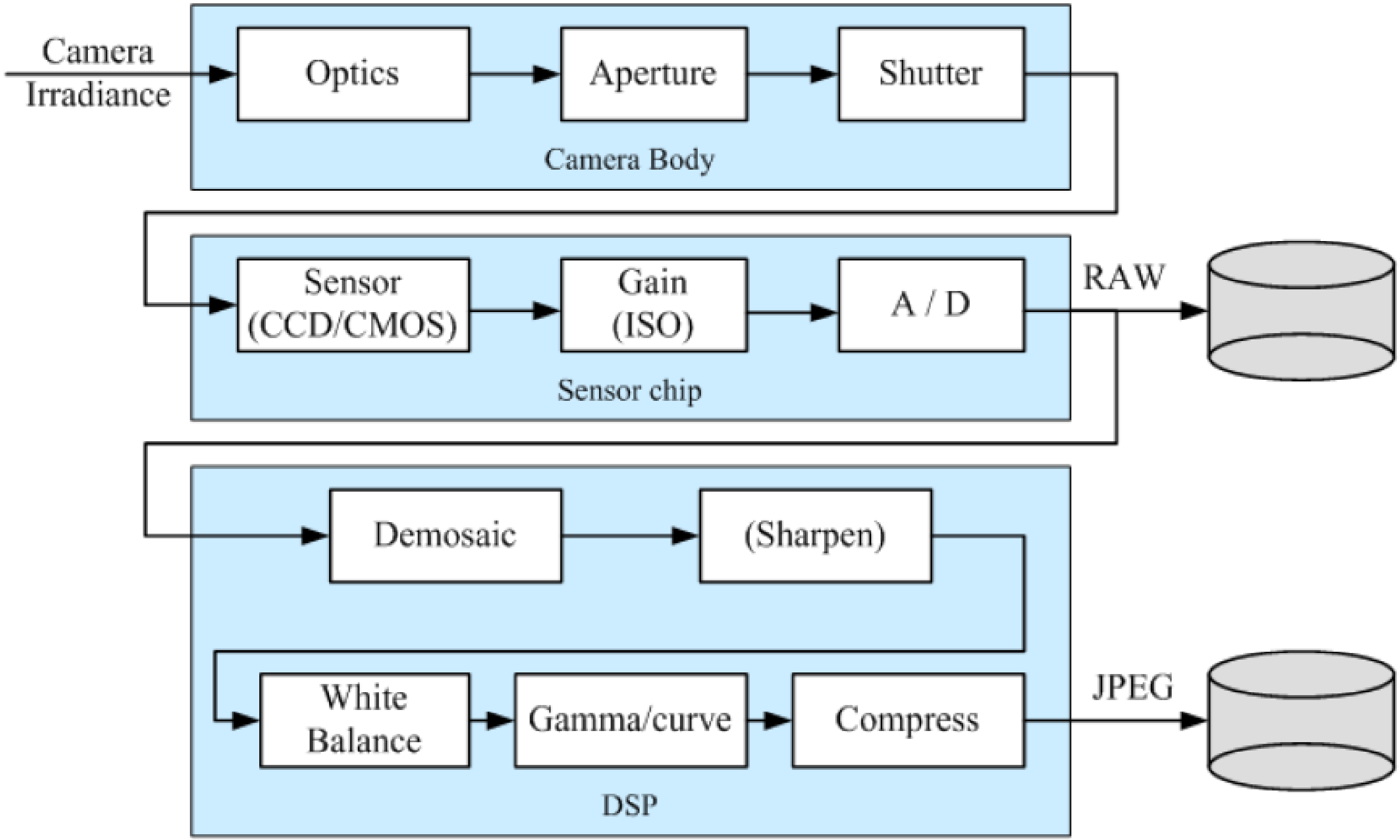
CCD vs CMOS

- Sensor types:
  - CCD (charge-coupled device)
    - most common
    - high sensitivity
    - high power
    - cannot be individually addressed
    - blooming
  - CMOS
    - simple to fabricate (cheap)
    - lower sensitivity, lower power
    - can be individually addressed





Camera



ISO referred to the sensitivity of film

Sampling and Quantization

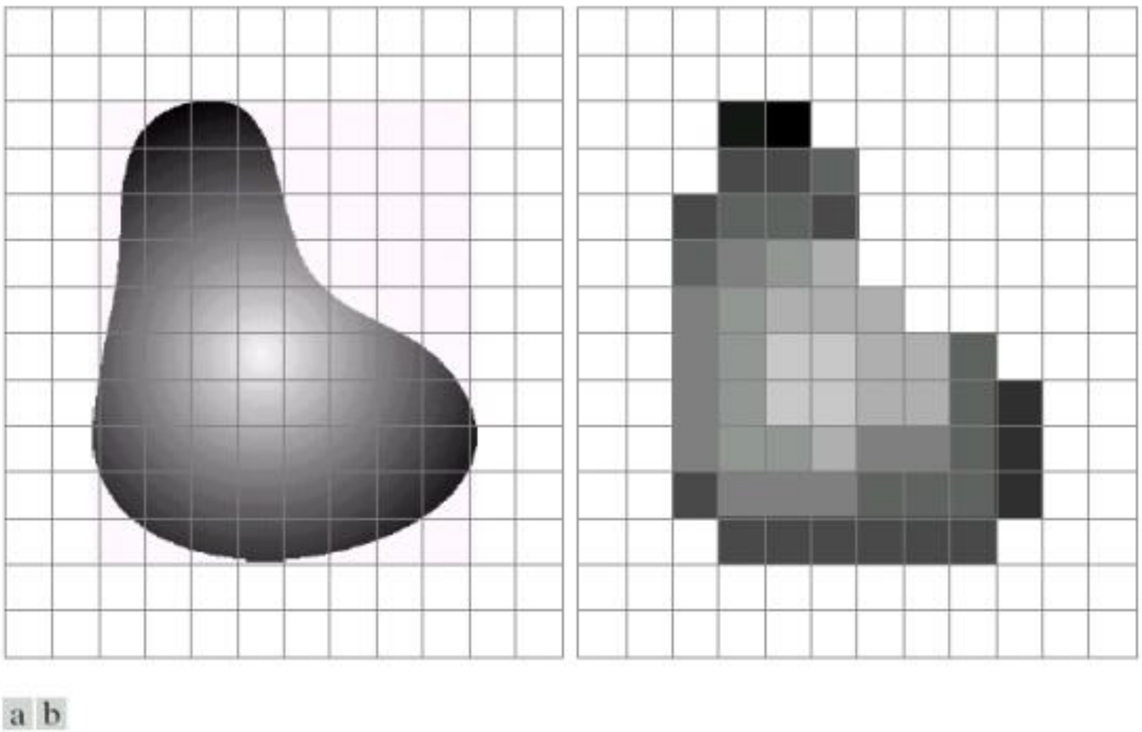


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

CMOS sensor

Sampling and Quantization: 1D Case

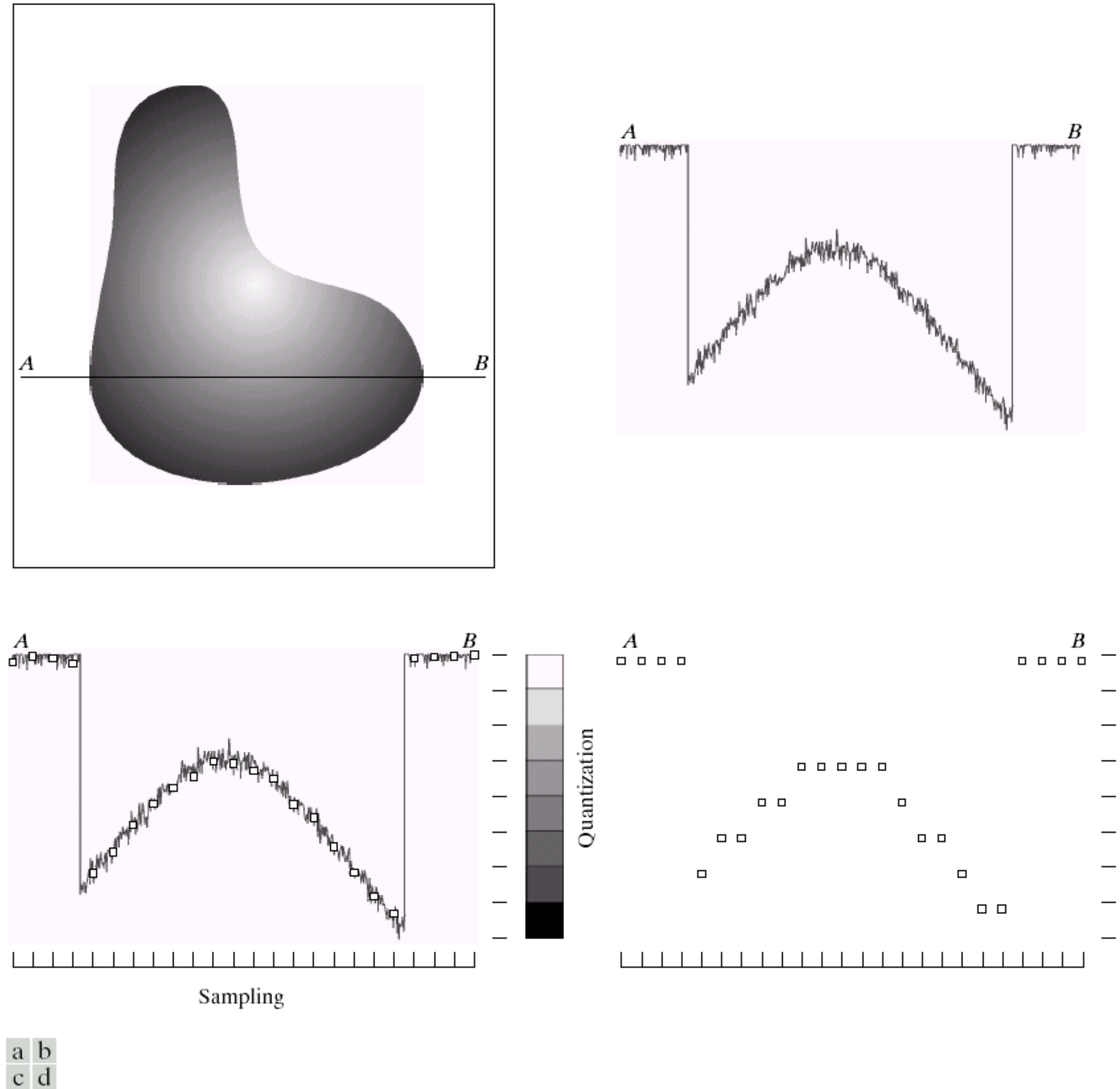


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

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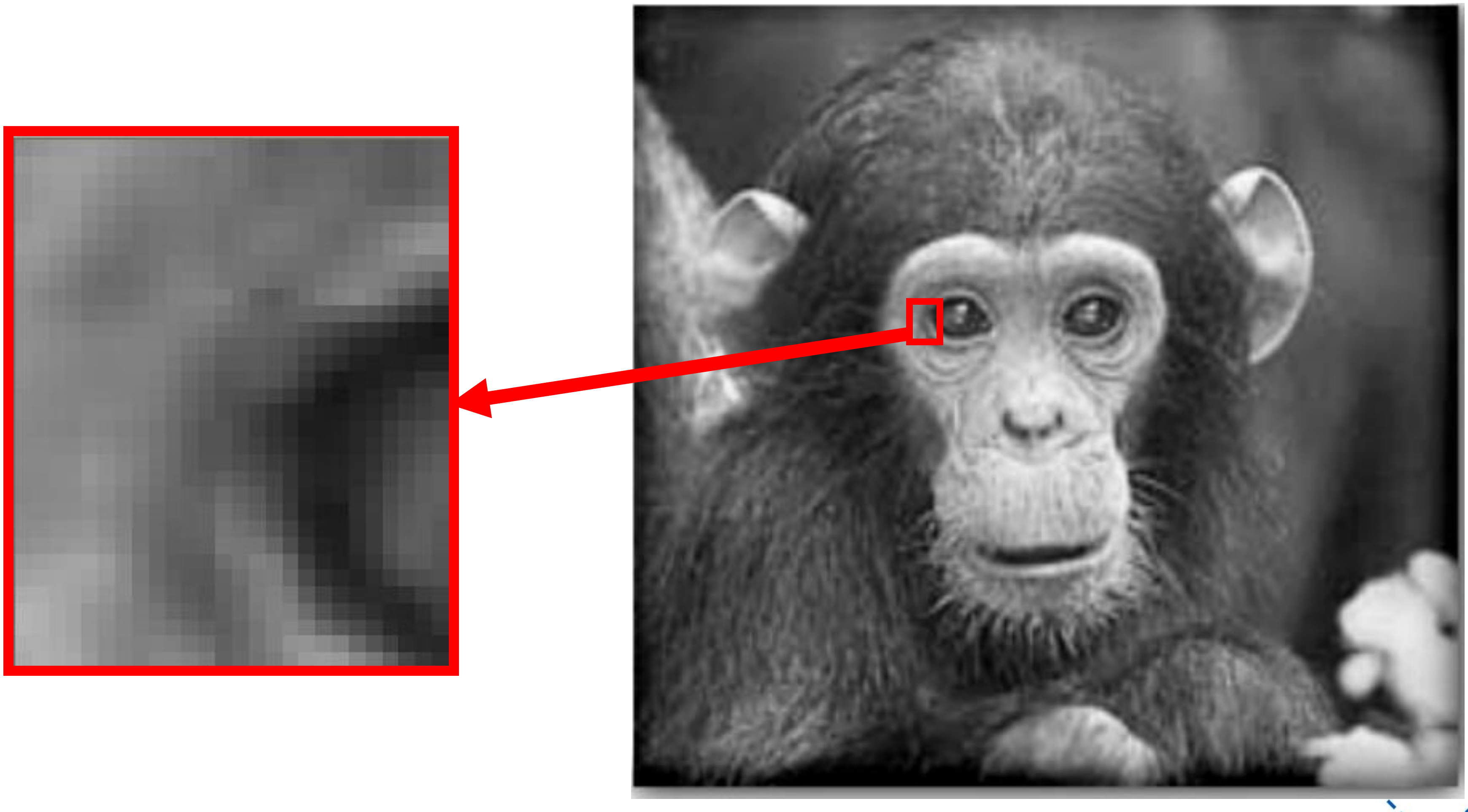
Digital Image

- Think of images as matrices taken from CCD array.



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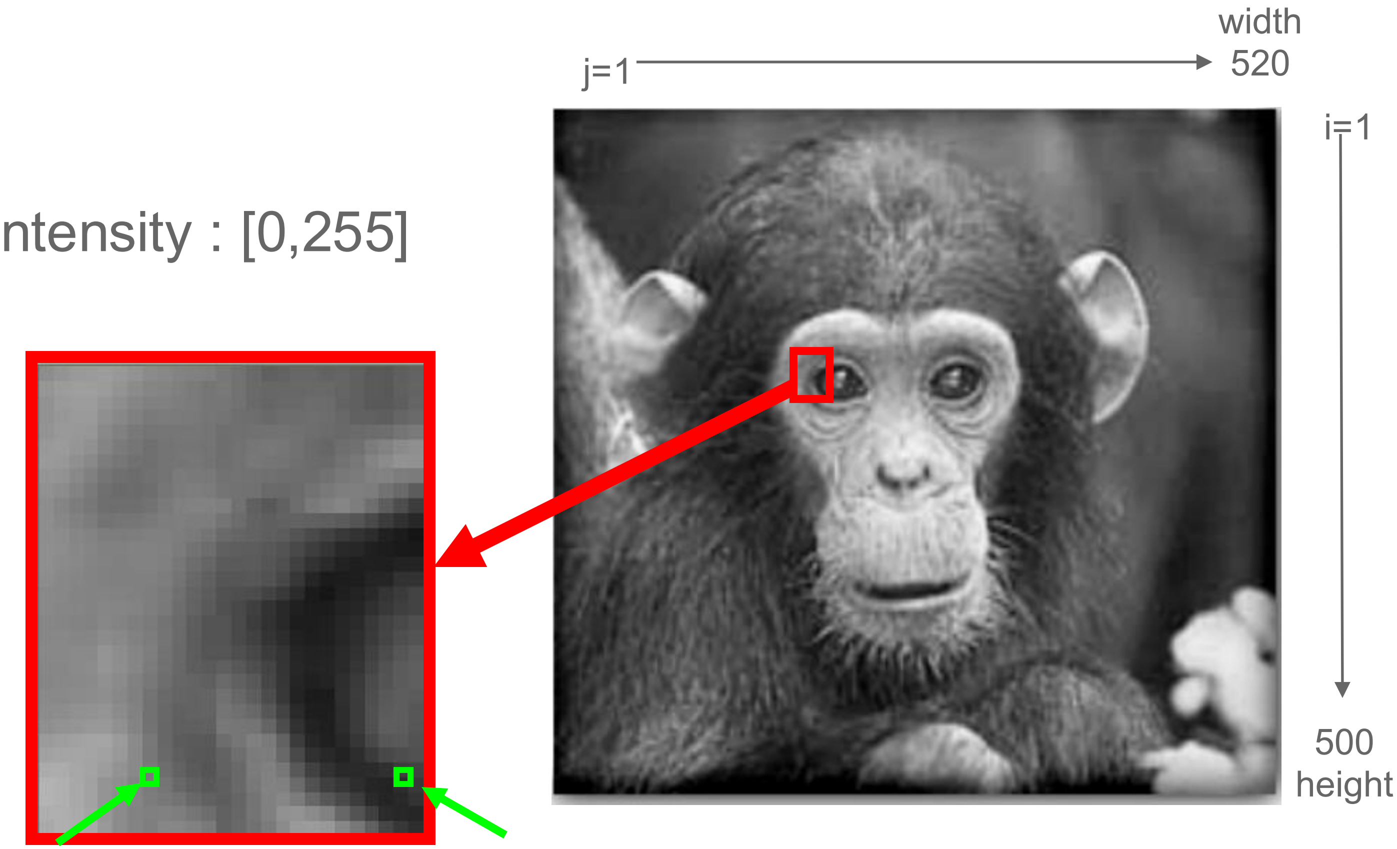
Digital Image

- Think of images as matrices taken from CCD array.

Intensity : [0,255]



im[176][201] has value 164

im[194][203] has value 37

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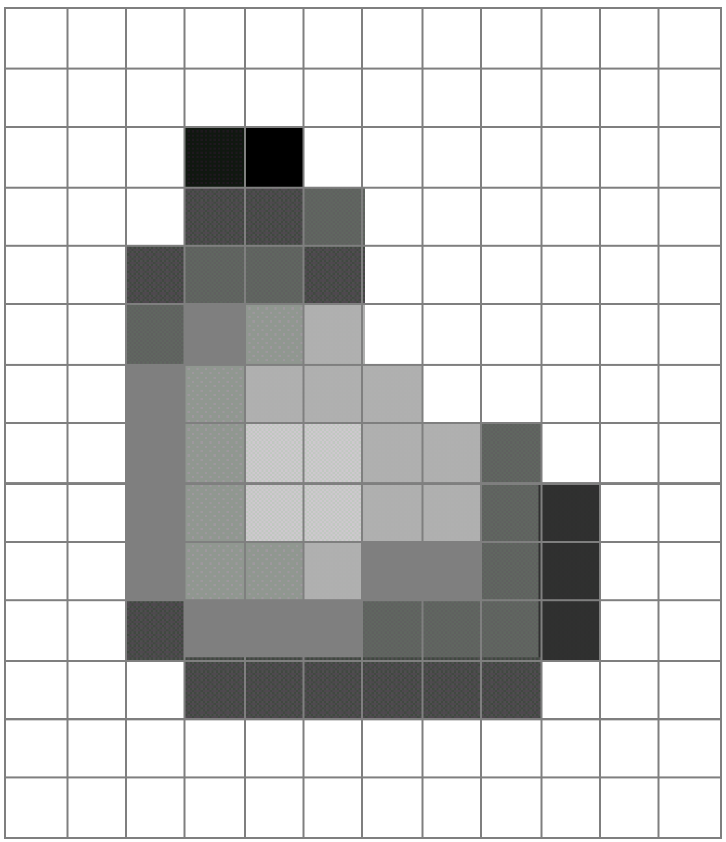
Digital image

- A grid (matrix) of intensity values.
- (common to use one byte per value: 0 = black, 255 = white)



=

255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	20	0	255	255	255	255	255	255	255
255	255	255	75	75	75	255	255	255	255	255	255
255	255	75	95	95	75	255	255	255	255	255	255
255	255	96	127	145	175	255	255	255	255	255	255
255	255	127	145	175	175	175	255	255	255	255	255
255	255	127	145	200	200	175	175	95	255	255	255
255	255	127	145	200	200	175	175	95	47	255	255
255	255	127	145	145	175	127	127	95	47	255	255
255	255	74	127	127	127	95	95	95	47	255	255
255	255	255	74	74	74	74	74	74	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255
255	255	255	255	255	255	255	255	255	255	255	255

