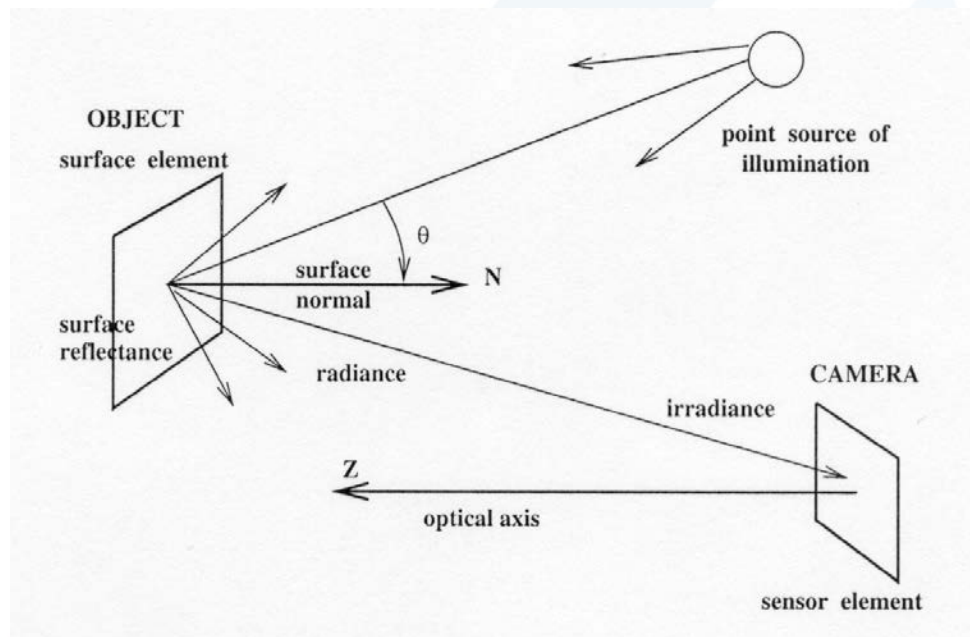


# Image Formation and Representation

# A Simple model of image formation

- The scene is illuminated by a single source.
- The scene reflects radiation towards the camera.
- The camera senses it via solid state cells (CCD cameras)



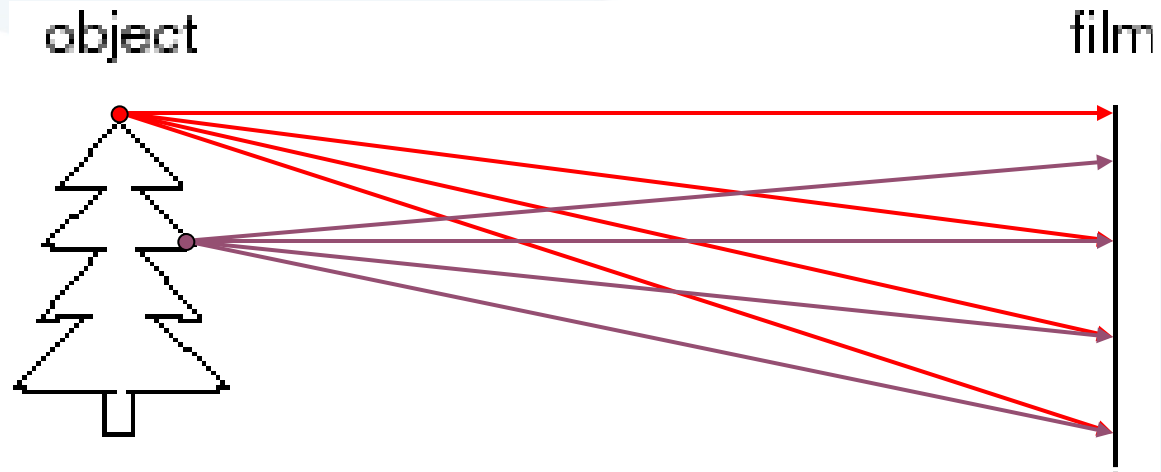


# Image formation (cont'd)

- There are two parts to the image formation process:
  - (1) The **geometry**, which determines where in the image plane the projection of a point in the scene will be located.
  - (2) The **physics of light**, which determines the brightness of a point in the image plane.

Simple model:  $f(x,y) = i(x,y) r(x,y)$   
i: illumination, r: reflectance

# Let's design a camera

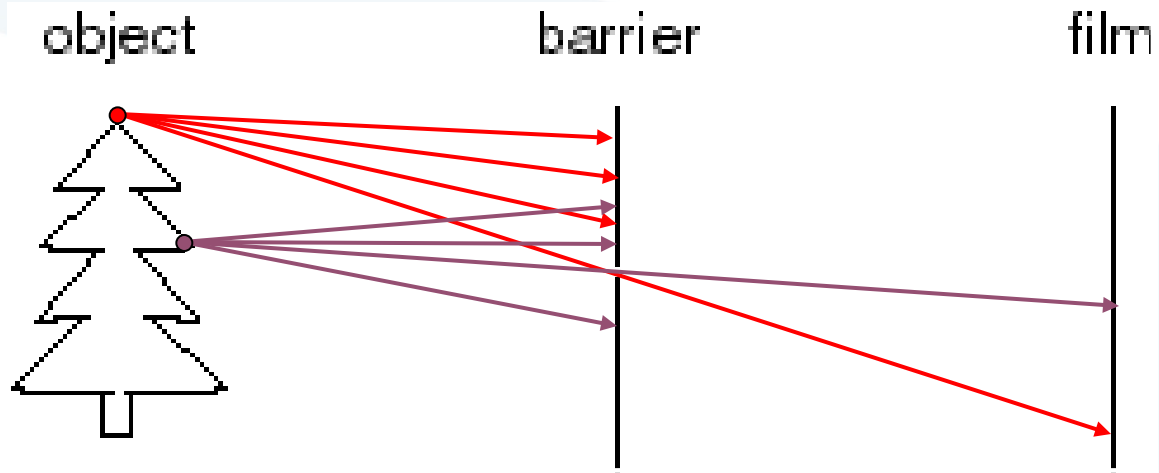


- Put a piece of film in front of an object - do we get a reasonable image?
  - Blurring - need to be more selective!