Image representation

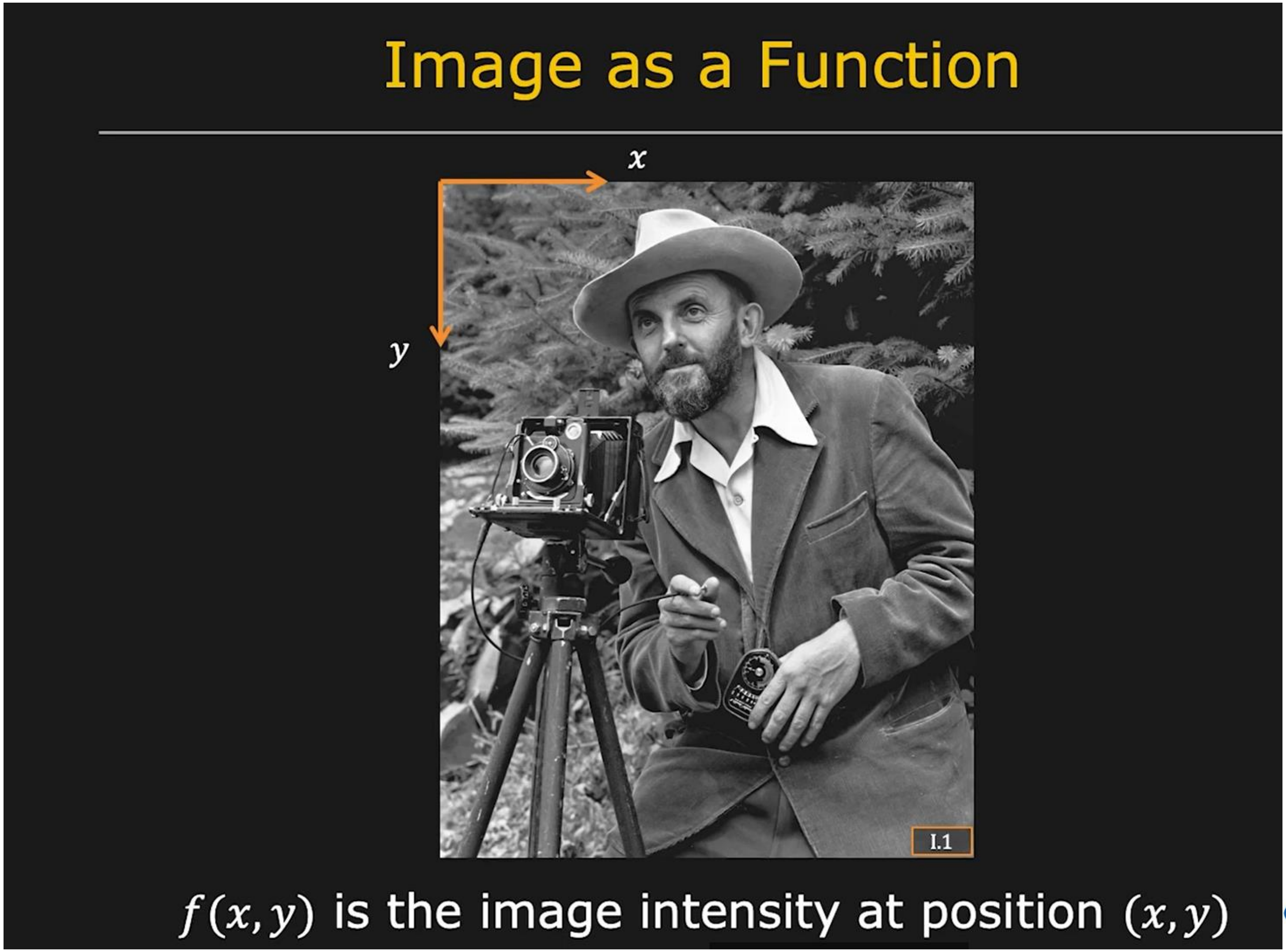
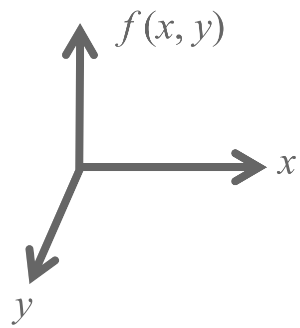


Image representation

- A (grayscale) image as a **function**, *f*, from R^2 to R:
  - $f(x, y)$ gives the **intensity** at position (x, y).
  - A **digital image** is a discrete (**sampled**, **quantized**) version of this function.



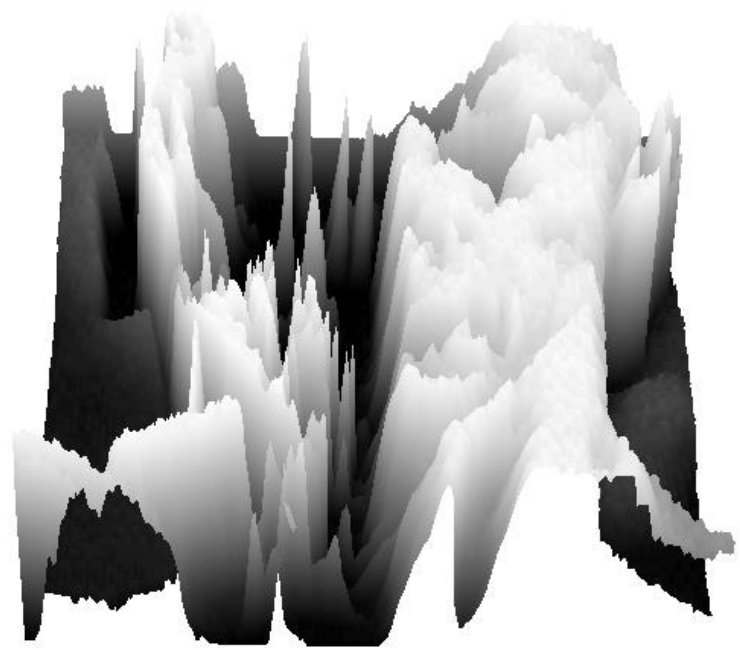


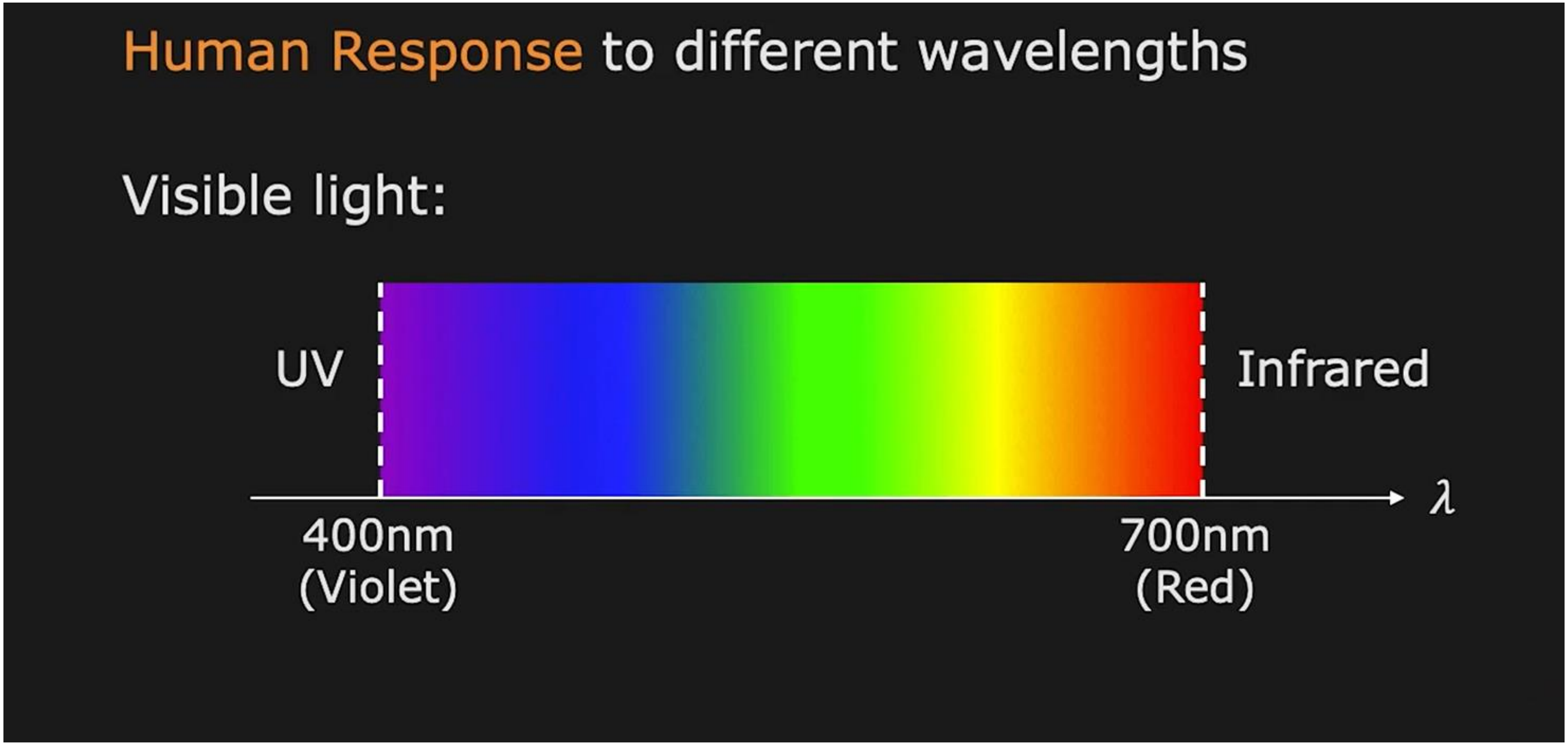
Image Resolution

- Sensor: size of real-world scene element that maps to a single pixel
- Influences what analysis is feasible, affects best representation choice.

FIGURE 2.19 A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.

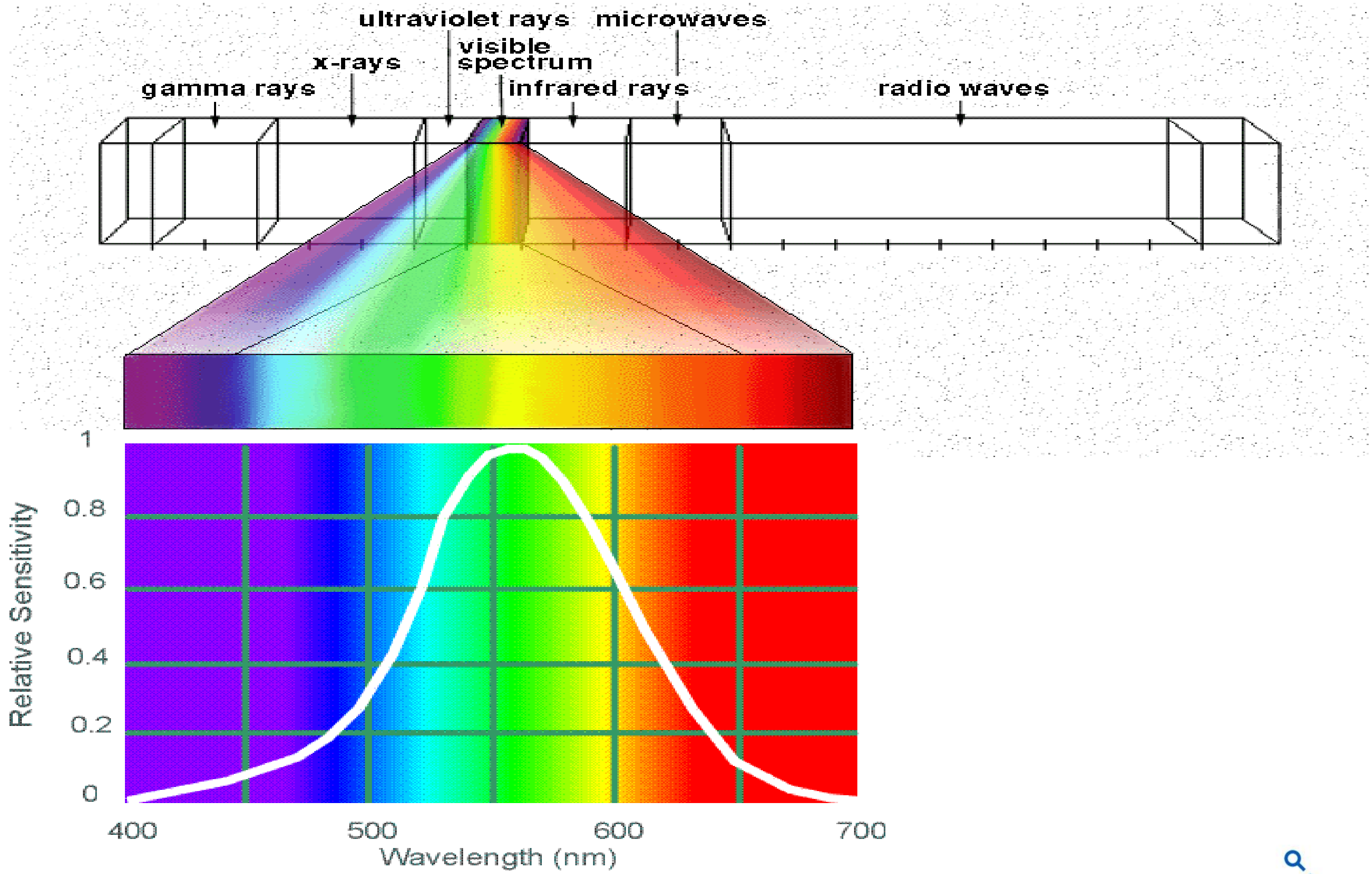
COLOR SPACE

What is Color?



Electromagnetic wave

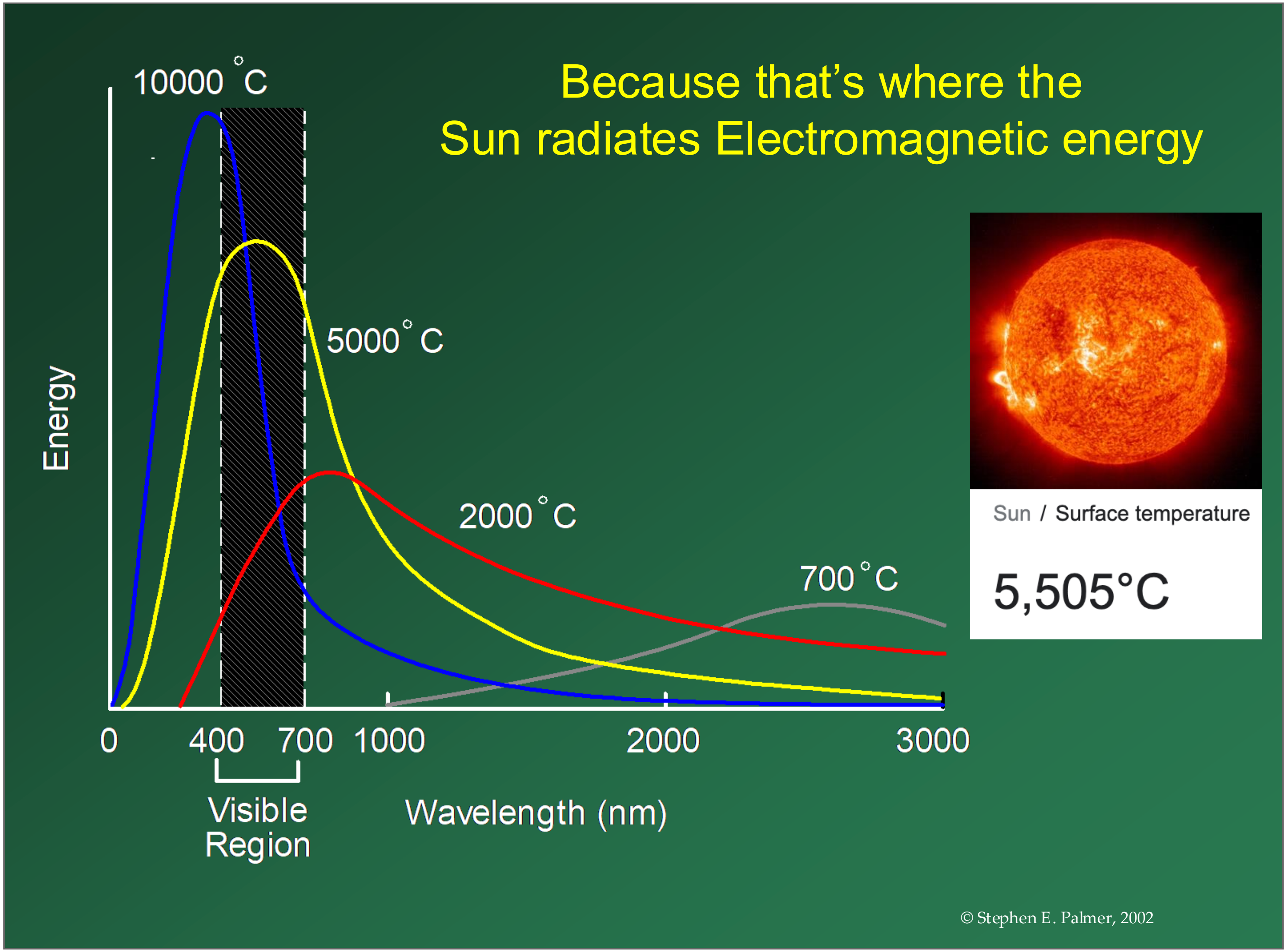
Electromagnetic Spectrum



Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm

Why do we see light of these wavelengths



Mixing of color

Young's Experiment on Color Mixture

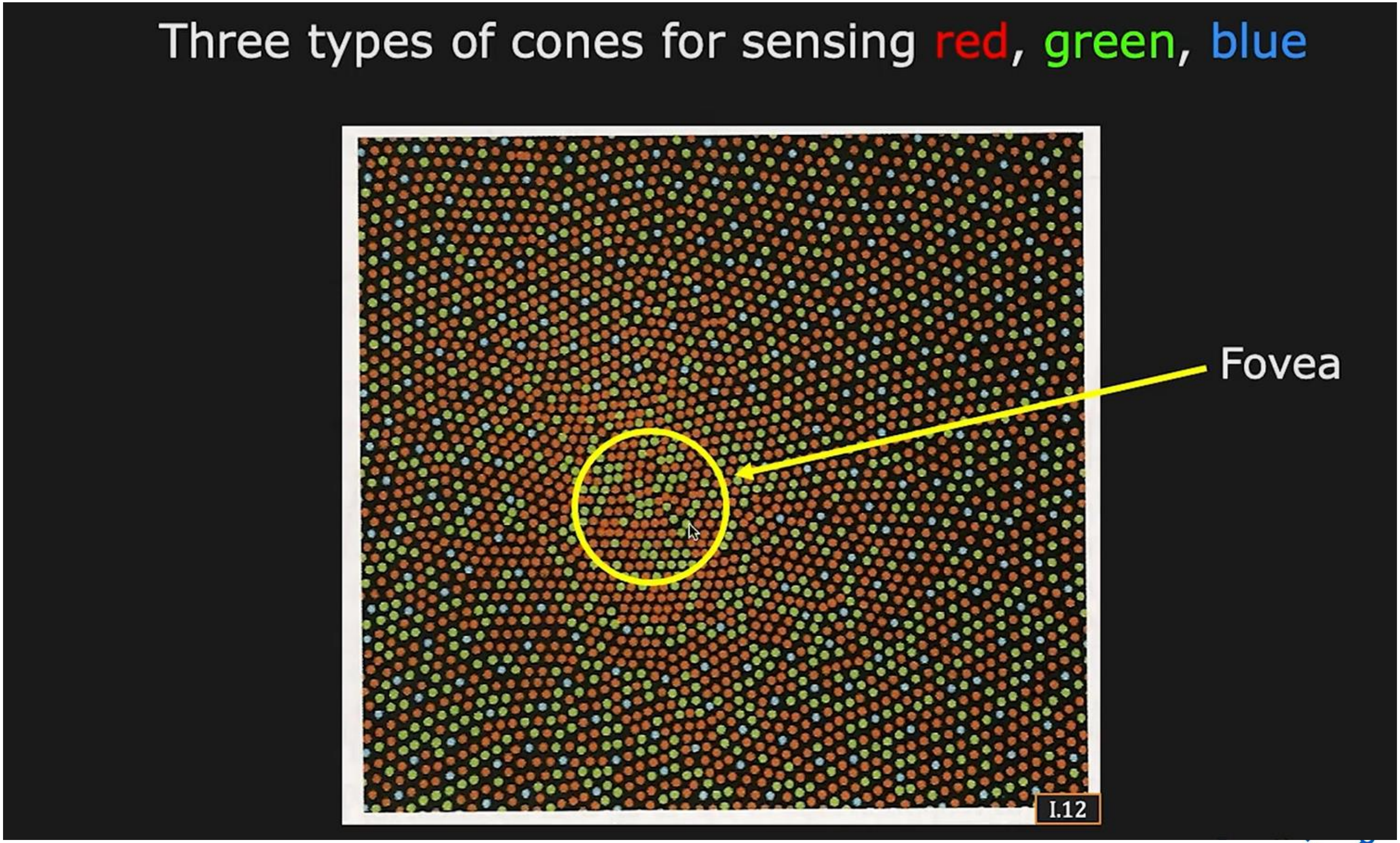
Human Sensation of nearly all colors can be produced using 3 wavelengths!

$$(\lambda_r, \lambda_g, \lambda_b) = (650, 530, 410)nm$$

Hence, cameras and displays often use 3 filters:

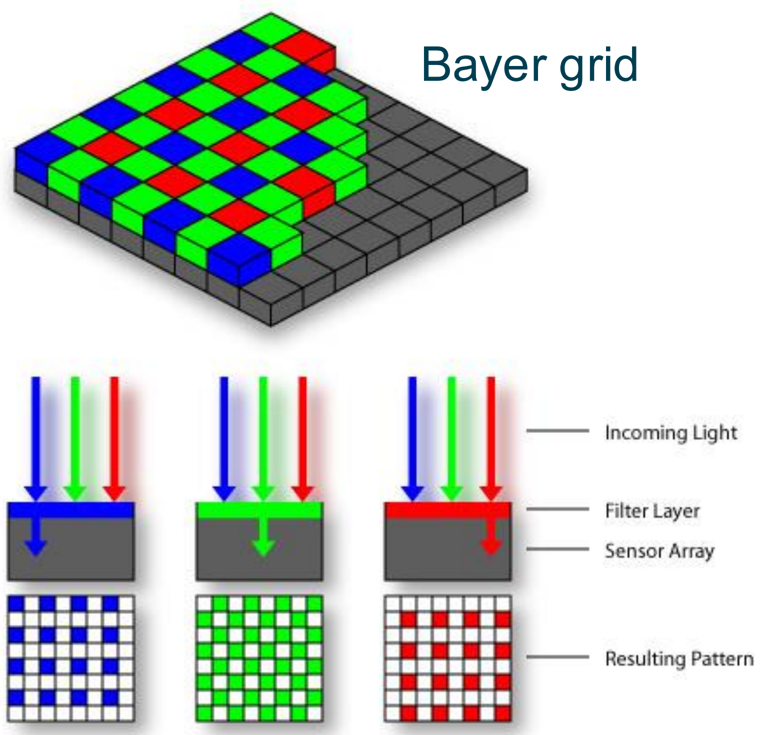
(red, green, blue)

Distribution of Cones in Human Retina



Color sensing in digital cameras

- Estimate missing components from neighboring values (demosaicing)



Anatomy of the Active Pixel Sensor Photodiode

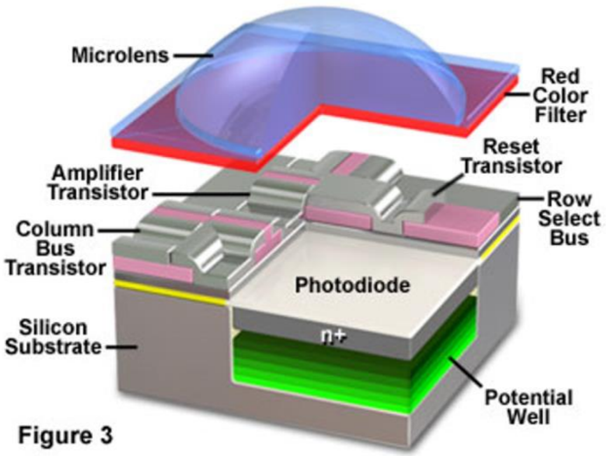
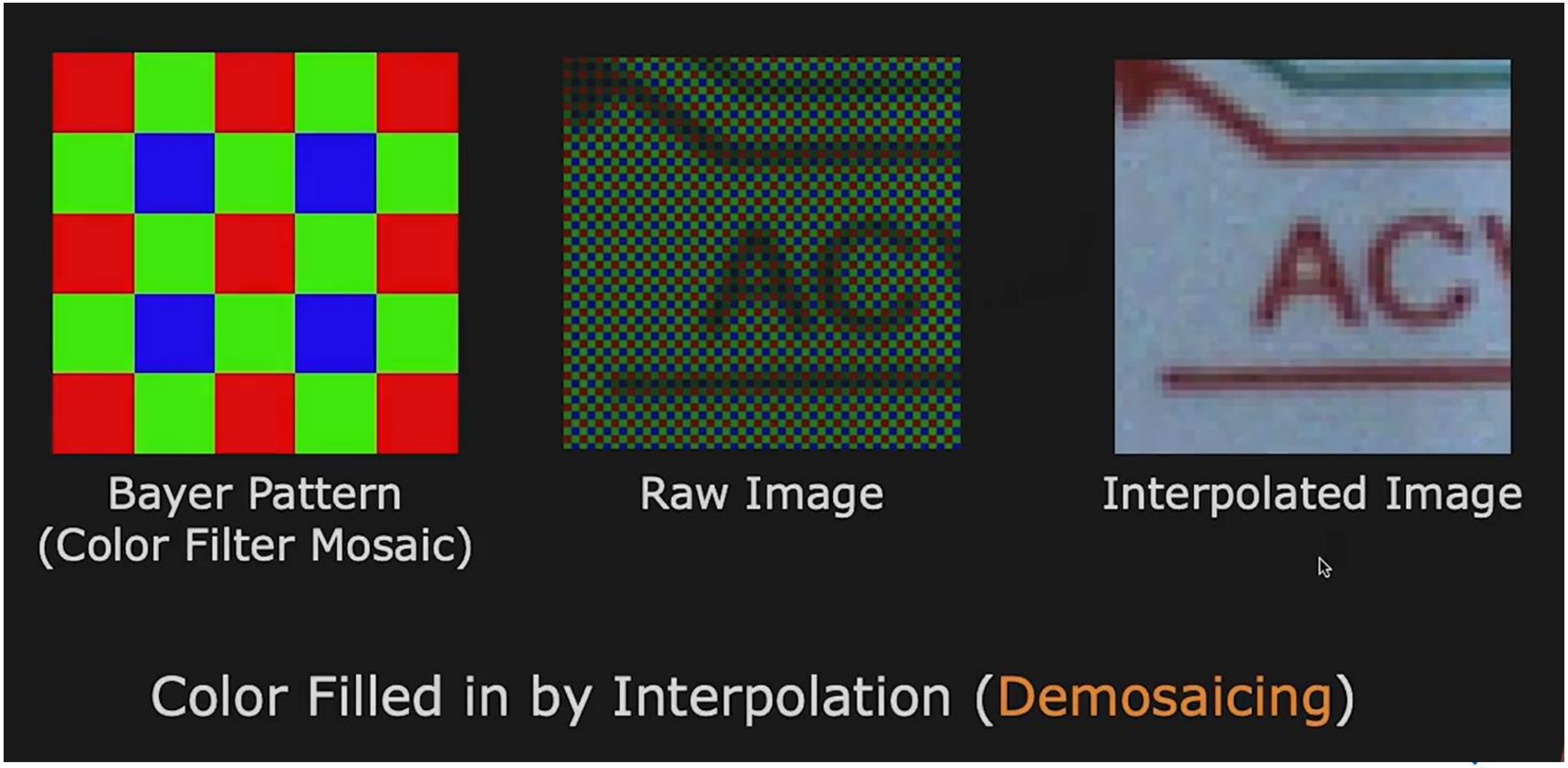


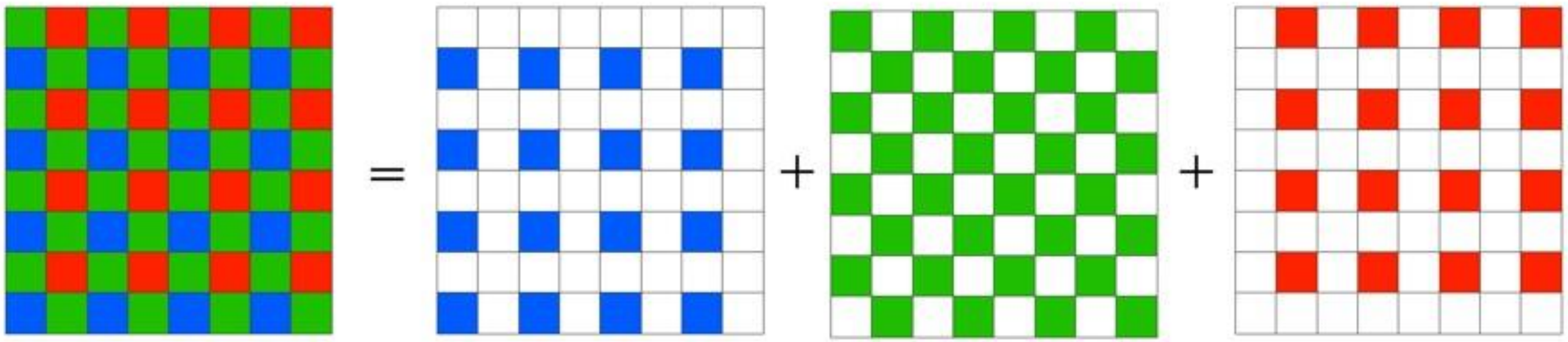
Figure 3

Source: Steve Seitz

Sensing Color Using Color Mosaic



Bayer pattern



- But why are there more green filters?
- Because human vision is more sensitive to green.
- So, the ratio is 50% green, 25% red, and 25% blue.

https://pixelcraft.photo.blog/2019/12/18/the-bayer-filter/

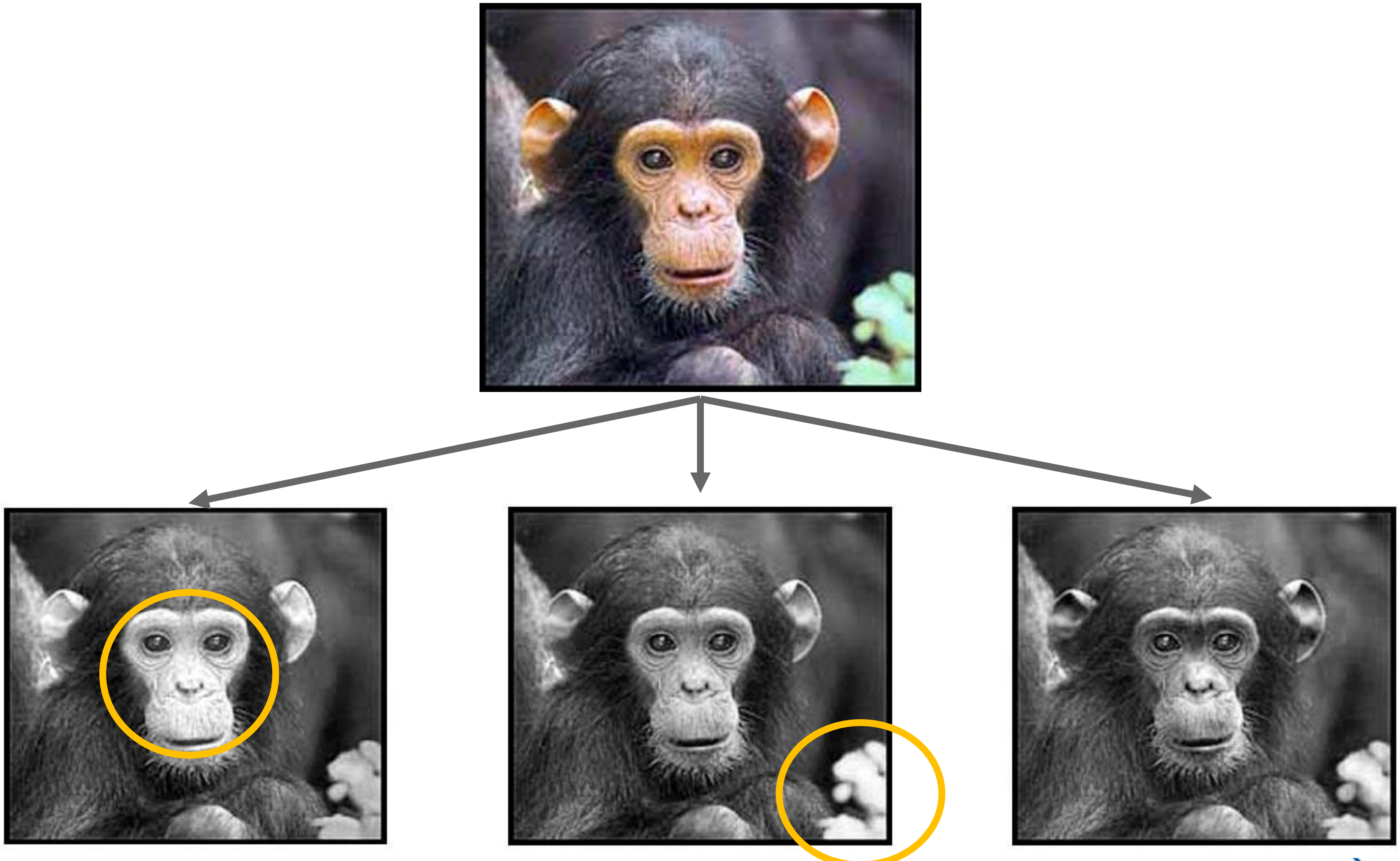
True vs interpolated values of RGB

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

rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb
rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb

Digital Color images

- RGB color space (3 Channels)



R G B

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Images in Python (PyTorch)

- Images represented as a matrix (Tensor)
- Suppose we have a $N \times M$ RGB image called "I"
  - I[0,0,0] = top-left pixel value in R-channel
  - I[b, r, c] = c pixels to right, r pixels down, in the bth channel
  - I[B, N-1, M-1] = bottom-right pixel in B-channel

column

row

R

0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

G

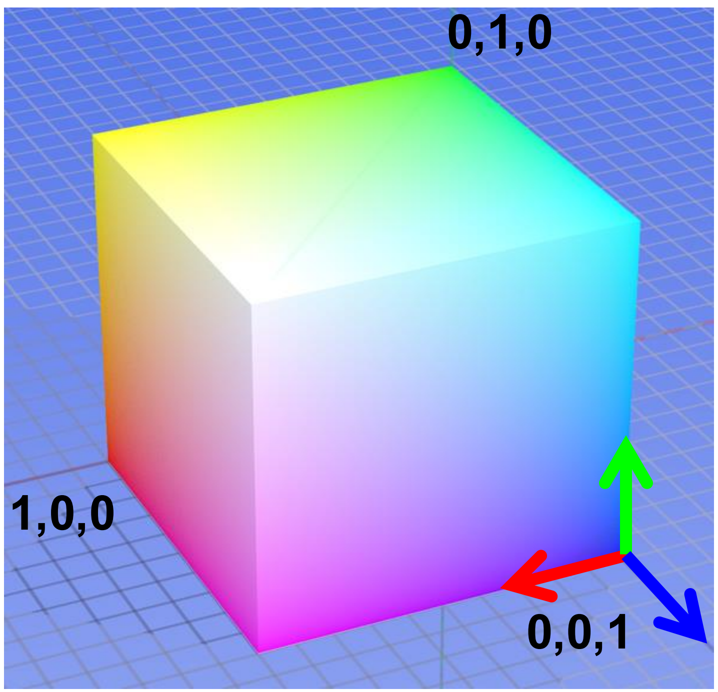
									.92	0.99
									.95	0.91
									.91	0.92
									.97	0.95
									.79	0.85
									.45	0.33
									.49	0.74
									.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

B

									.92	0.99
									.95	0.91
									.91	0.92
									.97	0.95
									.79	0.85
									.45	0.33
									.49	0.74
									.82	0.93
									.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

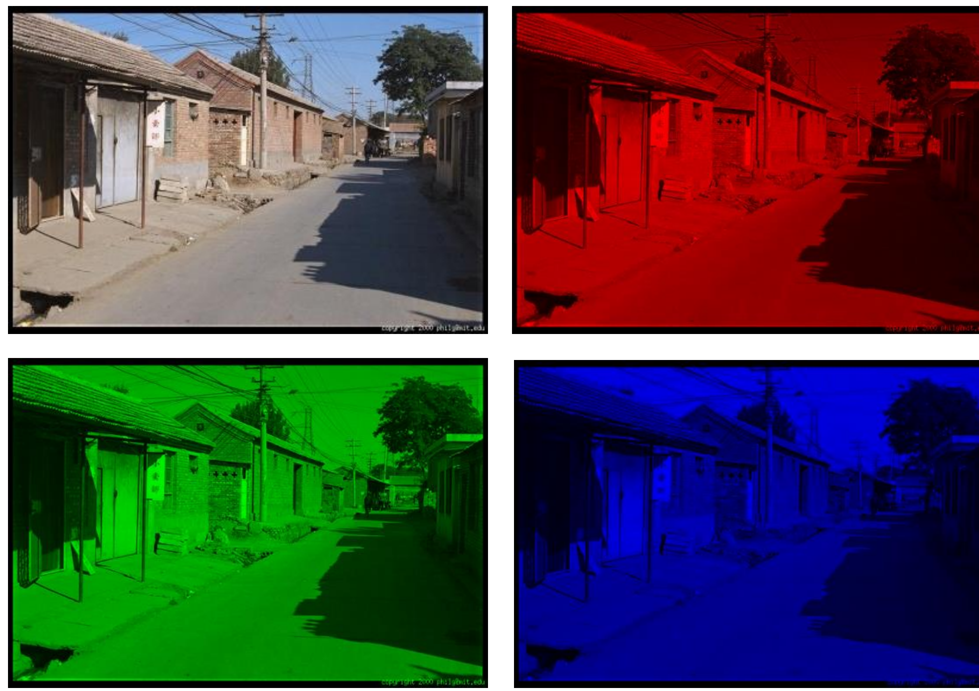
Color spaces: RGB

- Drawbacks
  - Strongly correlated channels
  - Non-perceptual



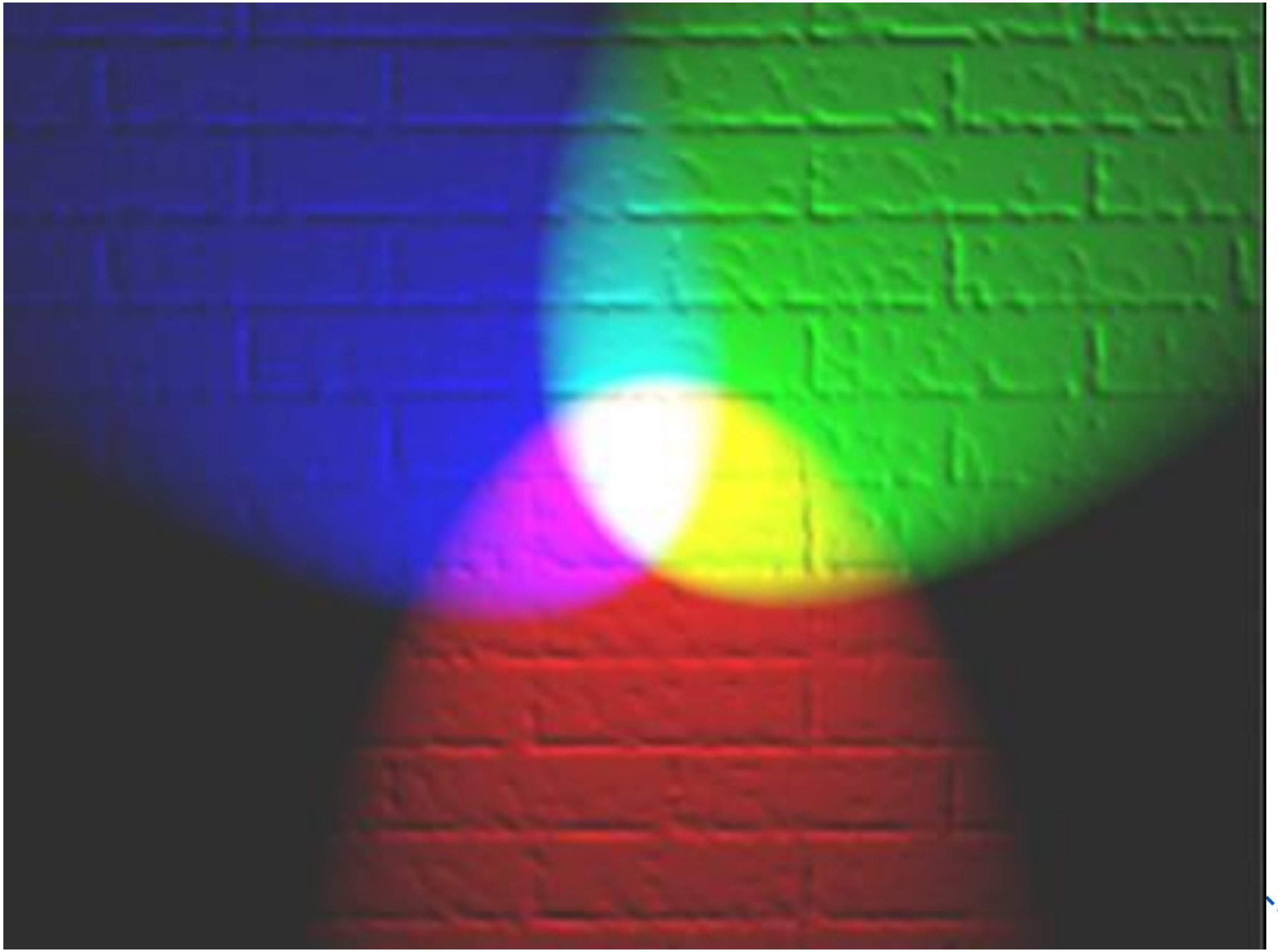
Default color space

Original　　R (G=0,B=0)



G (R=0,B=0)　　B (R=0,G=0)

Any other color space?