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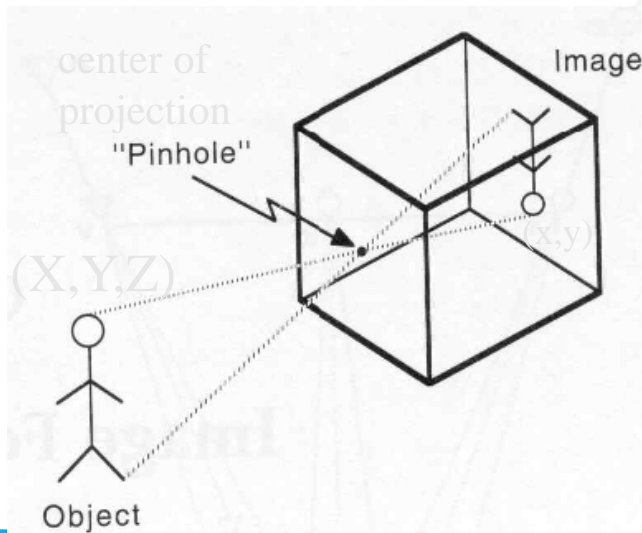
## Let's design a camera (cont'd)



- Add a barrier with a small opening (i.e. **aperture**) to block off most of the rays
  - Reduces blurring

# “Pinhole” camera model

- The simplest device to form an image of a 3D scene on a 2D surface.
- Rays of light pass through a "pinhole" and form an inverted image of the object on the image plane.



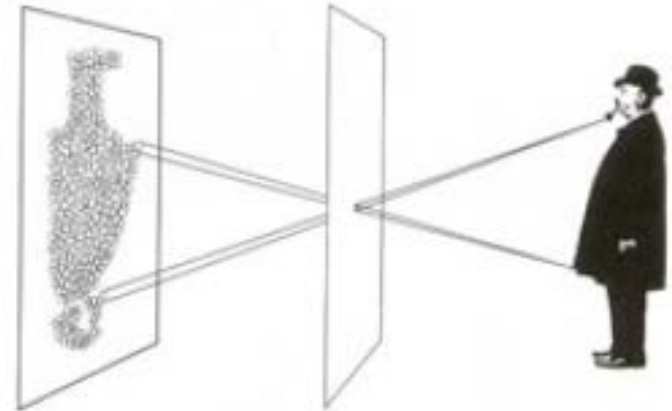
perspective projection:

$$x = \frac{fX}{Z} \quad y = \frac{fY}{Z}$$

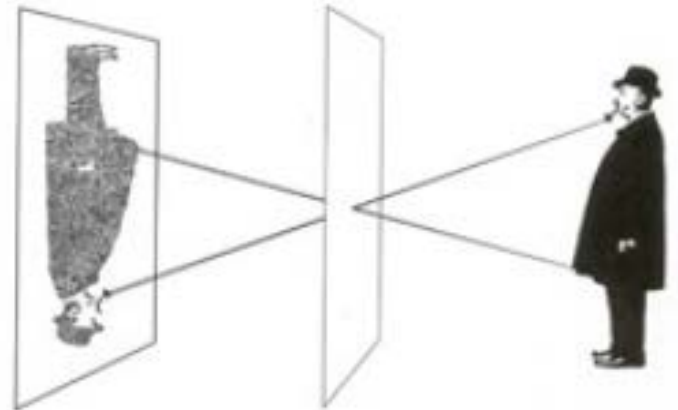
$f$ : focal length

# What is the effect of aperture size?

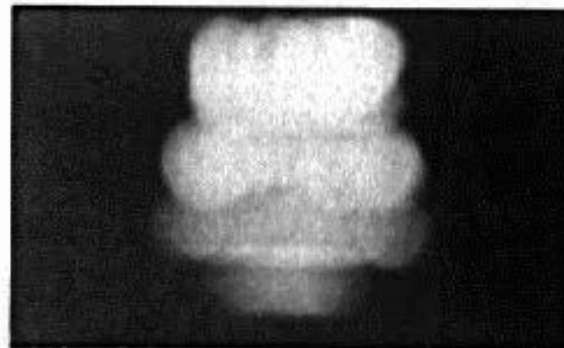
Large aperture: light from the source spreads across the image (i.e., not properly focused), making it **blurry**!



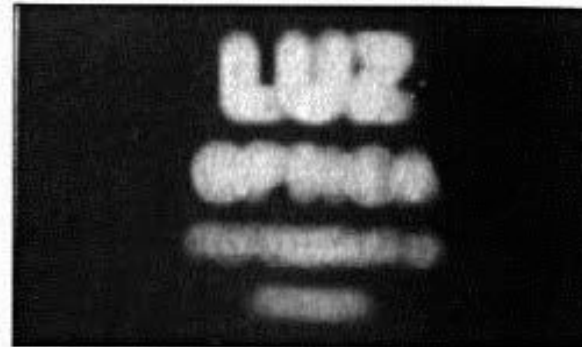
Small aperture: reduces **blurring** but (i) it limits the amount of light entering the camera and (ii) causes light **diffraction**.