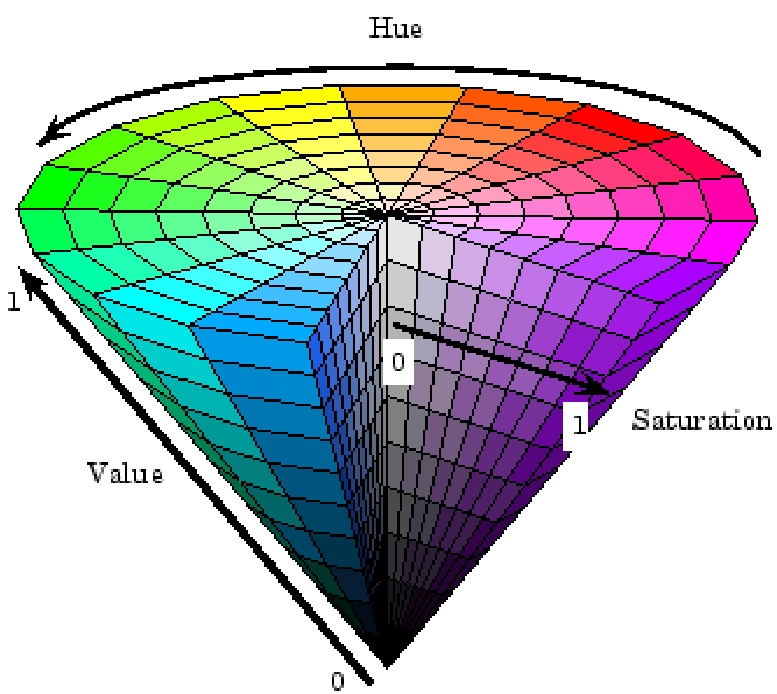


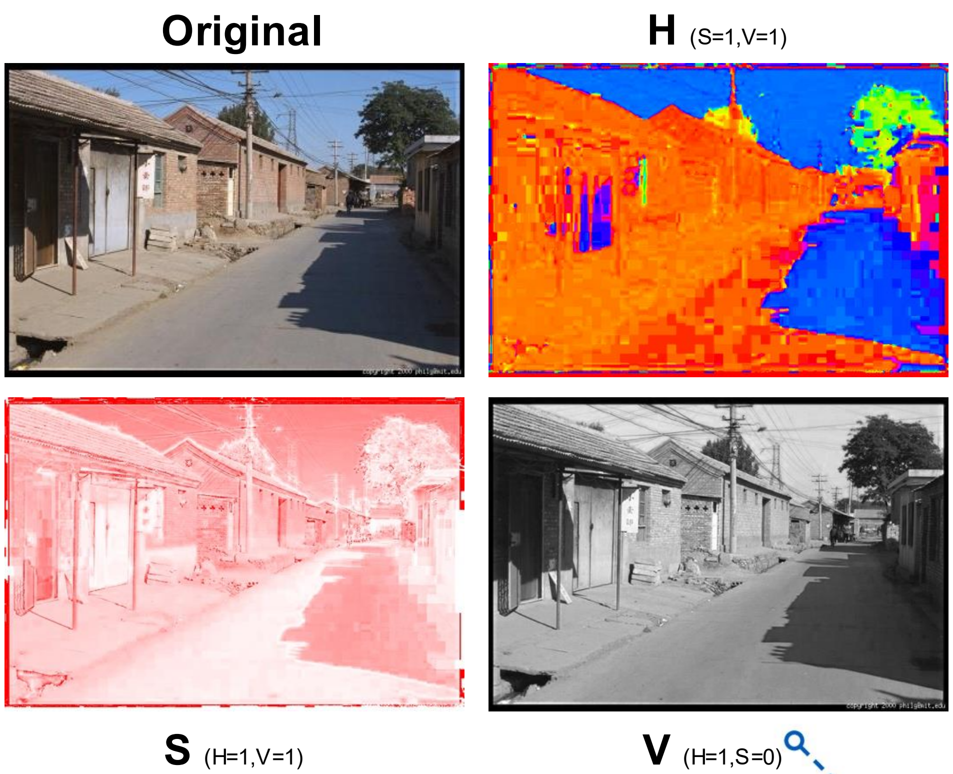
http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Color spaces: HSV

- **Hue, Saturation, Value (Brightness):** how colors appear under light.
- **Saturation** (photography): the intensity of a color, expressed as the degree to which it differs from gray.

Intuitive Color Space



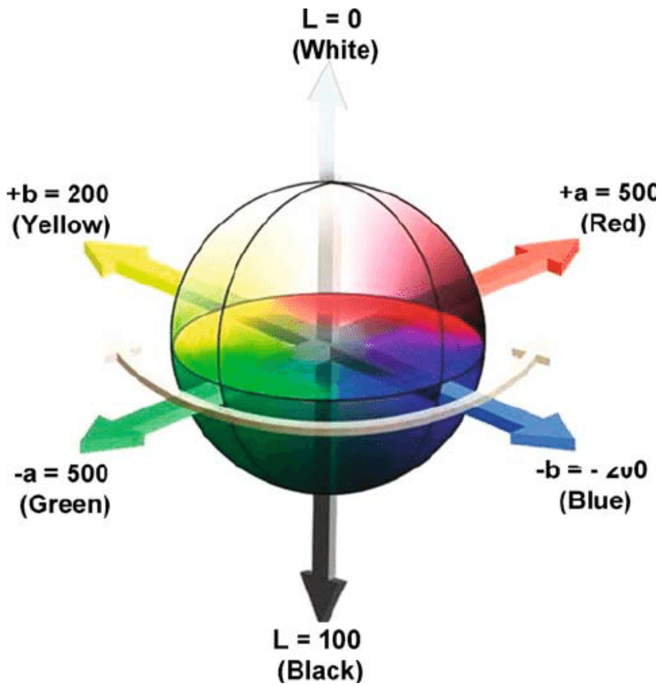


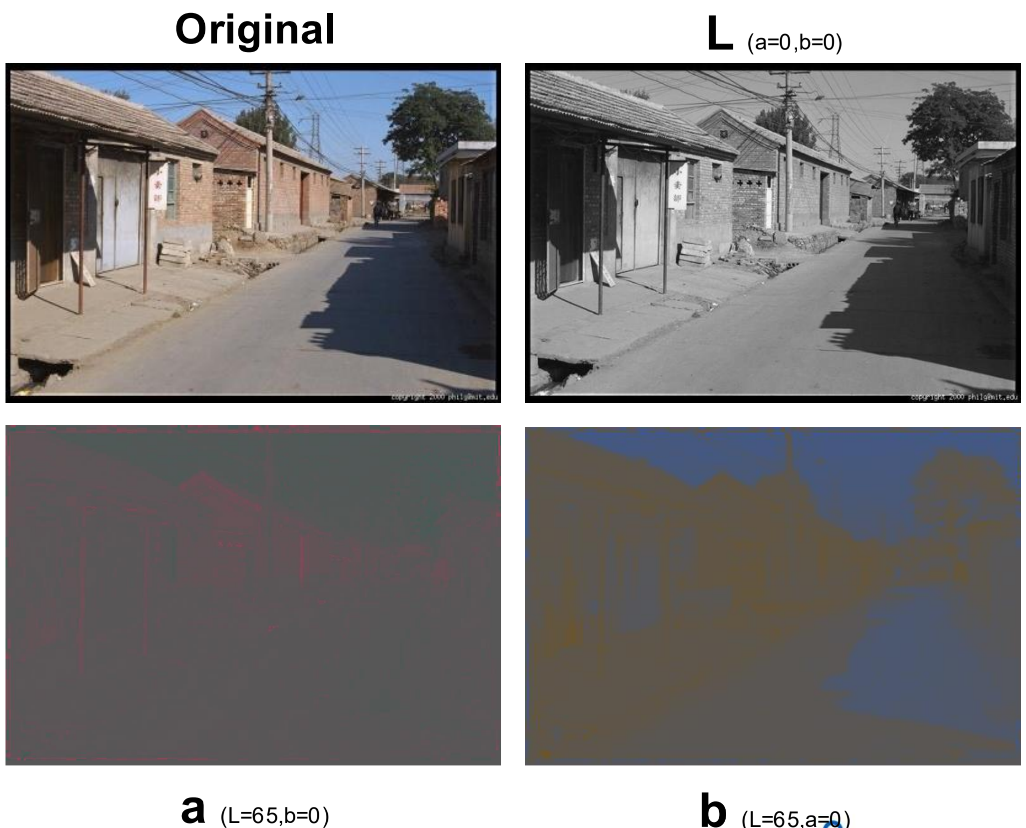
Friendly for human intuition

Color spaces: L*a*b*

- **L** is for lightness. It goes from 0 to 100, shows contrast between black and grays.
- **a** is red (+) to green (-).
- **b** is yellow (+) to blue (-).

"Perceptually uniform"* color space



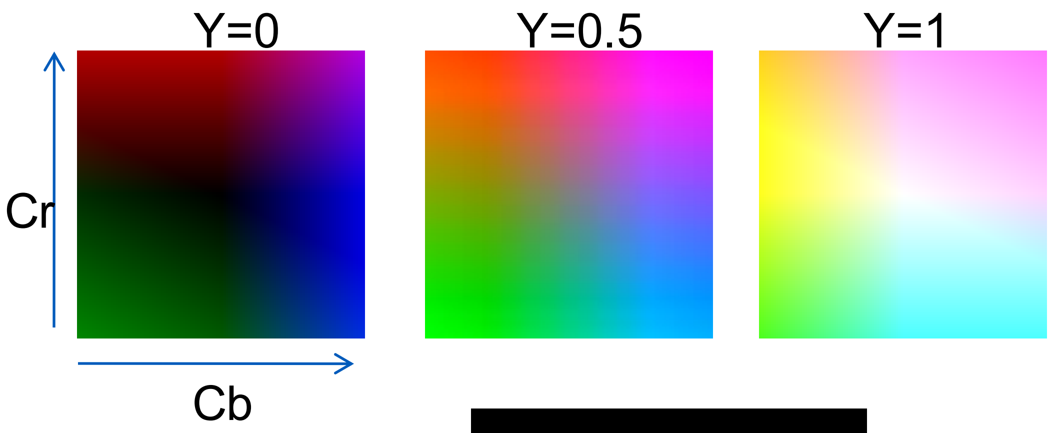


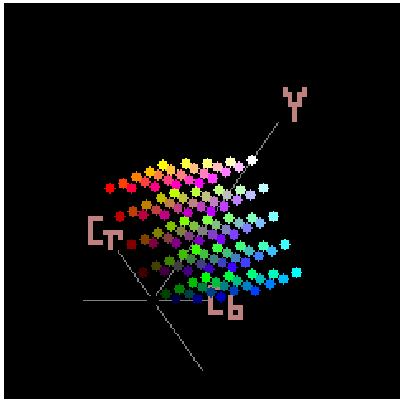
If a change of length in any direction X of the color space is perceived by a human as the same change.

More to read: https://www.printpeppermint.com/what-is-lab-color-space-and-what-should-you-know-about-it/

Color spaces: YCbCr

- **Y** is for luminance.
- **Cb** is difference between **blue** and a **luminance** component
- **Cr** is difference between **red** and a **luminance** component.





Original **Y** (Cb=0.5,Cr=0.5)

Cb (Y=0.5,Cr=0.5) **Cr** (Y=0.5,Cb=05)

Fast to compute, good for compression, used by TV

Think and Answer

If you had to choose, would you rather go without luminance or chrominance?

Most information in intensity

Only color shown – constant intensity

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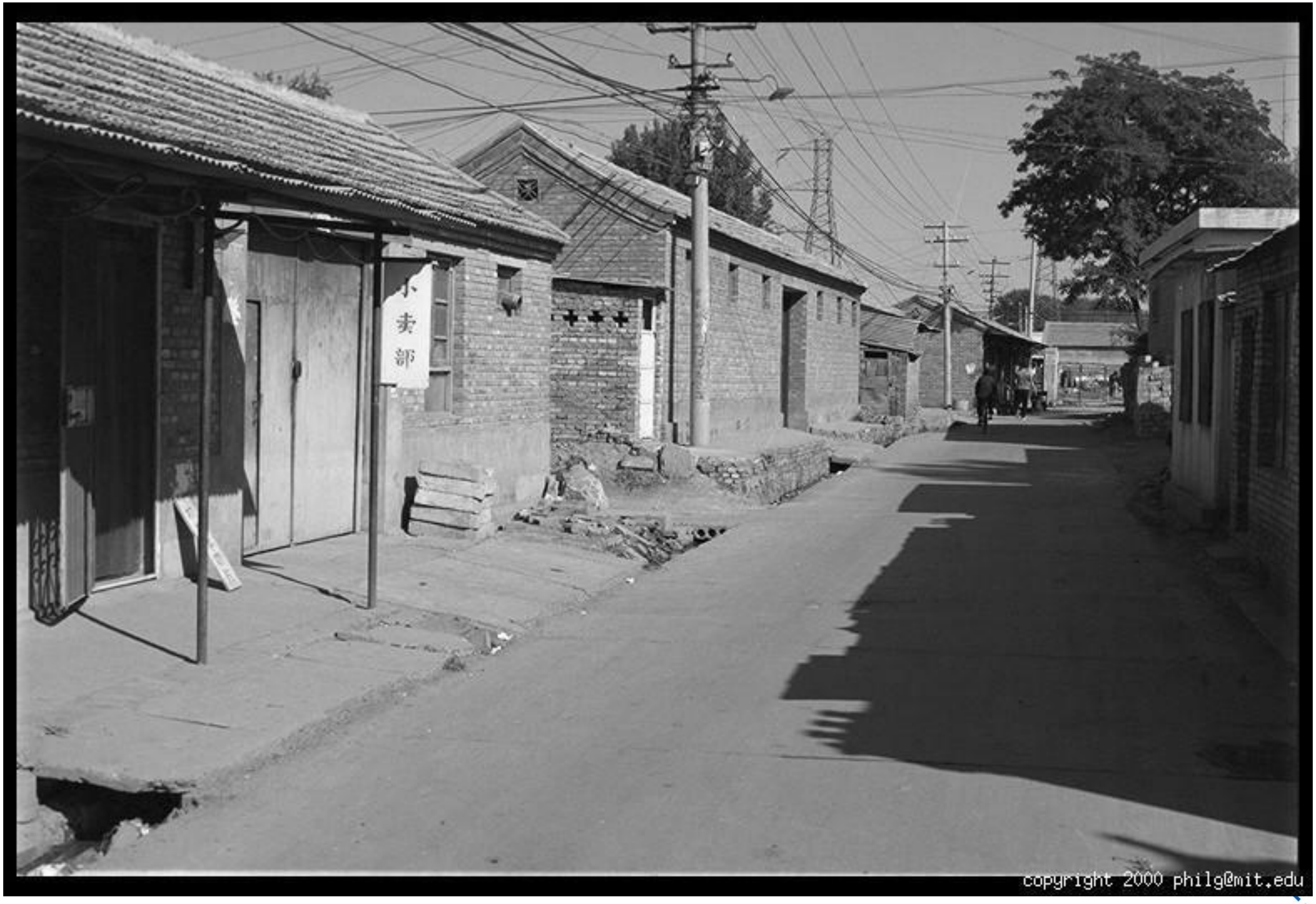
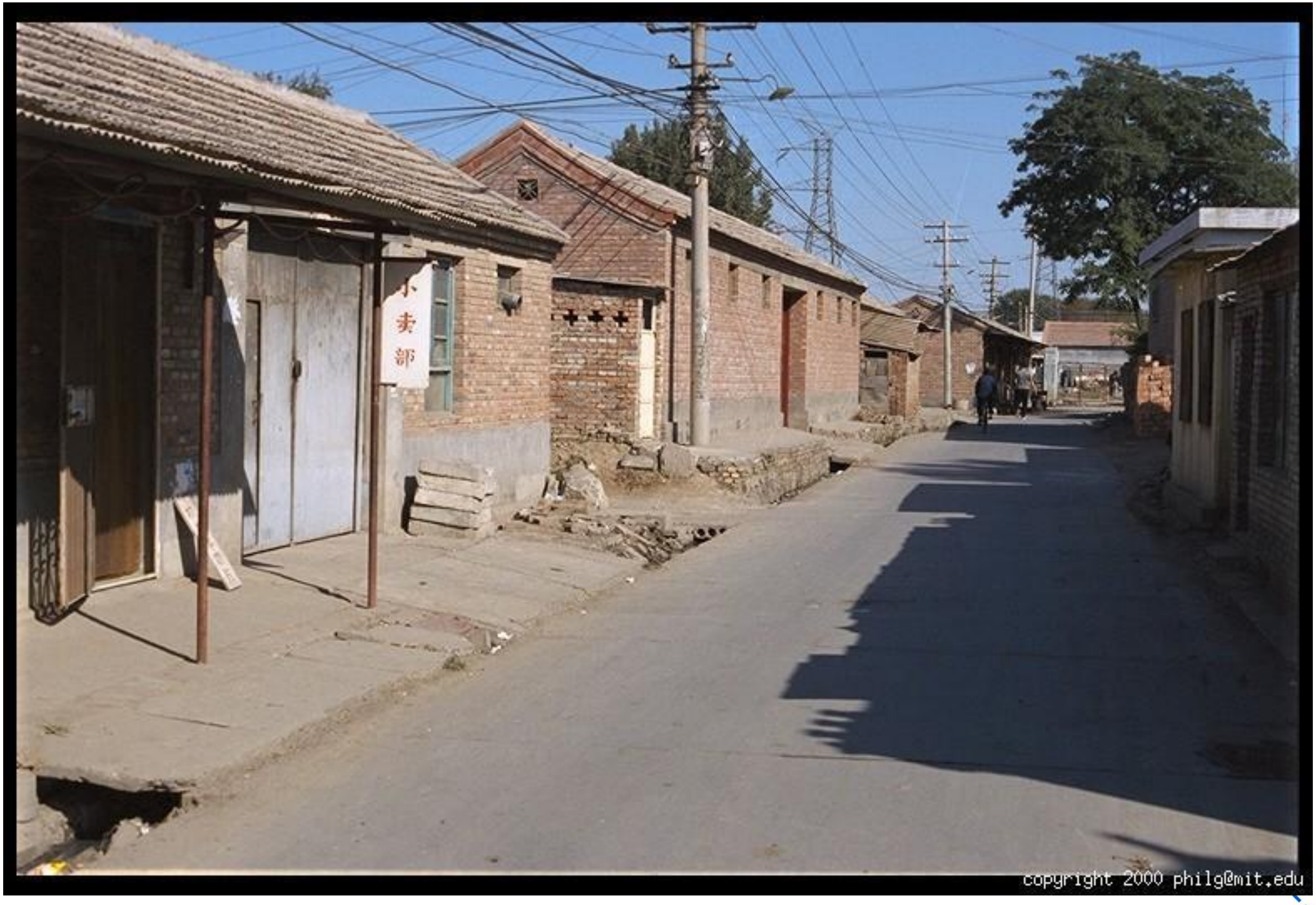
Most information in intensity



Only intensity shown – constant color

Most information in intensity



Original image

Summary for Important Concepts

- Optical Sensor
  - Image representation, resolution, sampling & quantization
- Coloring
  - RGB, HSV

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IMAGE FORMATION

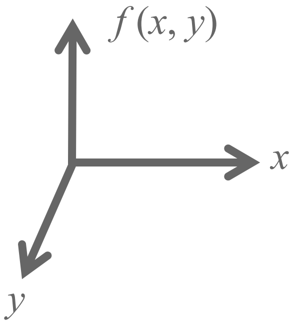
Image Warping

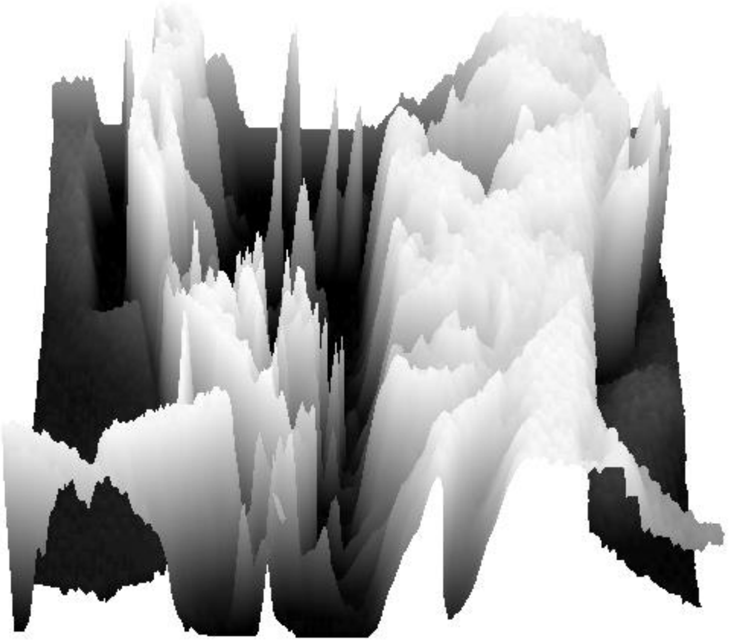
Content

- Image Warping
  - Mirror, rotation, translation, scaling, skewing
  - Euclidean, similarity, affine, projective (homograph)
- Optics
  - Lens, aperture, focal length.
  - Field of view, depth of view.
  - Vignetting, chromatic/spherical aberration
  - Pincushion, barrel distortion

Recap: Image representation

- A (grayscale) image as a **function**, f, from R^2 to R:
  - $f(x, y)$ gives the **intensity** at position (x, y).
  - A **digital image** is a discrete (**sampled**, **quantized**) version of this function.





Warping (Transformation)

image warping: change ***domain*** of image

$$g(x) = f(T(x))$$

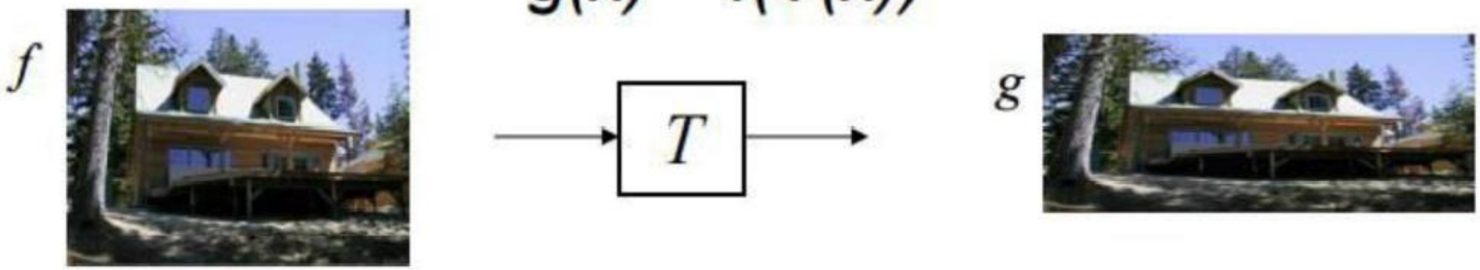
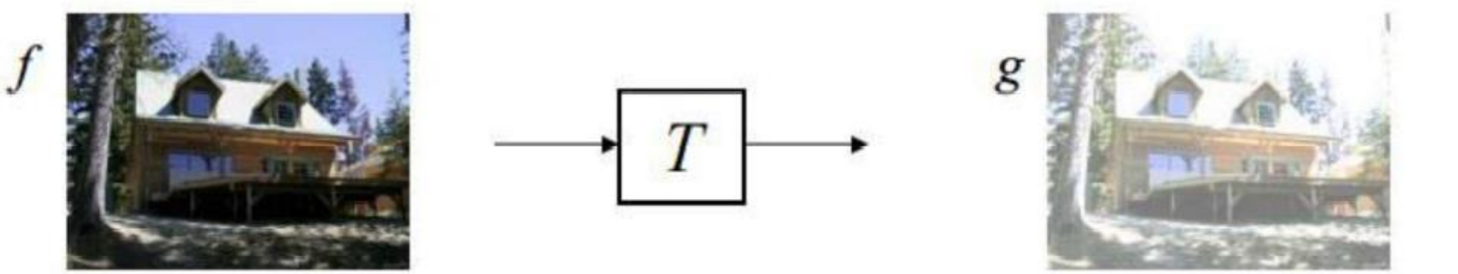


image filtering: change ***range*** of image (Next Week)

$$g(x) = T(f(x))$$



2D Planer Transformation

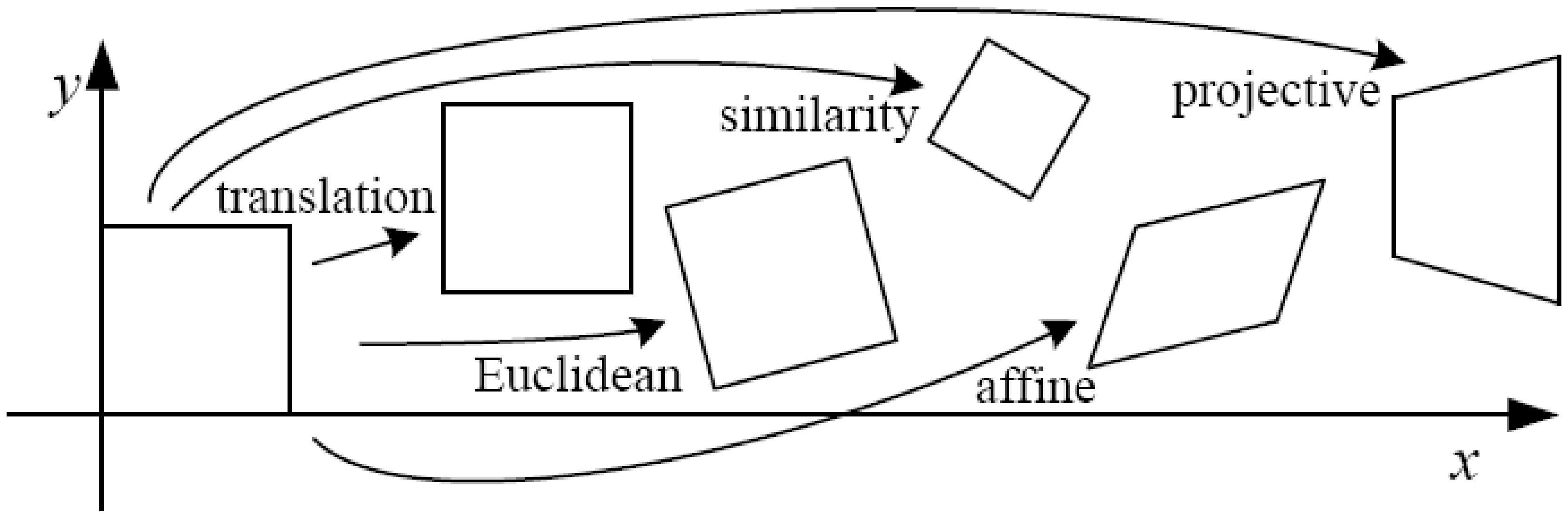
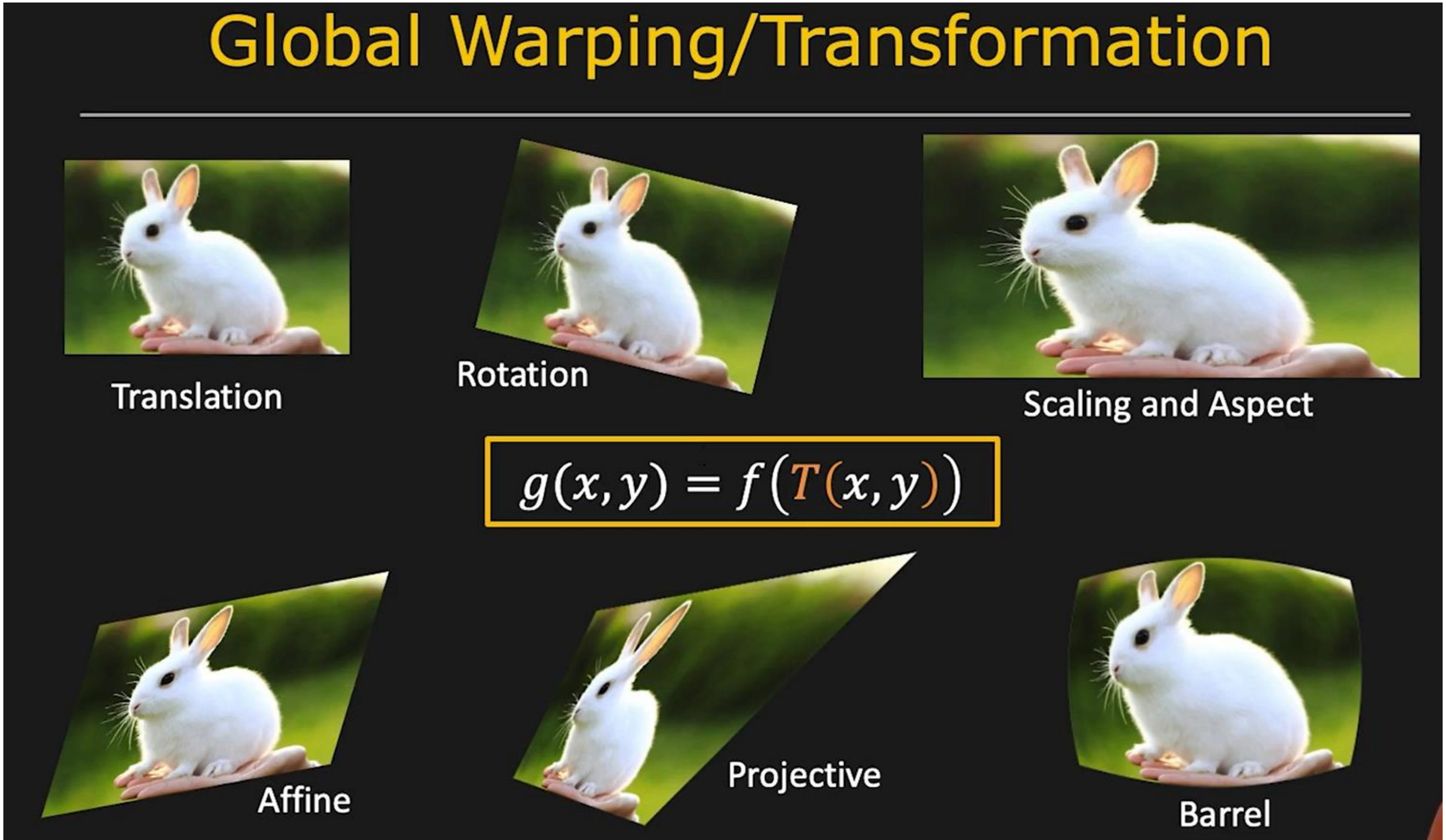
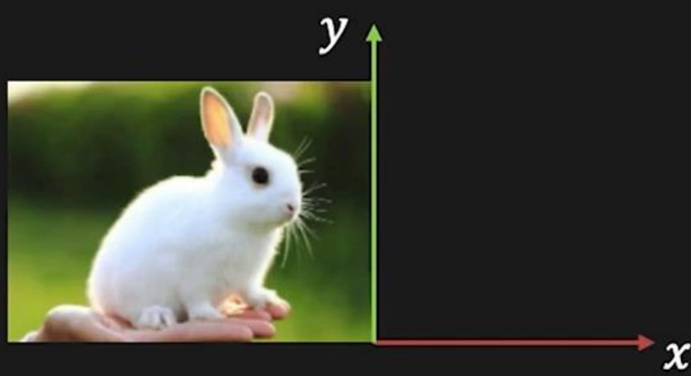


Figure 2.4: *Basic set of 2D planar transformations*

Image Warping



Mirror



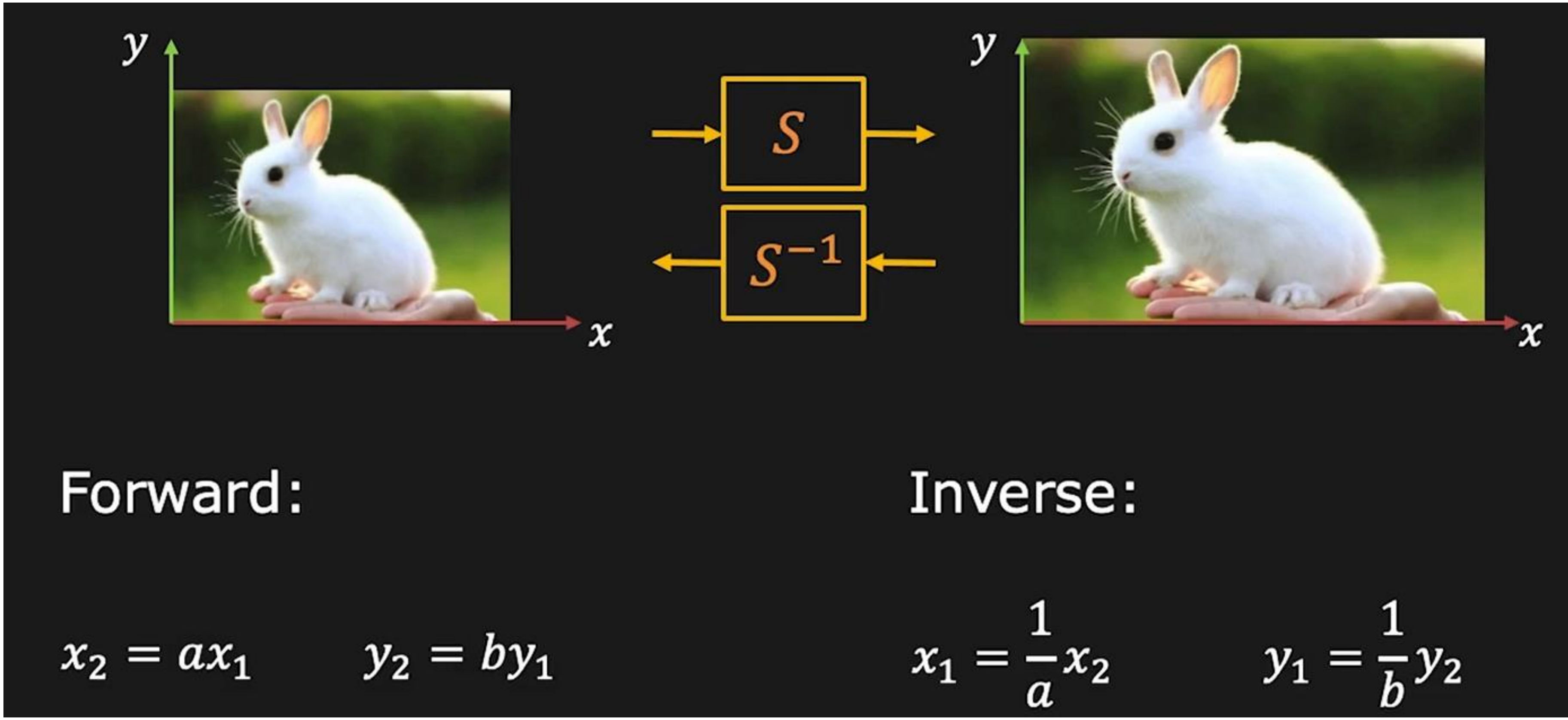
Mirror about Y-axis:

$$x_2 = -x_1$$
$$y_2 = y_1$$

Mirror about line $y = x$:

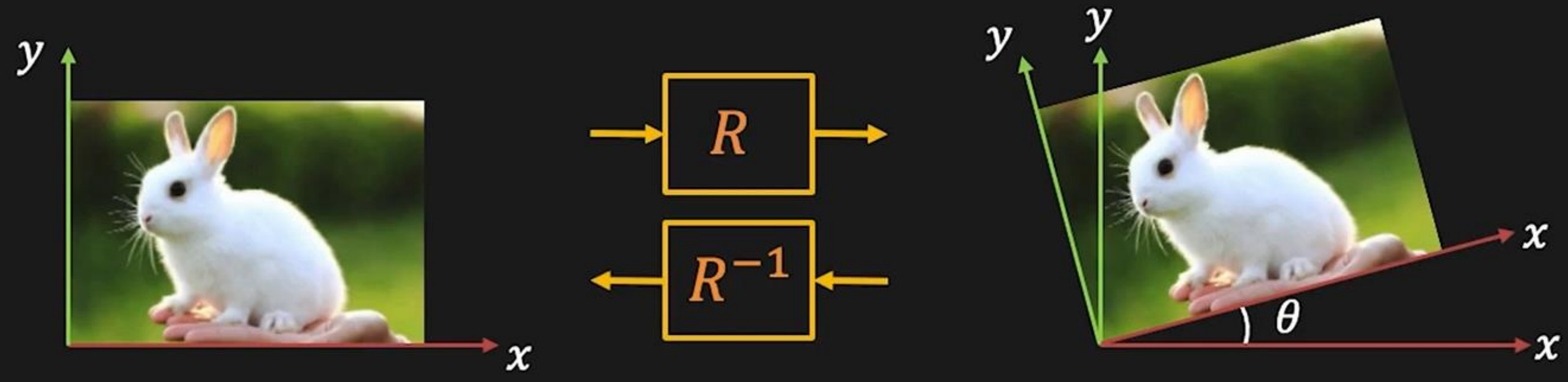
$$x_2 = y_1$$
$$y_2 = x_1$$

Scaling (Stretching or Squashing)



- Scaling a coordinate means multiplying each component by a scalar
- Uniform scaling means this scalar is the same for all component.

Rotation



Forward:

$$x_2 = x_1 cos\theta - y_1 sin\theta$$

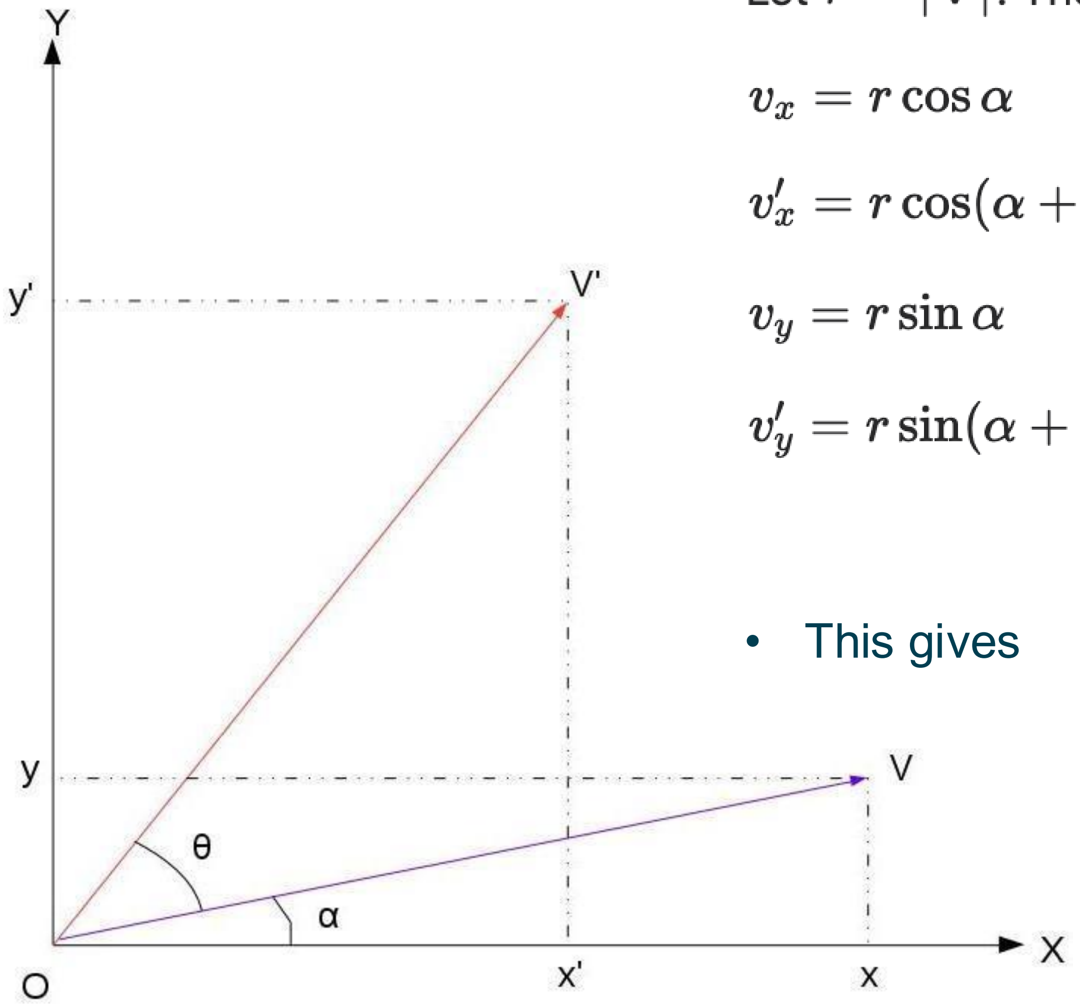
$$y_2 = x_1 sin\theta + y_1 cos\theta$$

Inverse:

$$x_1 = x_2 cos\theta + y_2 sin\theta$$

$$y_1 = -x_2 sin\theta + y_2 cos\theta$$

How to derive rotation matrix?