# Example: varying aperture size



2 mm



1 mm



0.6mm

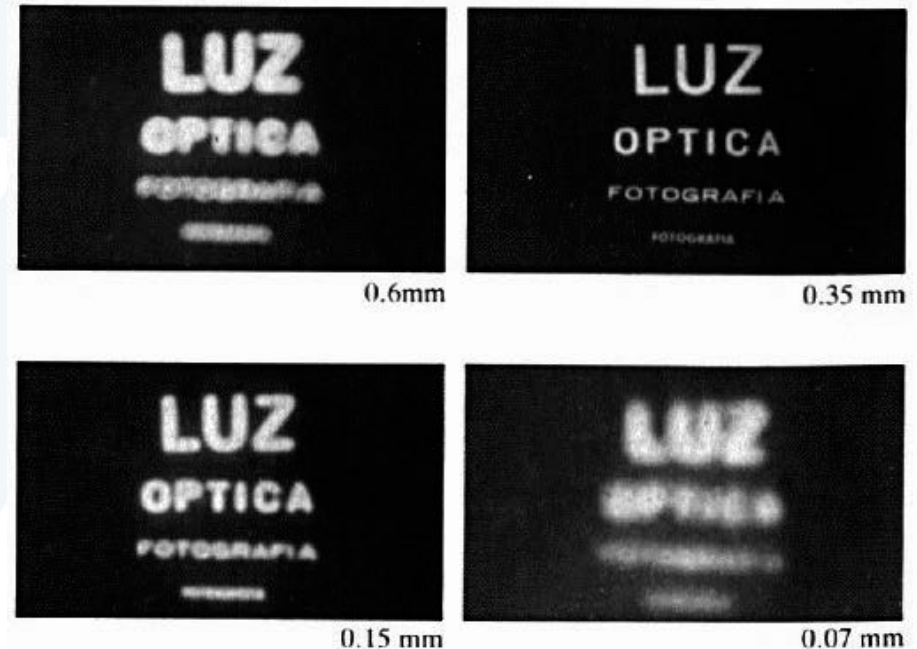


0.35 mm



## Example: varying aperture size (cont'd)

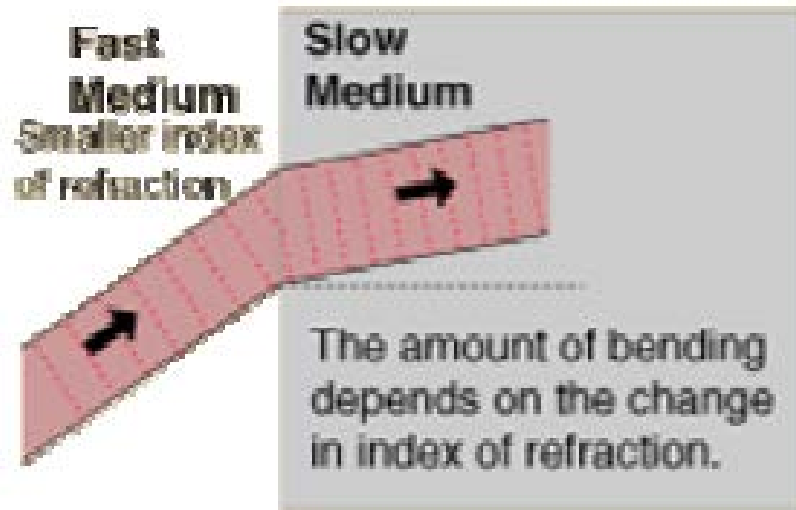
- What happens if we keep decreasing aperture size?
- When light passes through a small hole, it does not travel in a straight line and is scattered in many directions (i.e., **diffraction**)



SOLUTION: **refraction**

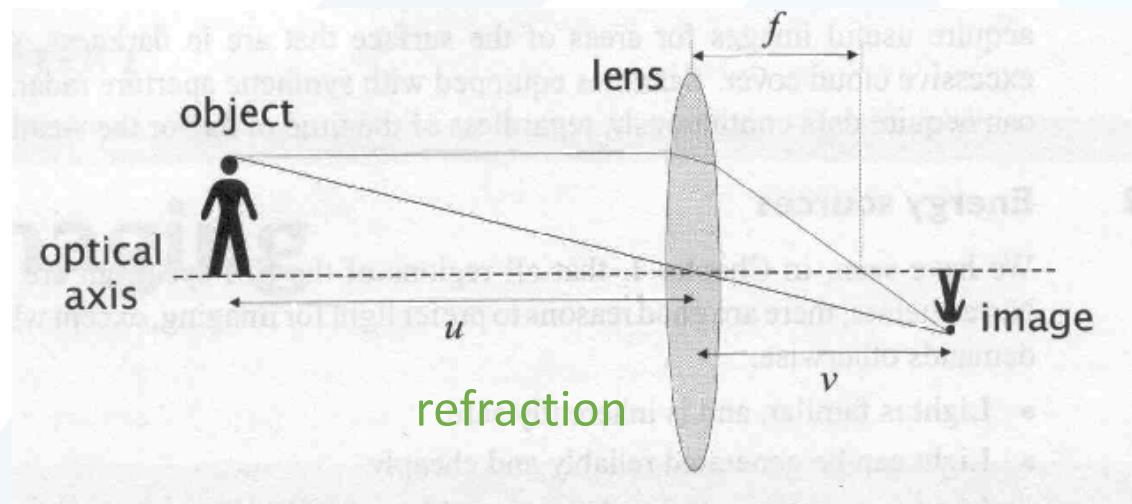
# Refraction

- Bending of wave when it enters a medium where its speed is different.