Let $r = |\mathbf{V}|$. Then, we have the relations:

$$v_x = r\cos\alpha$$

$$v'_x = r\cos(\alpha+\theta)$$

$$v_y = r\sin\alpha$$

$$v'_y = r\sin(\alpha+\theta)$$

$$v'_x = v_x\cos\theta - v_y\sin\theta$$

$$v'_y = v_x\cos\theta + v_y\sin\theta$$

- This gives $$\begin{pmatrix} v'_x \\ v'_y \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix}$$

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Skew

Horizontal Skew:

$$x_2 = x_1 + m_x y_1$$

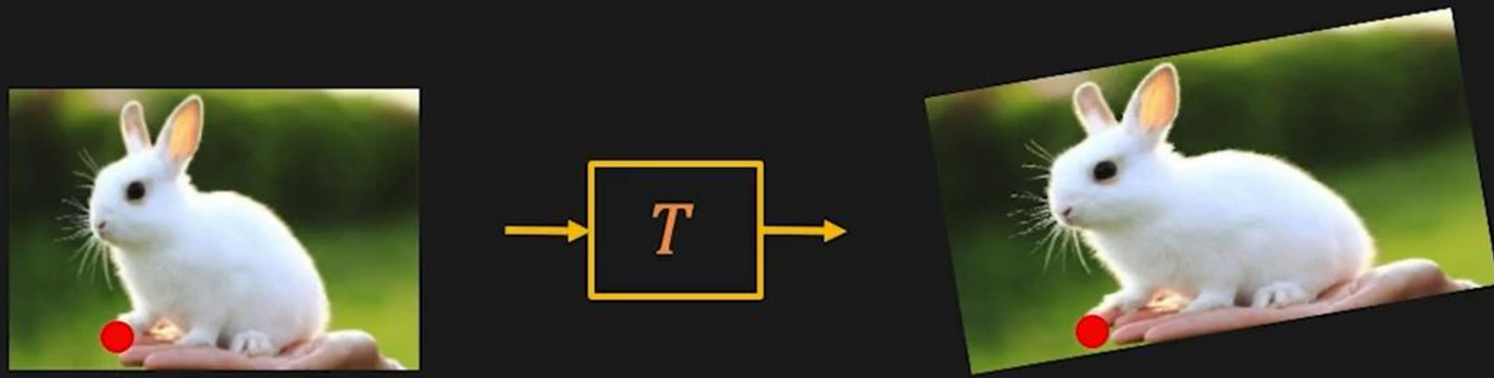
$$y_2 = y_1$$

Vertical Skew:

$$x_2 = x_1$$

$$y_2 = m_y x_1 + y_1$$

Linear Transformations



$\mathbf{p}_1 = (x_1, y_1)$ $\mathbf{p}_2 = (x_2, y_2)$

T can be represented by a matrix.

$$\mathbf{p}_2 = T\mathbf{p}_1 \qquad \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = T \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \qquad \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$$

2 x 2 Matrix Transformations

Any transformation of the form:

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$$

- Origin maps to the origin
- Lines map to lines
- Parallel lines remain parallel
- Closed under composition

Scaling, Rotation, Skew, Translation

$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

Scaling

$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} 1 & m_x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

Skew

$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

Translation

$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

Rotation

Affine Transformation

Any transformation of the form:

$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} \equiv \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ \boxed{0 \quad 0 \quad 1} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix}$$

parallelogram

Affine Transformation

Any transformation of the form:

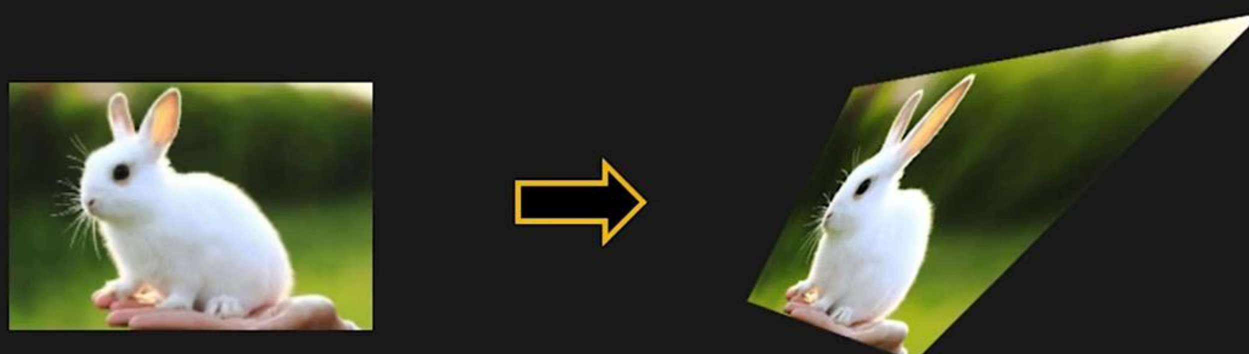
$$\begin{bmatrix} x_2 \\ y_2 \\ 1 \end{bmatrix} \equiv \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix}$$

- Origin does not necessarily map to the origin
- Lines map to lines
- Parallel lines remain parallel
- Closed under composition

Projective Transformation

Any transformation of the form:

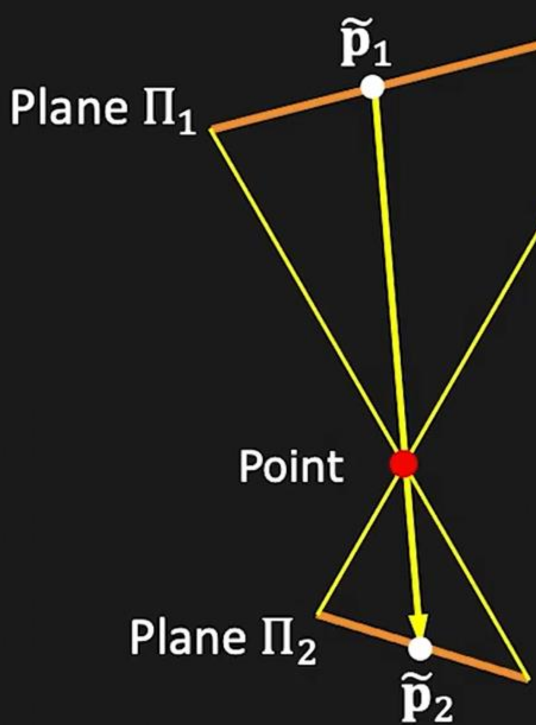
$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix} \qquad \tilde{\mathbf{p}}_2 = H\tilde{\mathbf{p}}_1$$



Also called Homography, or perspective transform

Projective Transformation

Mapping of one plane to another through a point



$$\tilde{\mathbf{p}}_2 = H\tilde{\mathbf{p}}_1$$

$$\begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix}$$

Same as imaging a plane through a pinhole

Projective Transformation

Homography can only be defined up to a scale.

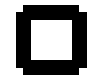
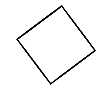
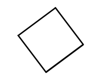
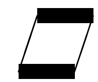
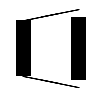
$$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix} \equiv \begin{bmatrix} \tilde{x}_2 \\ \tilde{y}_2 \\ \tilde{z}_2 \end{bmatrix} \equiv k \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{y}_1 \\ \tilde{z}_1 \end{bmatrix}$$

If we fix scale such that $\sqrt{\Sigma (h_{ij})^2} = 1$ then 8 free parameters

- Origin does not necessarily map to the origin
- Lines map to lines
- Parallel lines do not necessarily remain parallel
- Closed under composition

2D vs 3D transform

2D

Transformation	Matrix	# DoF	Preserves	Icon
translation	$\left[\, \boldsymbol{I} \mid \boldsymbol{t} \,\right]_{2\times 3}$	2	orientation	
rigid (Euclidean)	$\left[\, \boldsymbol{R} \mid \boldsymbol{t} \,\right]_{2\times 3}$	3	lengths	
similarity	$\left[\, s\boldsymbol{R} \mid \boldsymbol{t} \,\right]_{2\times 3}$	4	angles	
affine	$\left[\, \boldsymbol{A} \,\right]_{2\times 3}$	6	parallelism	
projective	$\left[\, \tilde{\boldsymbol{H}} \,\right]_{3\times 3}$	8	straight lines	

3D

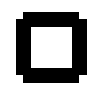
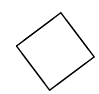
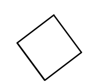
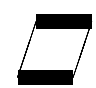
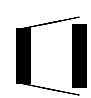
Transformation	Matrix	# DoF	Preserves	Icon
translation	$\left[\, \boldsymbol{I} \mid \boldsymbol{t} \,\right]_{3\times 4}$	3	orientation	
rigid (Euclidean)	$\left[\, \boldsymbol{R} \mid \boldsymbol{t} \,\right]_{3\times 4}$	6	lengths	
similarity	$\left[\, s\boldsymbol{R} \mid \boldsymbol{t} \,\right]_{3\times 4}$	7	angles	
affine	$\left[\, \boldsymbol{A} \,\right]_{3\times 4}$	12	parallelism	
projective	$\left[\, \tilde{\boldsymbol{H}} \,\right]_{4\times 4}$	15	straight lines	

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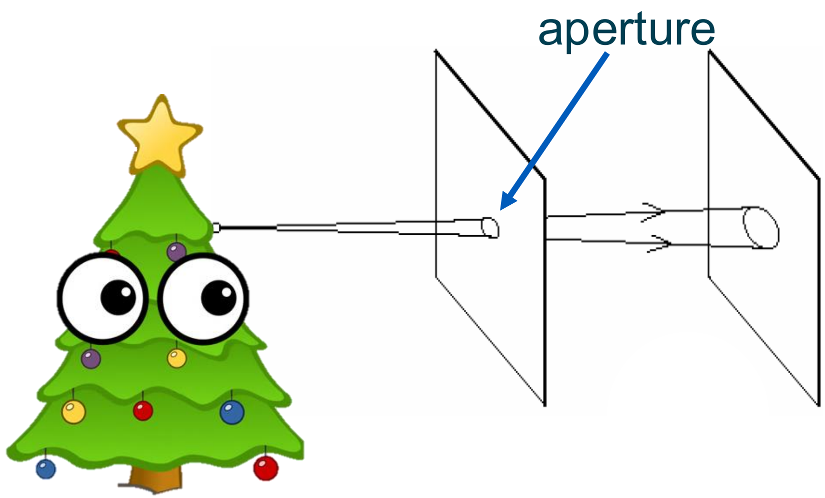
IMAGE FORMATION II

Optics

Previous Model - Pinhole

How does the size of the “Pinhole” affect the image we’d get?



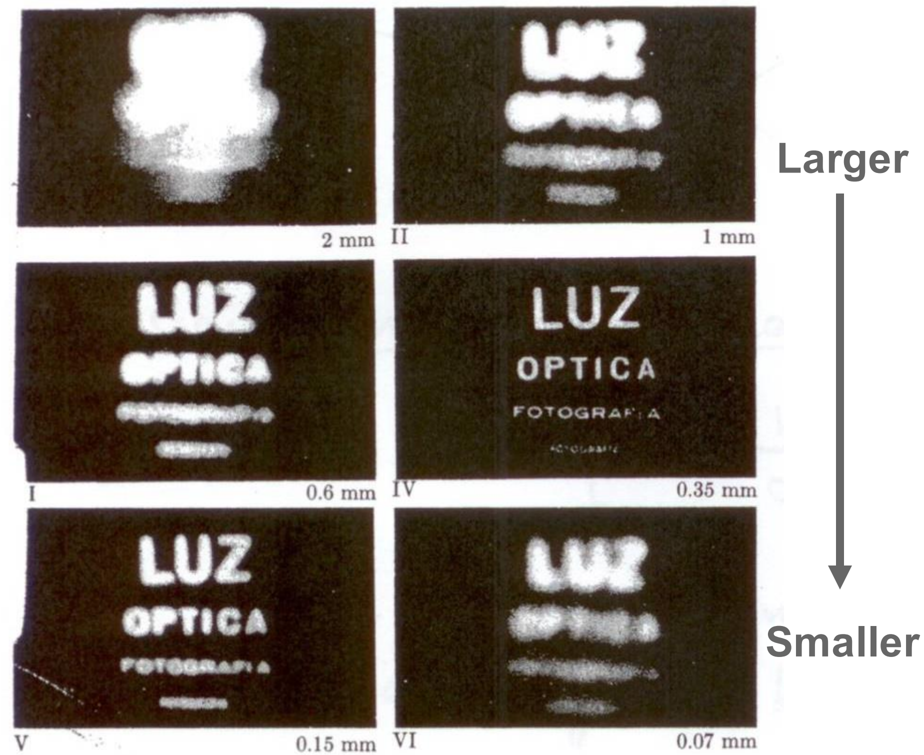
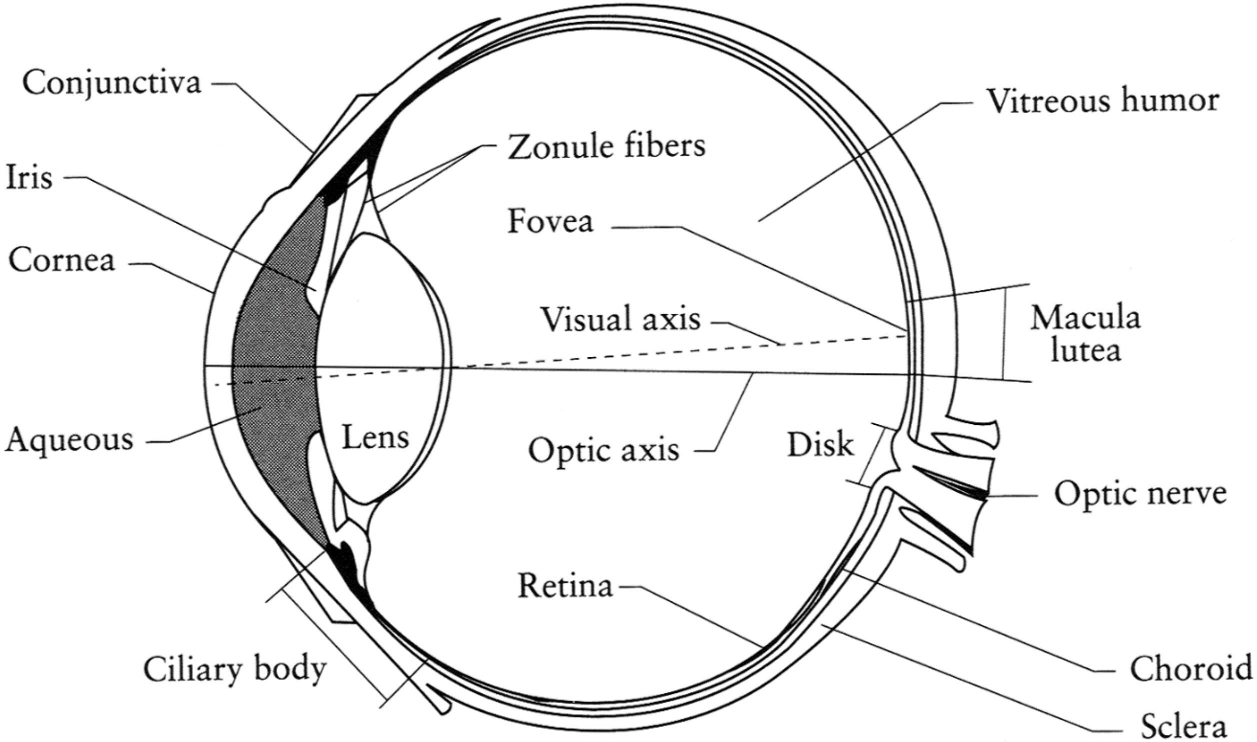


Fig. 5.96 The pinhole camera. Note the variation in image clarity as the hole diameter decreases. [Photos courtesy Dr. N. Joel, UNESCO.]

- Make the aperture smaller?
  - How small?
  - Like a pinhole? Infinitely Small?
- What is the problem then?
  - How much light do we need?
- Solution?
  - Use a Lens

Human Eye

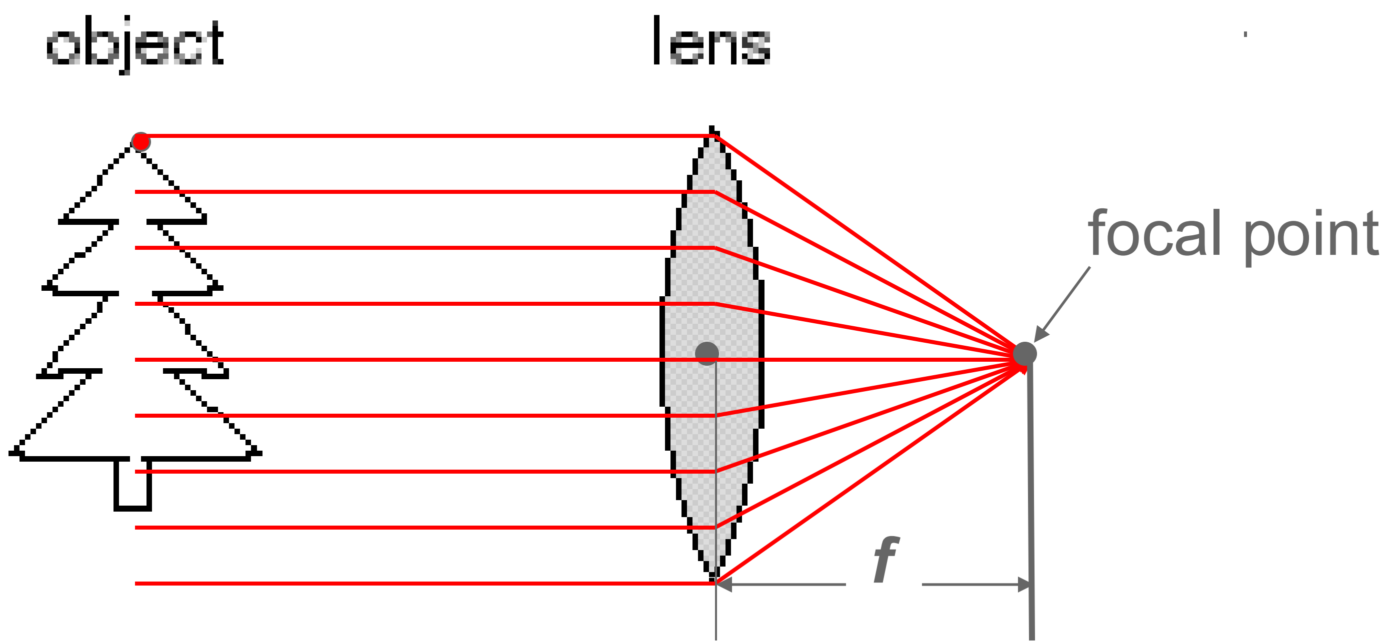
- **Iris:** Colored annulus with radial muscles
- **Pupil:** the hole (aperture) whose size is controlled by the iris.
- What's the "film"?



  – photoreceptor cells (rods and cones) in the **retina**

Lens

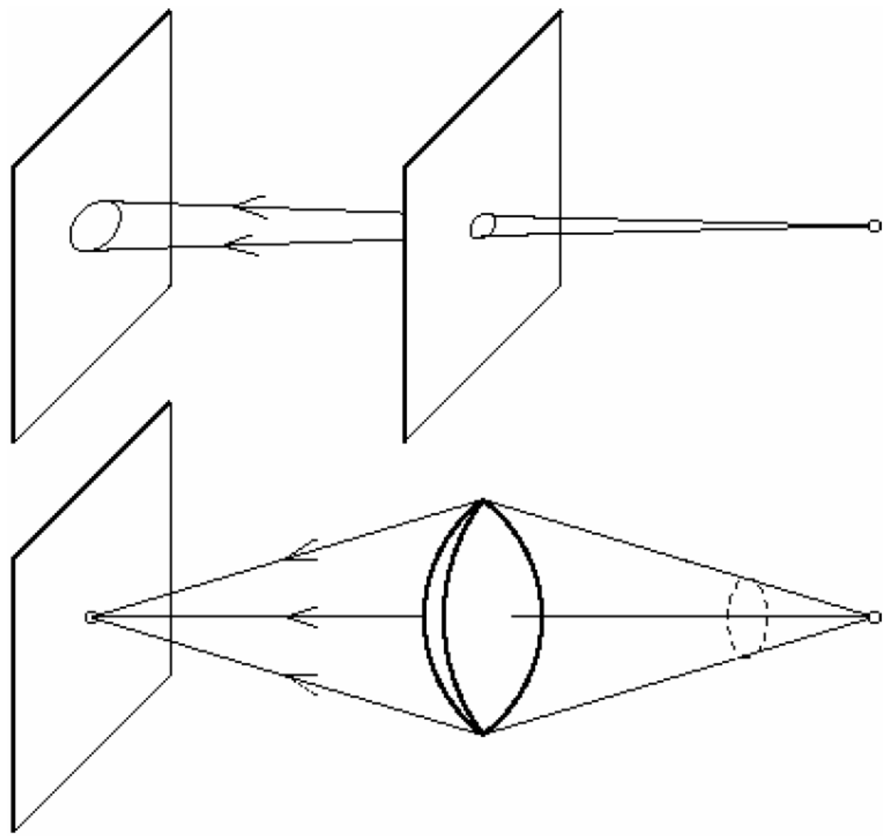
- A lens focuses parallel rays onto a single focal point
  - Gathers more lights; while keeping focus;
  - Make pinhole perspective projection practical



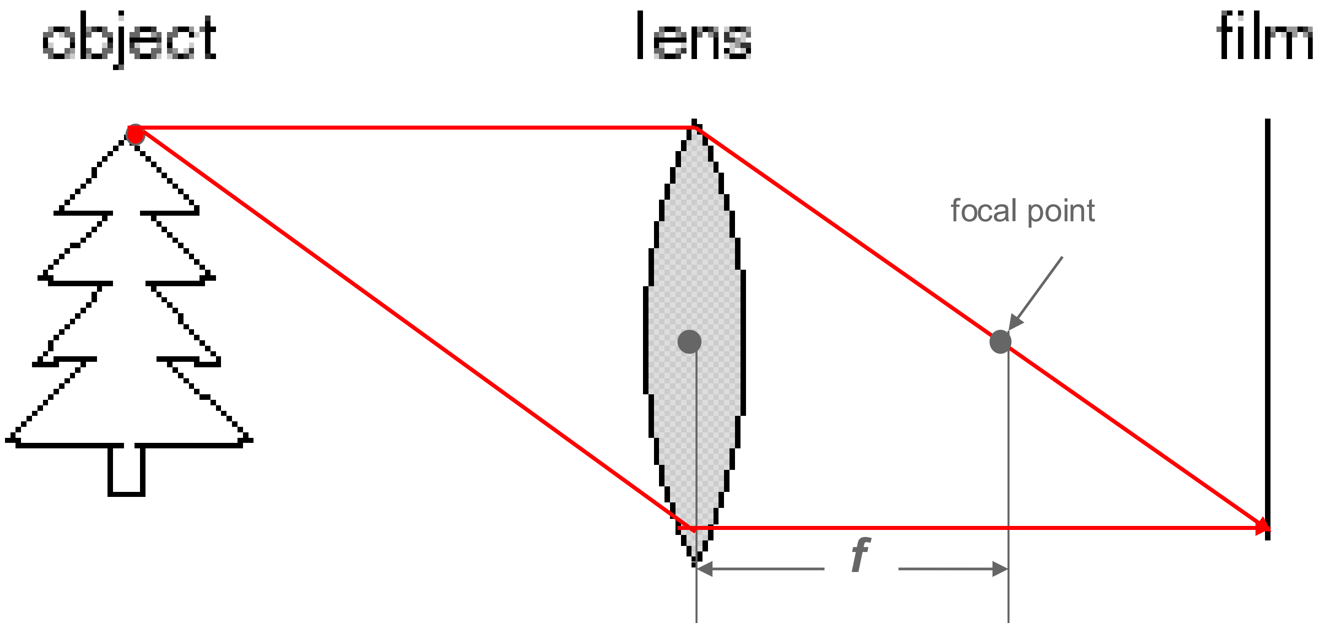
Benefits and challenges of adding lens

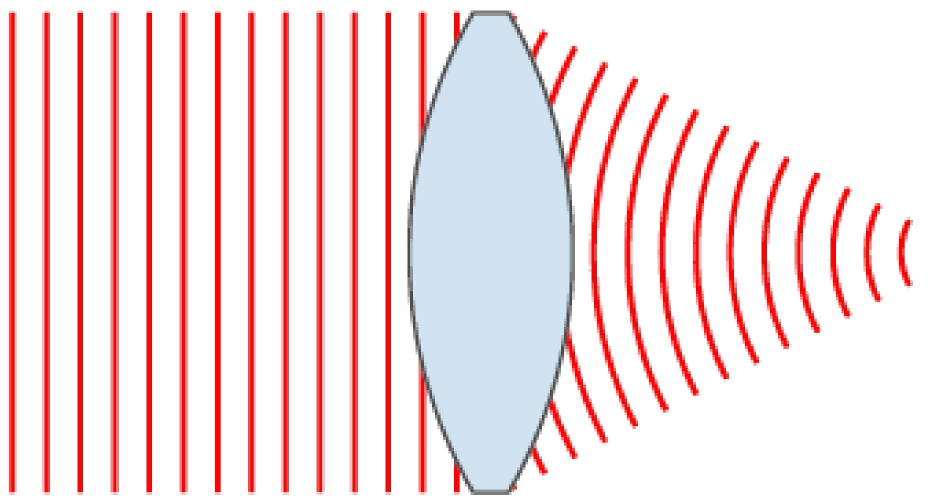
- Benefits
  - Light Concentration
  - Change the Focus
  - Depth of Field
  - Field of View

- Problems
  - Vignetting
  - Aberration



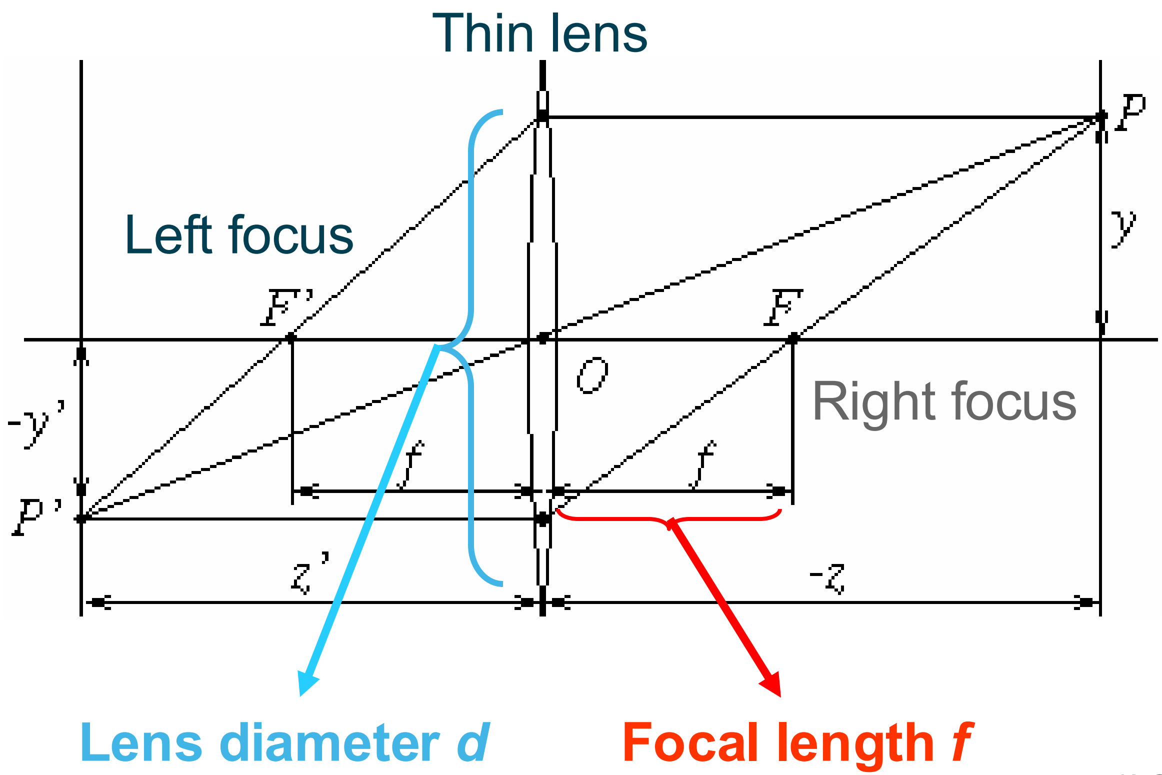
Light Concentration





Thin lens

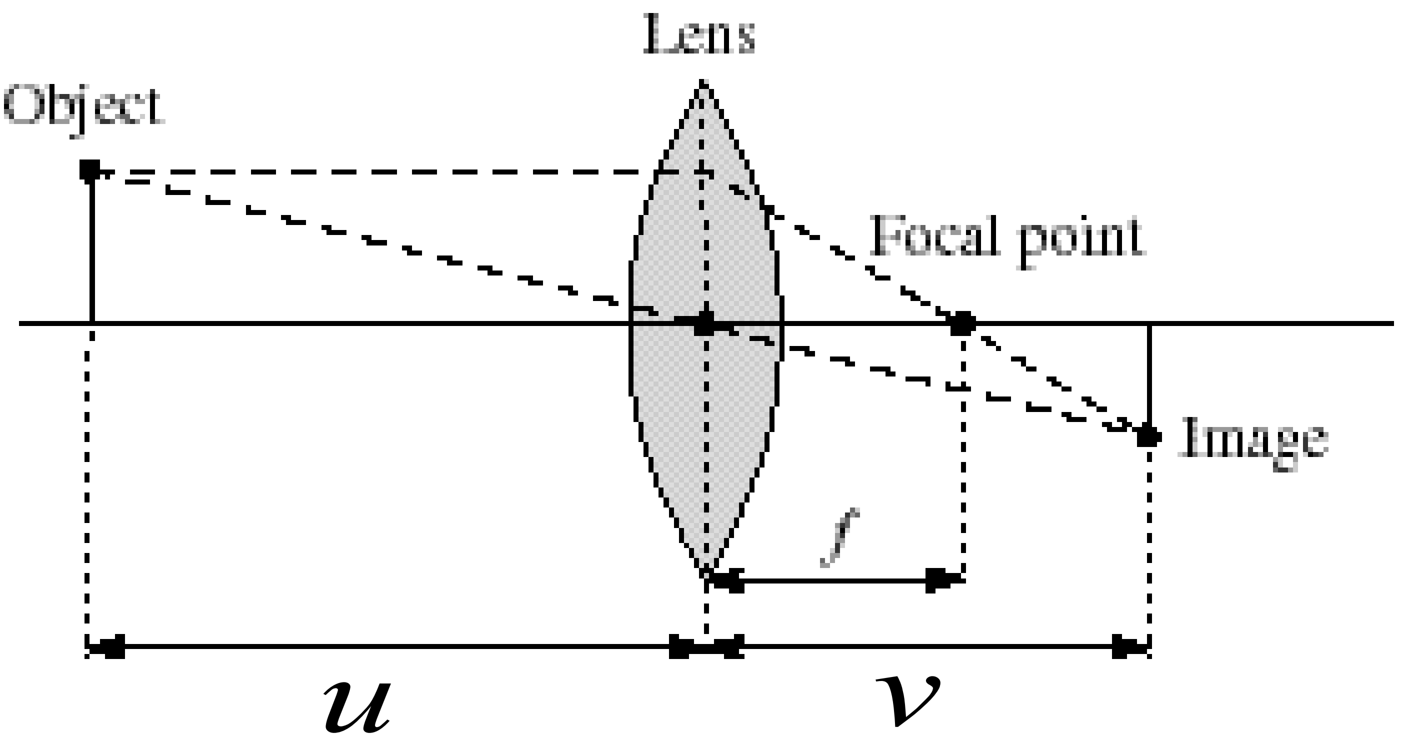
- Rays entering parallel on one side go through focus on other, and vice versa.
- In ideal case, all rays from P imaged at P'.



K. Grauman

Thin Lens

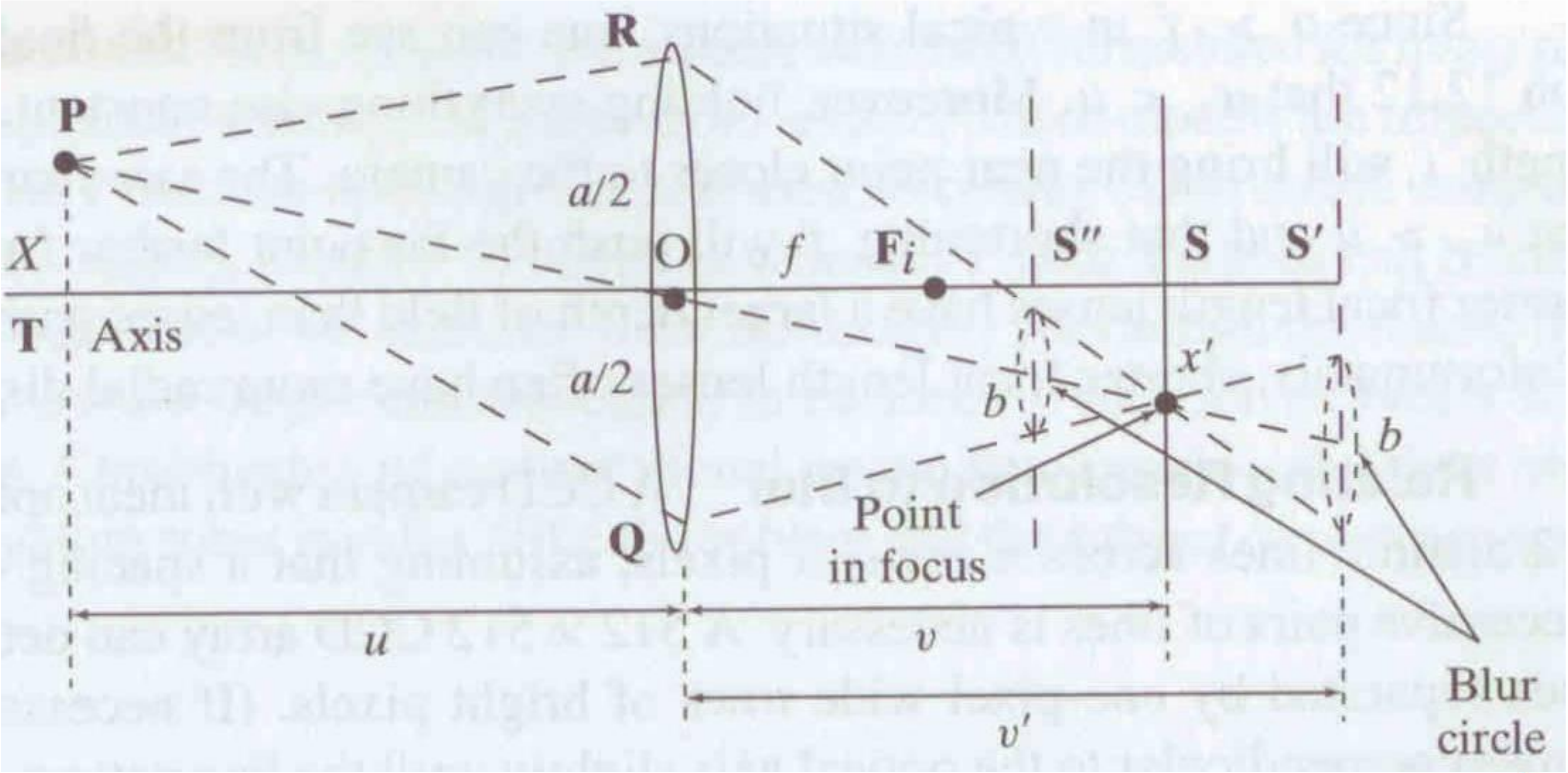
- Scene points at distinct depths come in focus at different image planes.



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

Depth of field

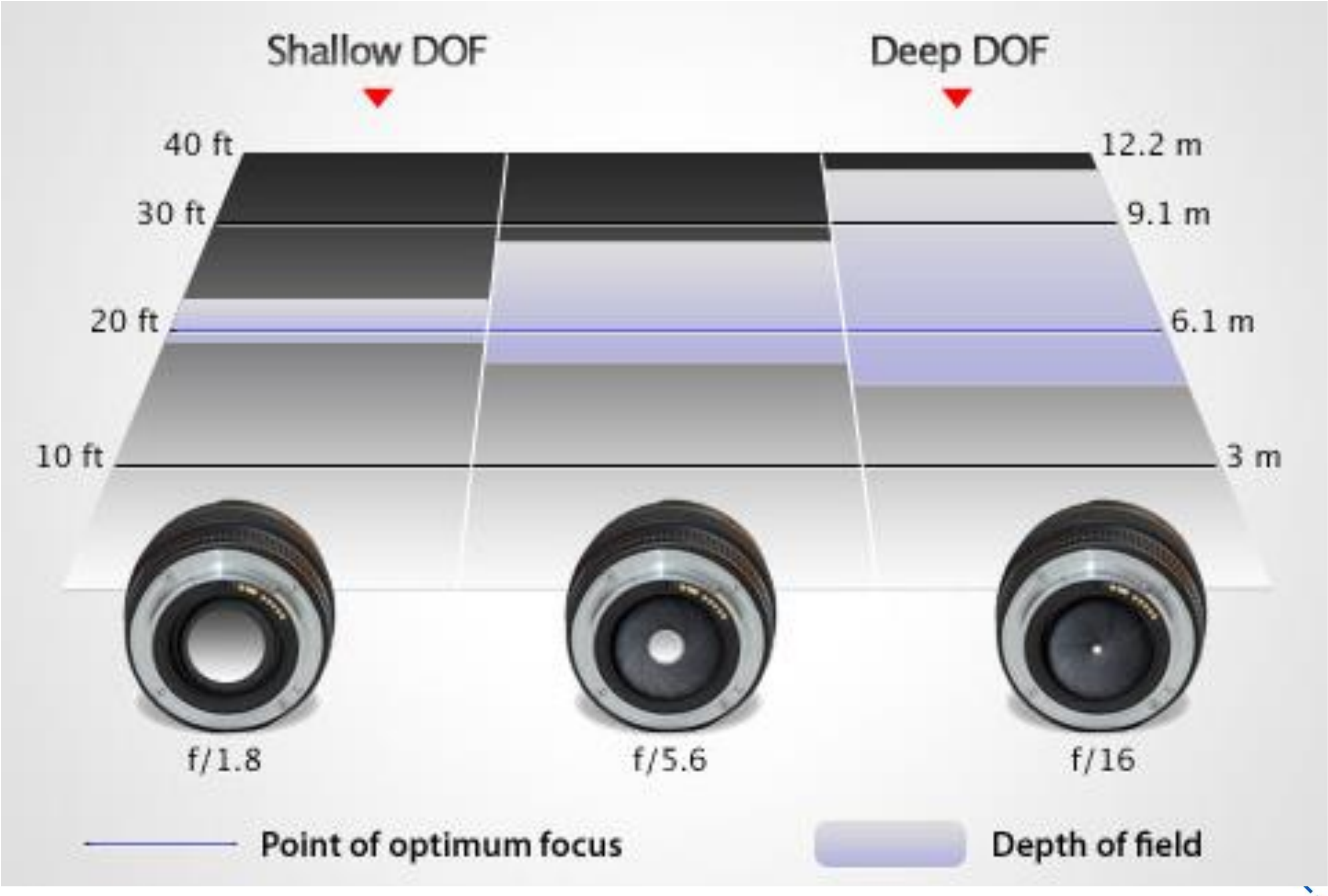
- Distance between image planes where blur is tolerable
- (Real camera lens systems have greater depth of field)