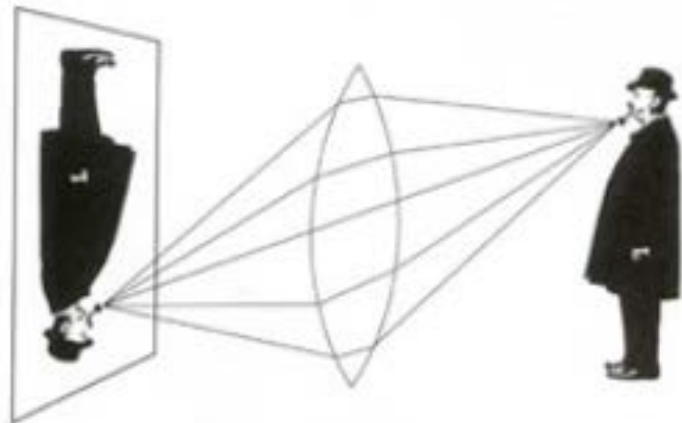
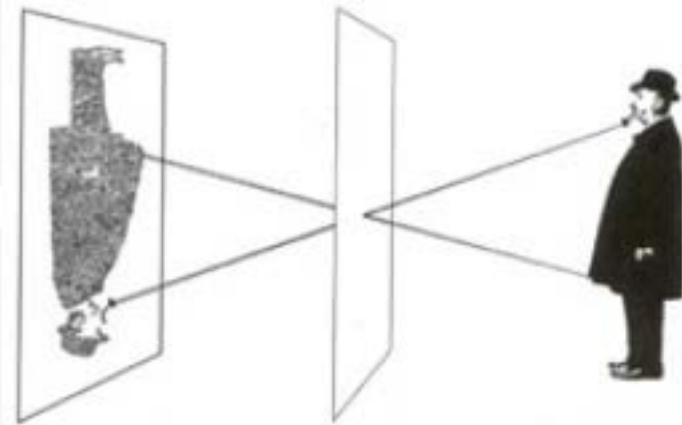
# Lens

- Lens **duplicate** pinhole geometry without resorting to undesirably small apertures.
  - Gather all the light radiating from an object point towards the lens's finite aperture .
  - Bring light into **focus** at a single distinct image point.

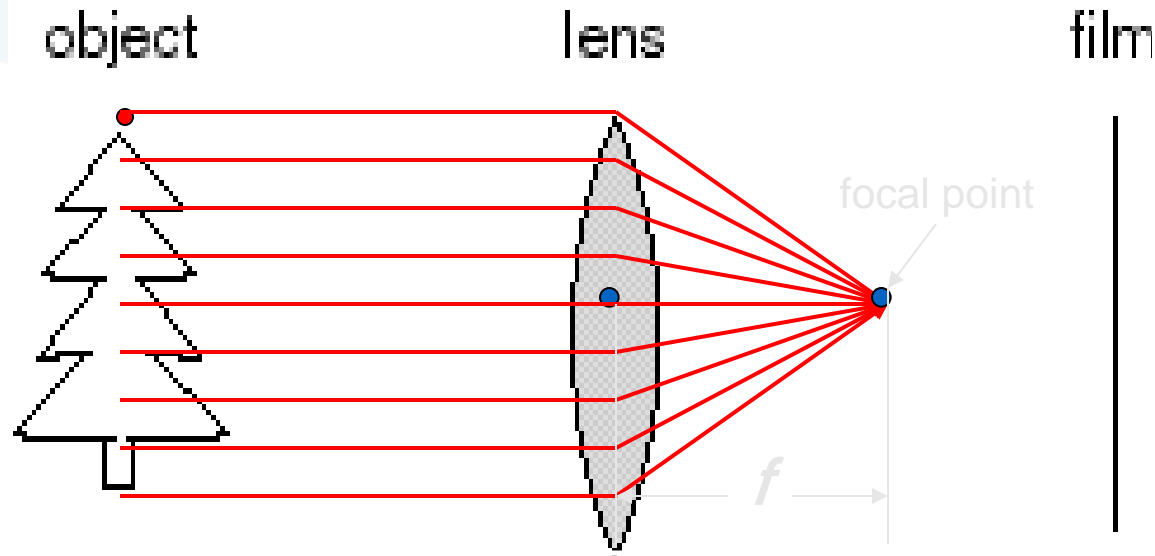


## Lens (cont'd)

- Lens improve image quality, leading to sharper images.

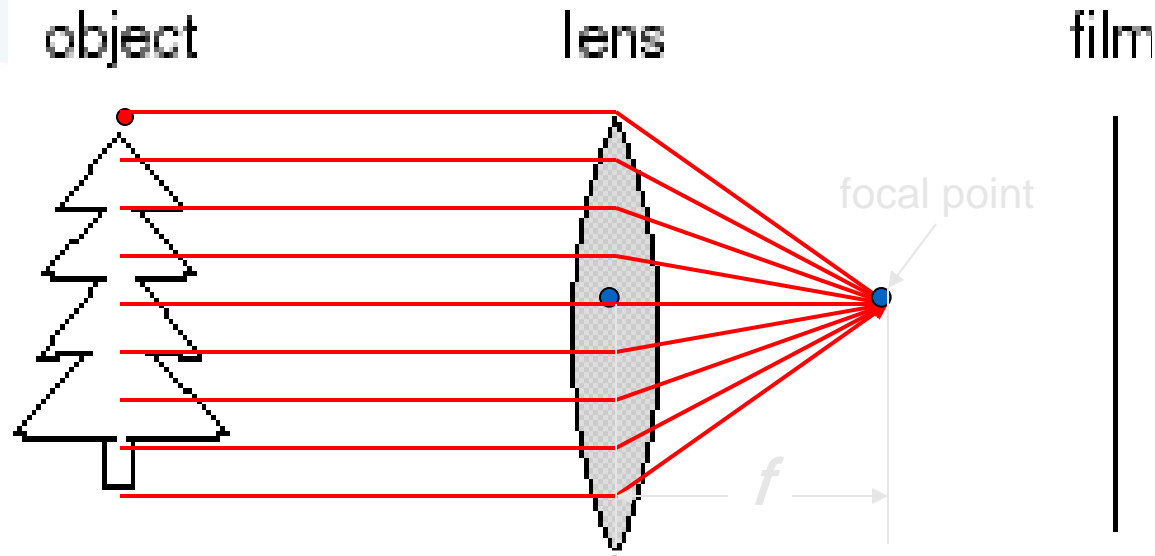


# Properties of “thin” lens (i.e., ideal lens)



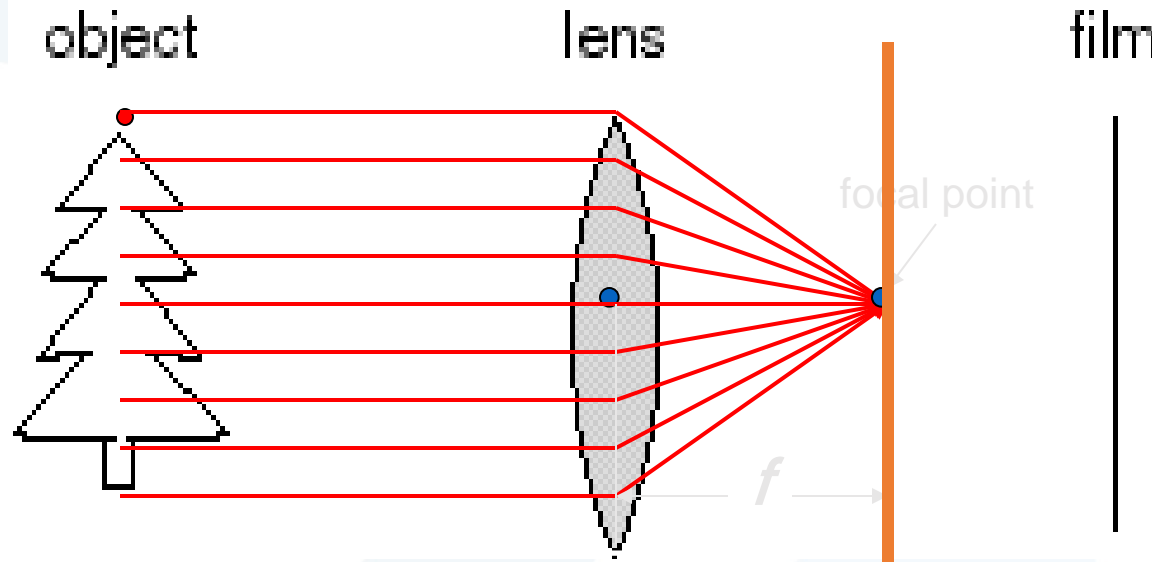
- Light rays passing through the center are not deviated.
- Light rays passing through a point far away from the center are deviated more.

# Properties of “thin” lens (i.e., ideal lens)



- All parallel rays converge to a single point.
- When rays are perpendicular to the lens, it is called **focal point**.

# Properties of “thin” lens



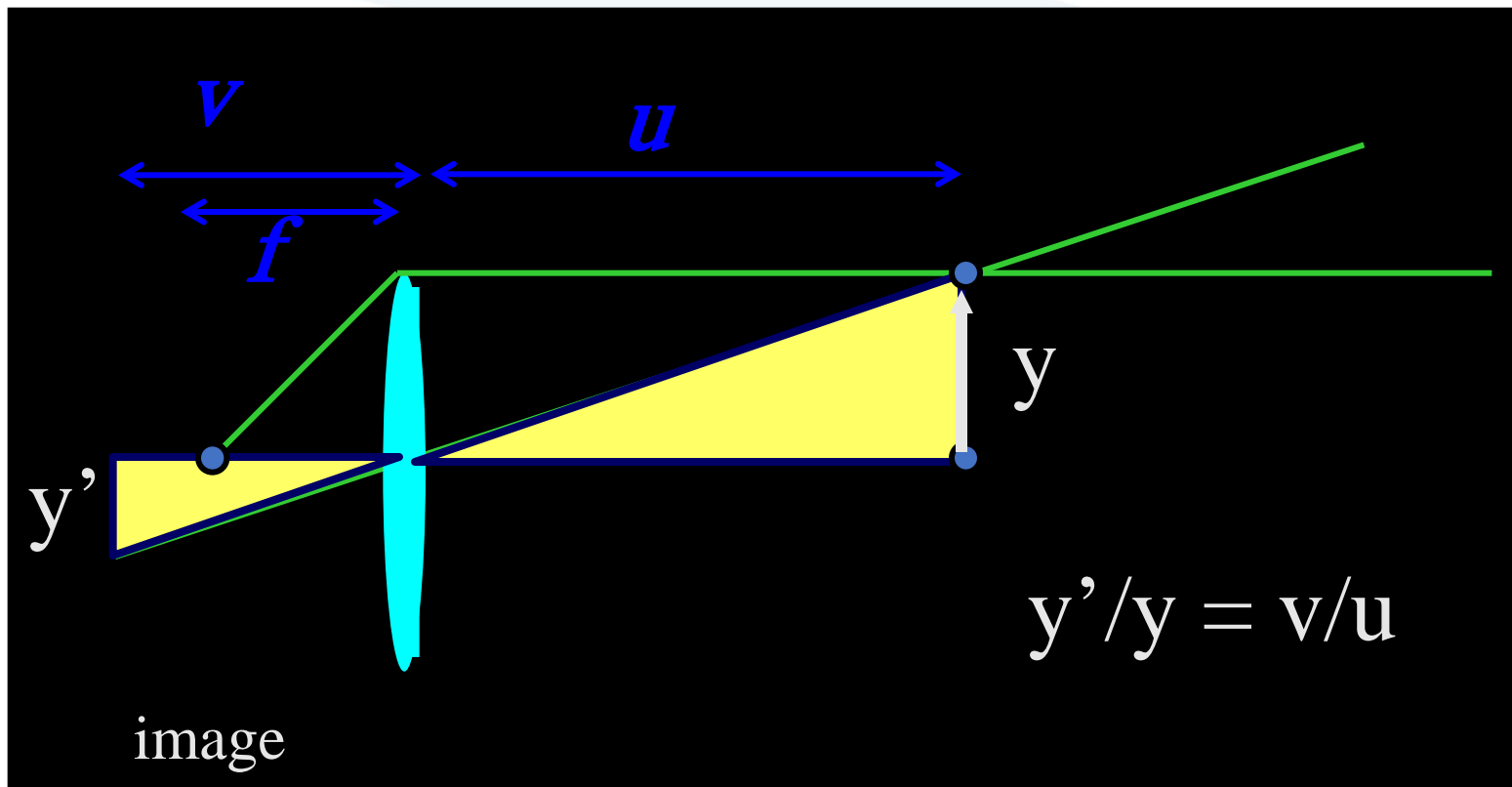
- The plane parallel to the lens at the focal point is called the **focal plane**.
- The distance between the lens and the focal plane is called the **focal length** (i.e.,  $f$ ) of the lens.