K. Grauman

Focus and depth of field

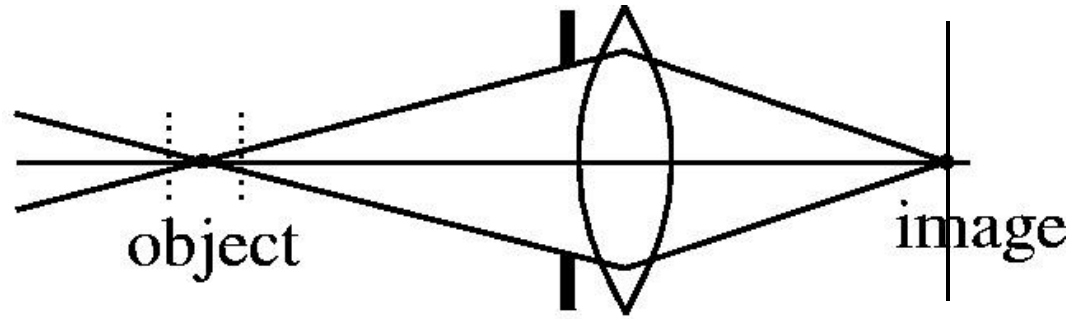
Depth of field

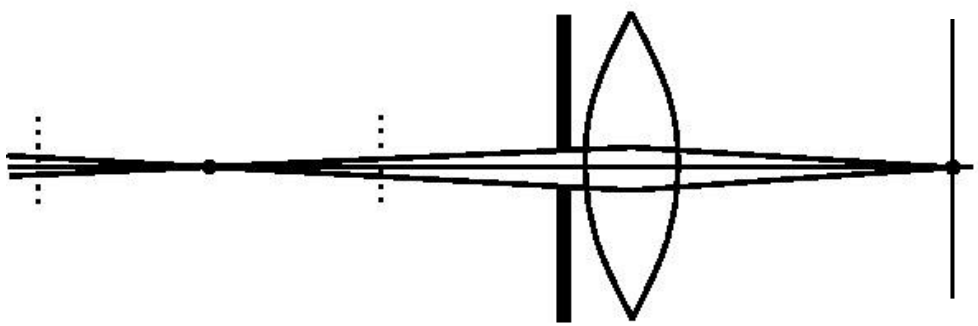


http://www.exposureguide.com/focusing-basics.htm

Aperture affects the depth of field

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

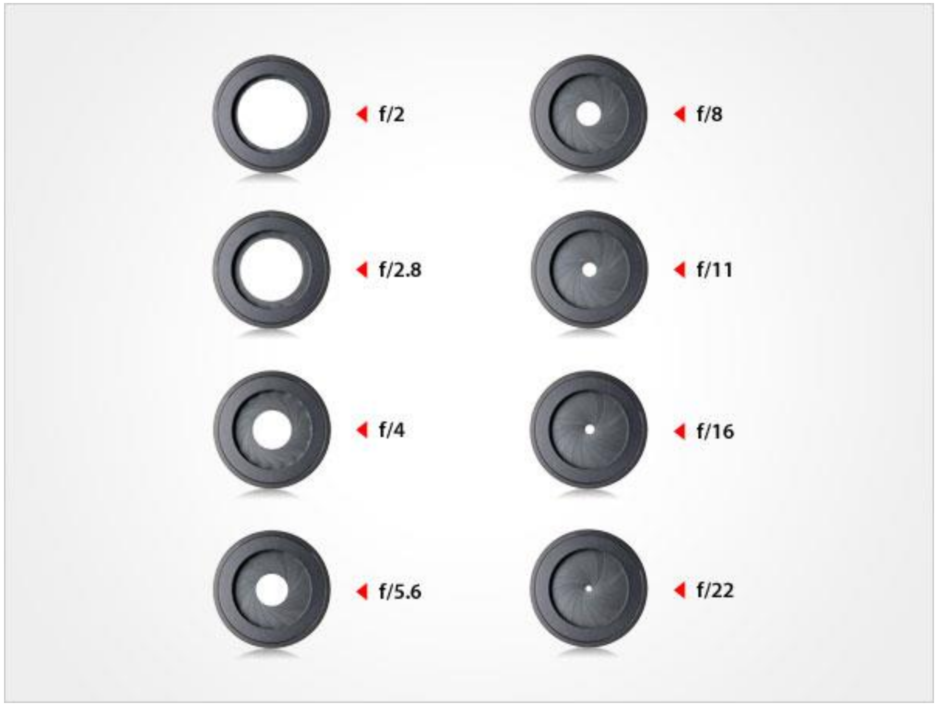




Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field

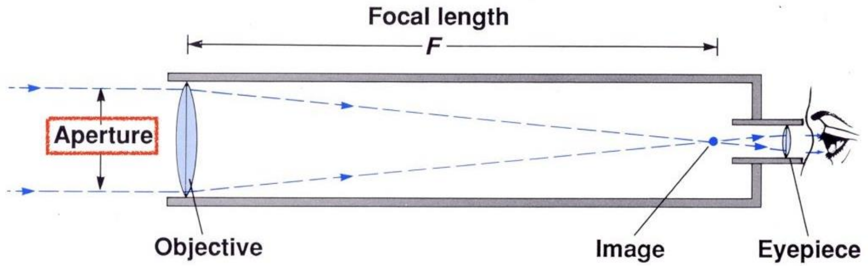
Slide from S. Seitz

Aperture settings



http://www.exposureguide.com/focusing-basics.htm

Brightness vs Aperture

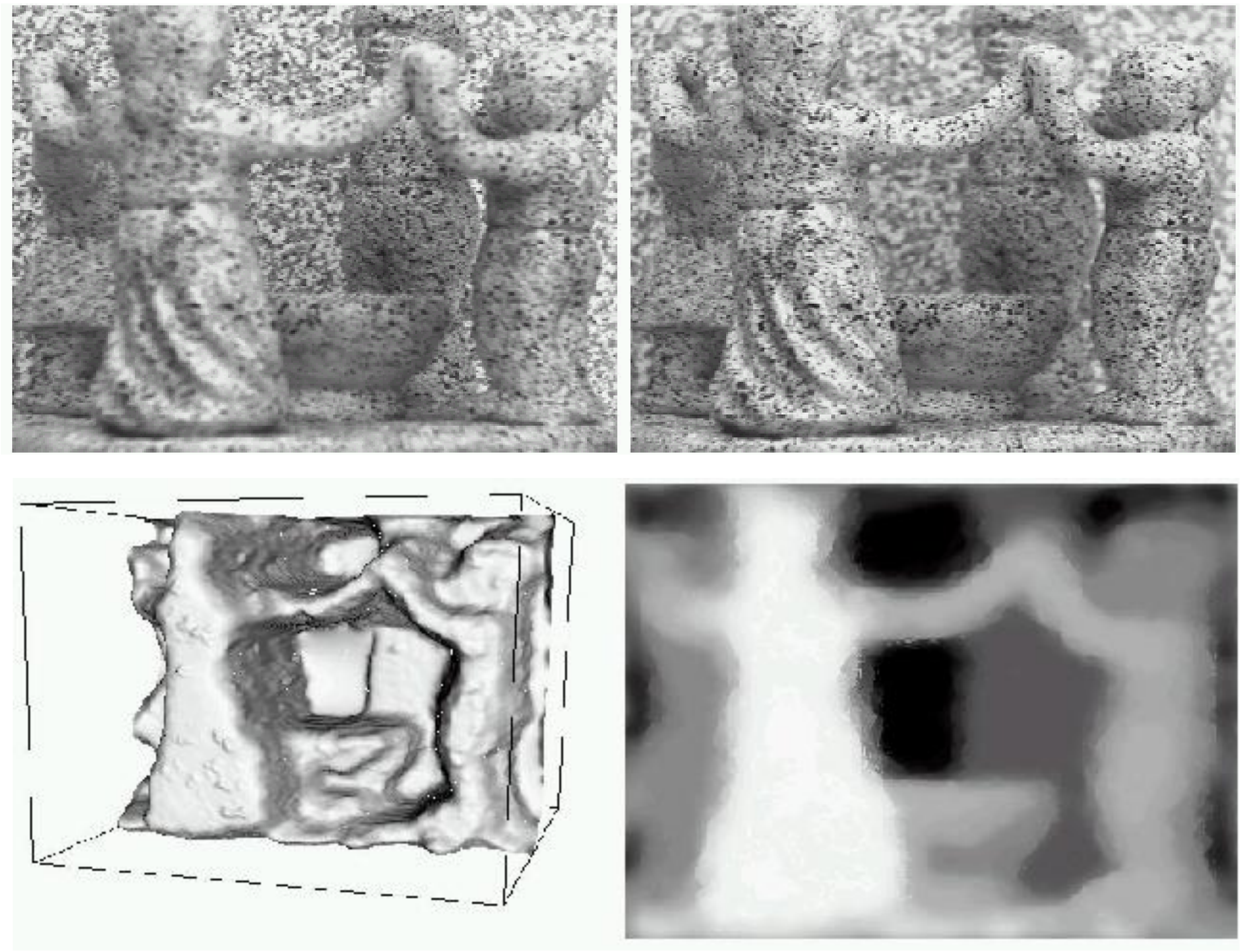


- **F-number**
  - Ratio of focal length to the diameter of the lens.
    - F-number = $\frac{f}{d}$
  - Greater f-number projects darker images.
- Brightness of the projected image (illuminance):
  - relative to the brightness of the scene (luminance)
  - decreases with the **square** of the f-number.
- Doubling the f-number decreases:
  - the relative brightness by a factor of four.
  - To maintain the same photographic exposure
  - The exposure time would need to be four times as long.

https://en.wikipedia.org/wiki/F-number

Depth from focus

- 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°

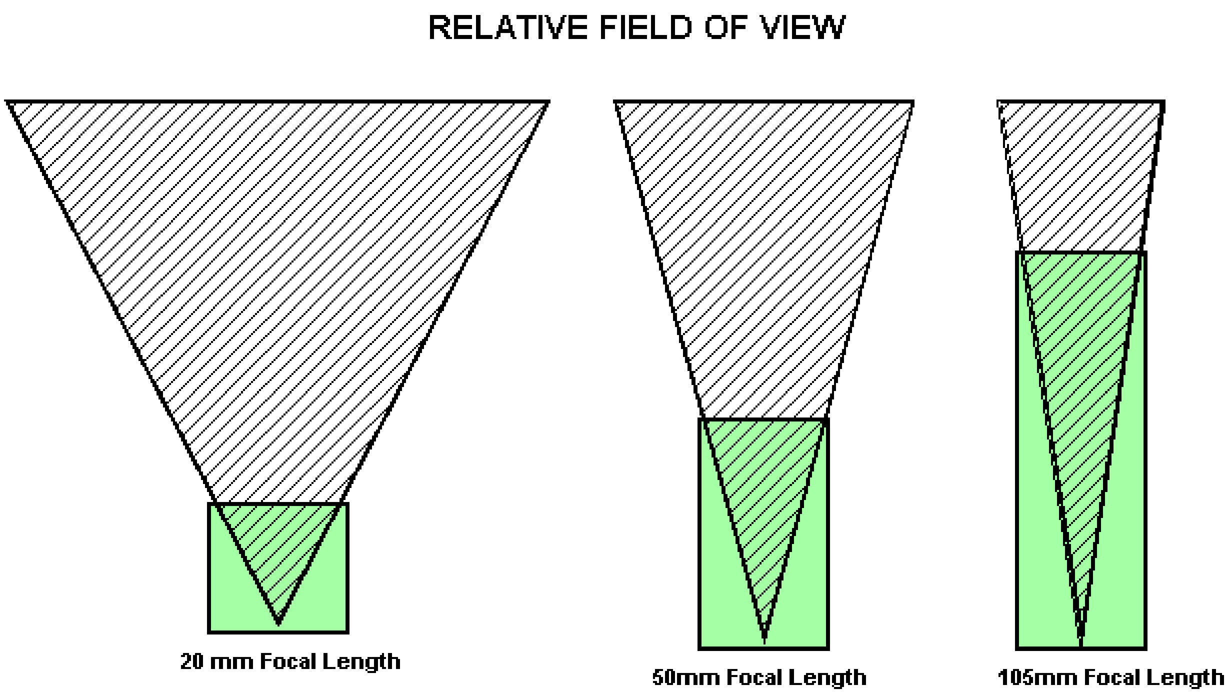
210 mm lens, 9.8° × 6.5°

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

K. Grauman

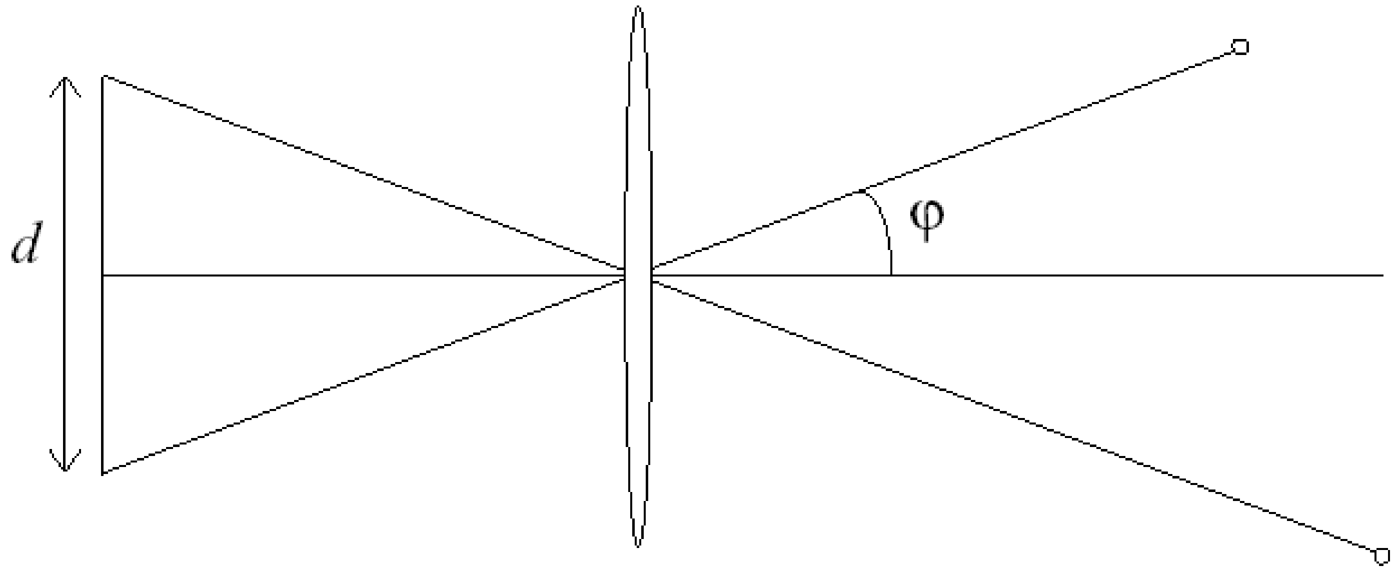
Field of view depends on focal length

- As ***F*** gets smaller, image becomes **wider angle**.
  - More world points project onto the image
- As ***F*** gets larger, image becomes **more *telescopic.***
  - Less world points project onto the image



Field of view depends on camera retina

- Smaller FOV = larger Focal Length



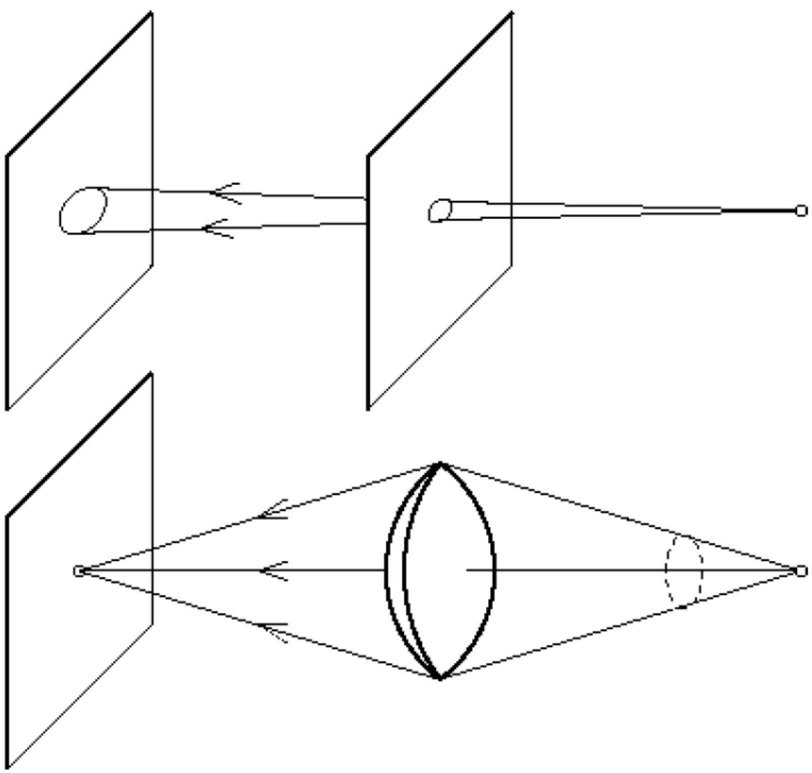
Size of field of view governed by size of the camera retina:

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

Benefits and challenges of adding lens

- Benefits
  - Light Concentration
  - Change the Focus
  - Depth of Field
  - Field of View

- Problems
  - Vignetting
  - Aberration



Vignetting

- Lens vignetting is **a reduction in brightness or saturation on the periphery of an image**.

http://www.tlucretius.net/Photo/eHolga.html
http://www.ptgui.com/examples/vigntutorial.html

Vignetting

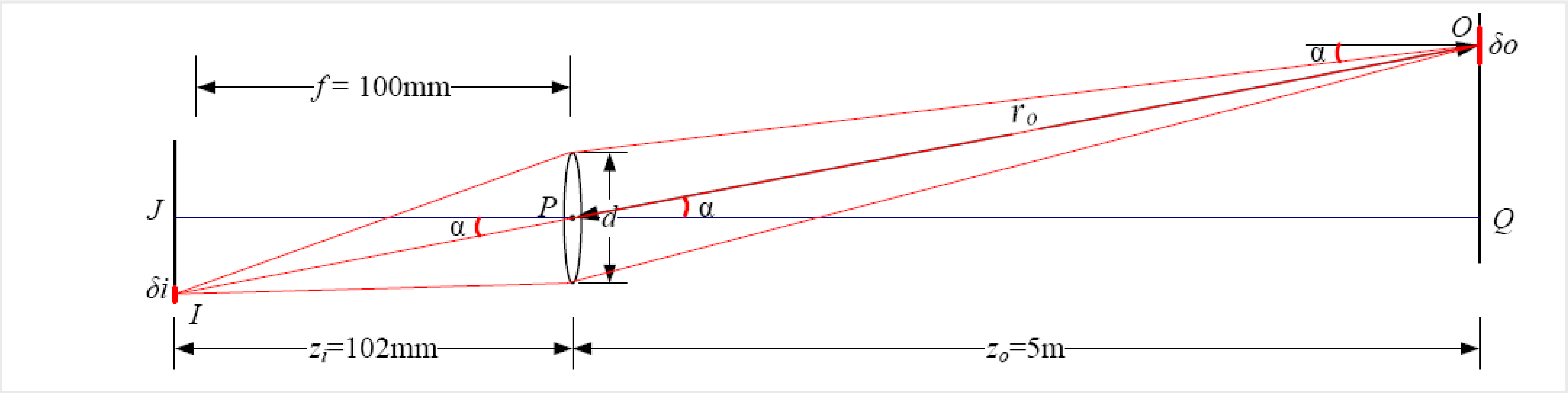


Figure 2.23: *The amount of light hitting a pixel of surface area δi depends on the square of the ratio of the aperture diameter d to the focal length f, as well as the fourth power of the off-axis angle α cosine, $\cos^4 \alpha$.*

$$l \propto \left(\frac{d}{f}\right)^2 \cos^4 \alpha$$

Chromatic aberration

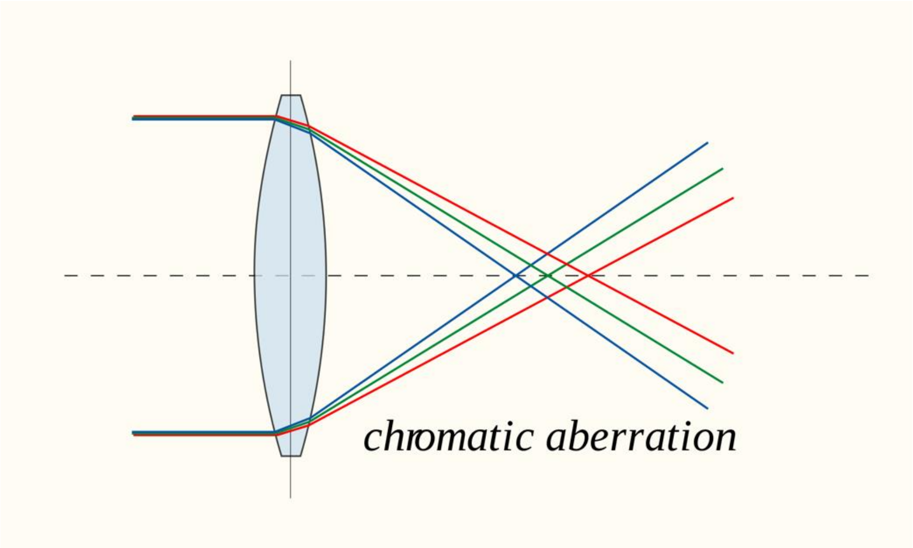
- Transverse chromatic aberration
  - a blur and a rainbow edge in areas of contrast.

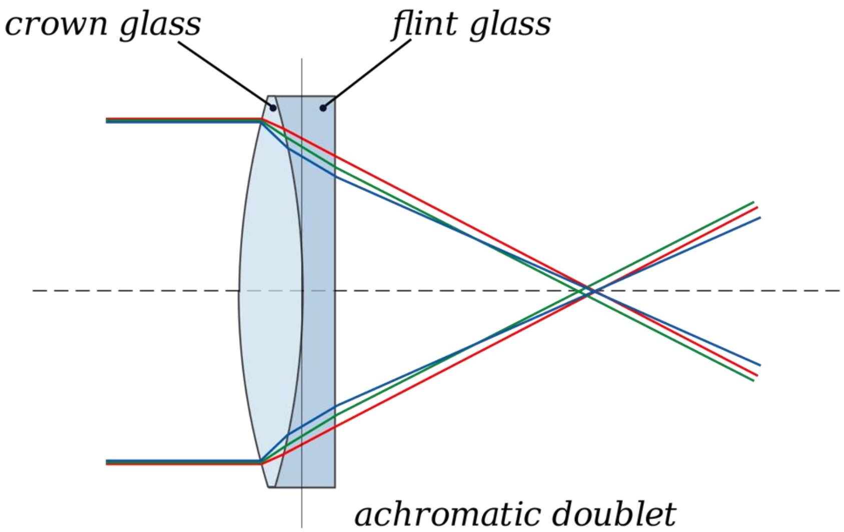
low quality lens

high quality lens

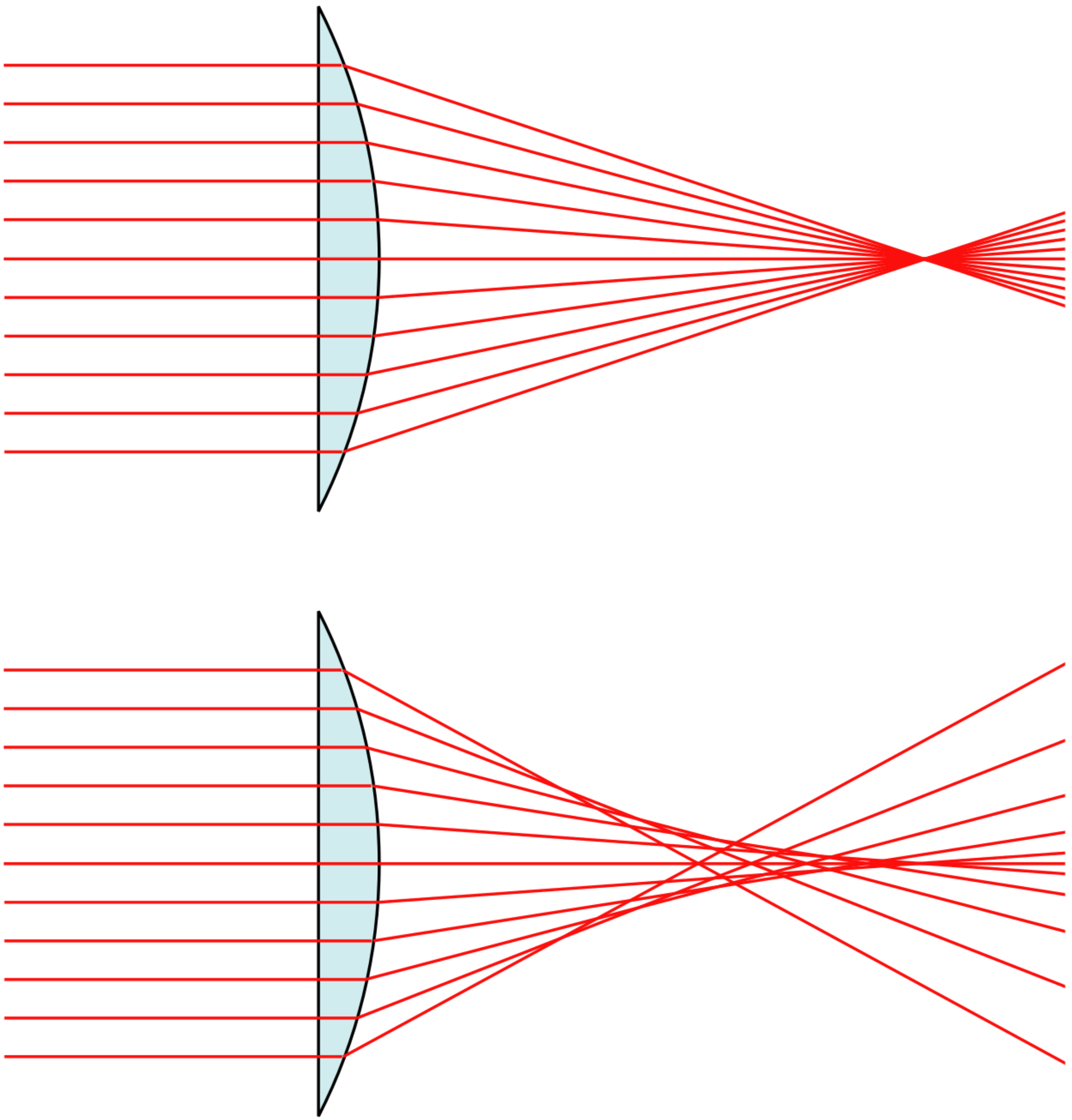
Chromatic aberration

- Dispersion of light





Spherical aberration



Other Distortions

- Imperfect Lenses
  - Deviations are most noticeable for rays passing through the edge of lens