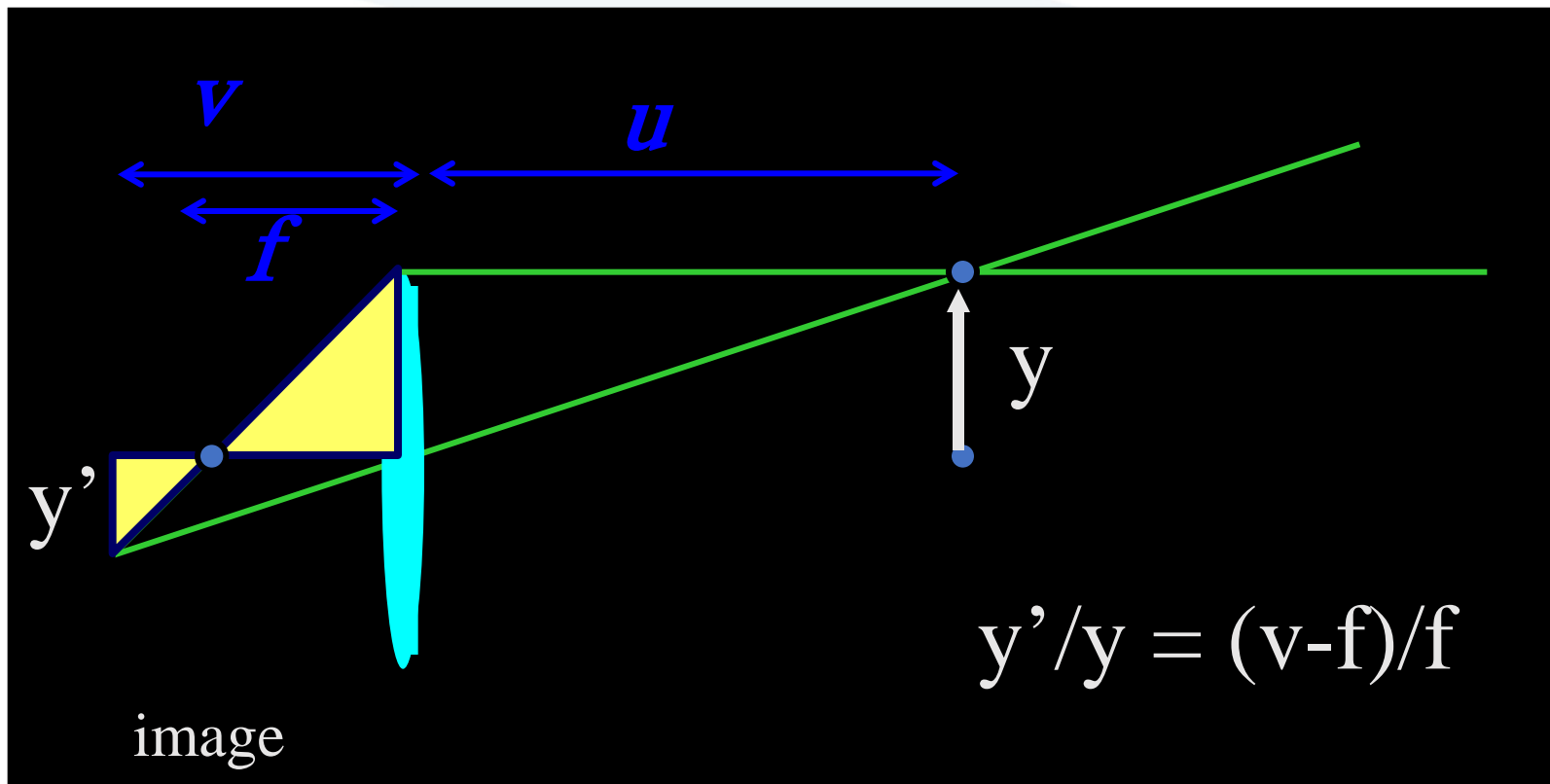
# Thin lens equation (cont'd)

Using similar triangles:



# Thin lens equation (cont'd)

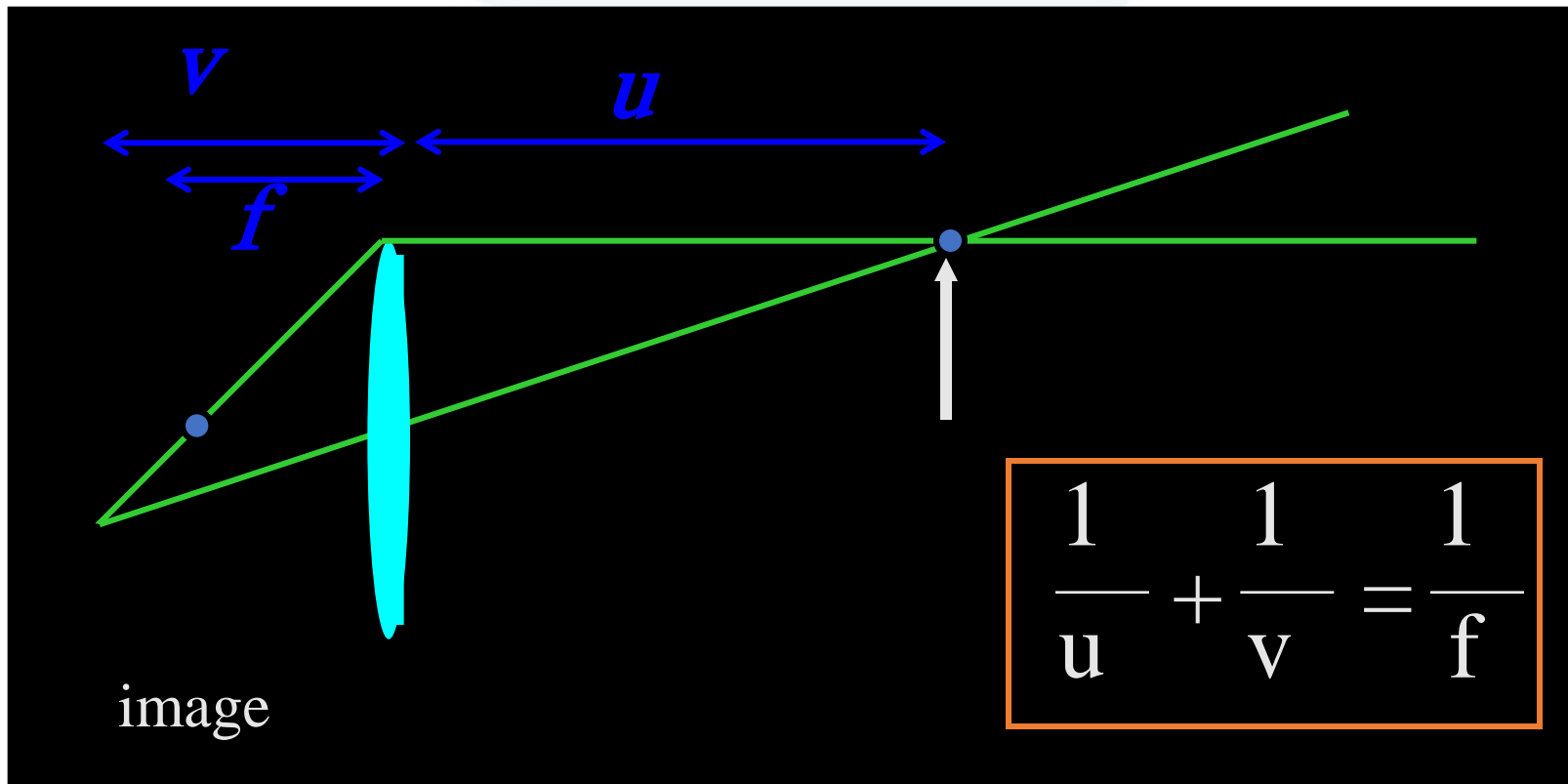
Using similar triangles:



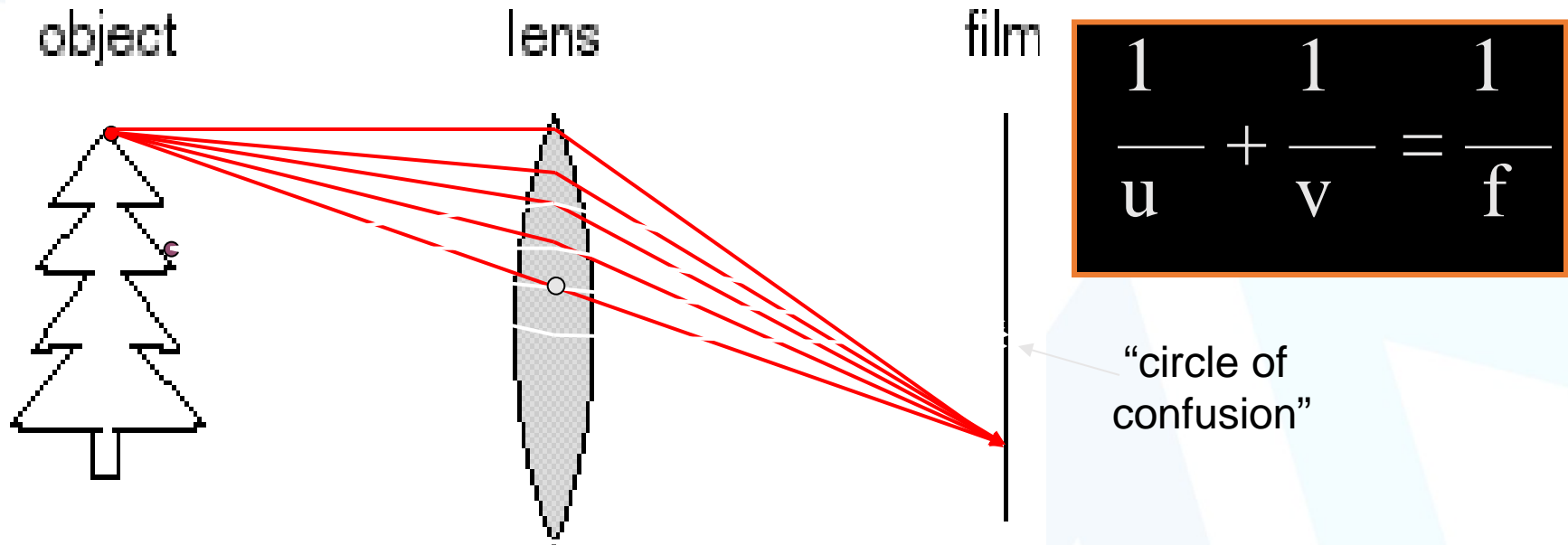


# Thin lens equation (cont'd)

Combining the equations:

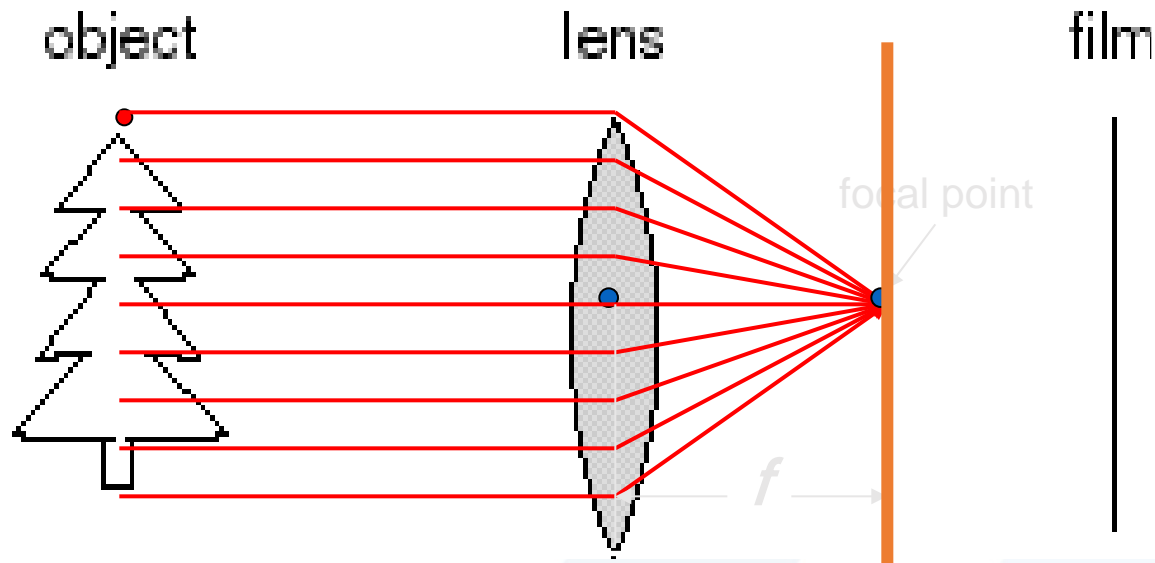


# Thin lens equation (cont'd)



- The thin lens equation implies that **only** points at distance  $u$  from the lens are “in focus” (i.e., focal point lies on image plane).
- Other points project to a “**blur circle**” or “**circle of confusion**” in the image (i.e., blurring occurs).

# Thin lens equation (cont'd)



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

- When objects move far away from the camera, then the focal plane approaches the image plane.



# Depth of Field

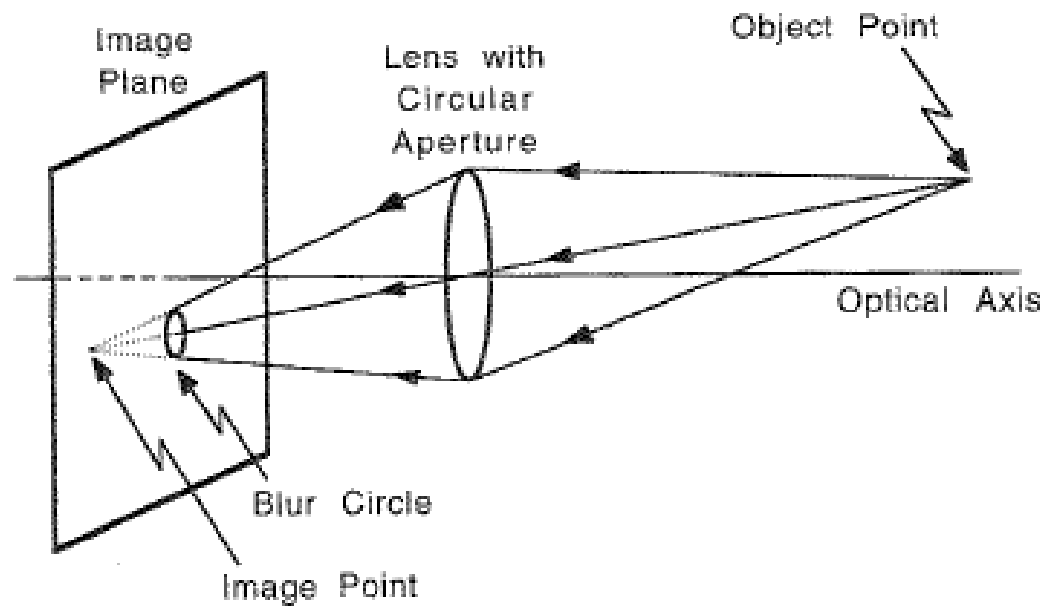
The range of depths over which the world is approximately sharp (i.e., in focus).



<http://www.cambridgeincolour.com/tutorials/depth-of-field.htm>

# How can we control depth of field?

- The size of blur circle is proportional to aperture size.

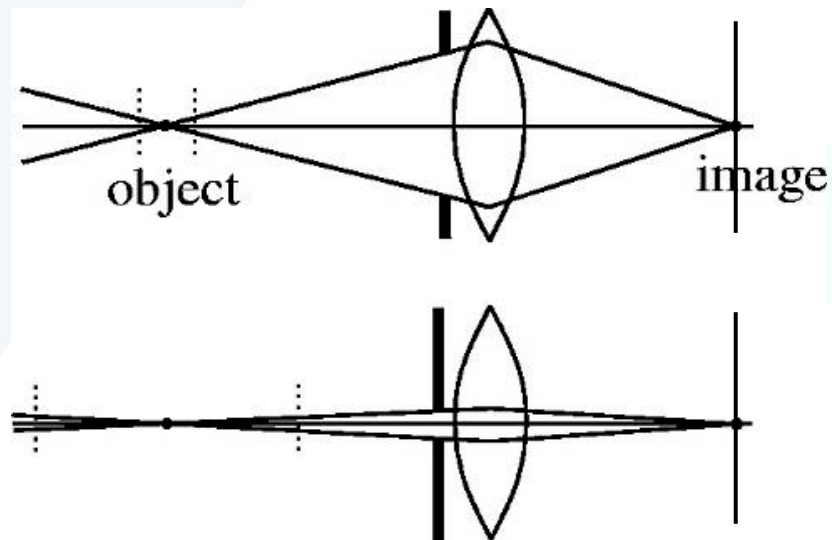




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# How can we control depth of field? (cont'd)

- Changing aperture size (controlled by diaphragm) affects depth of field.
  - A smaller aperture increases the range in which an object is approximately in focus (but need to increase **exposure time**).
  - A larger aperture decreases the depth of field (but need to decrease **exposure time**).





# Varying aperture size

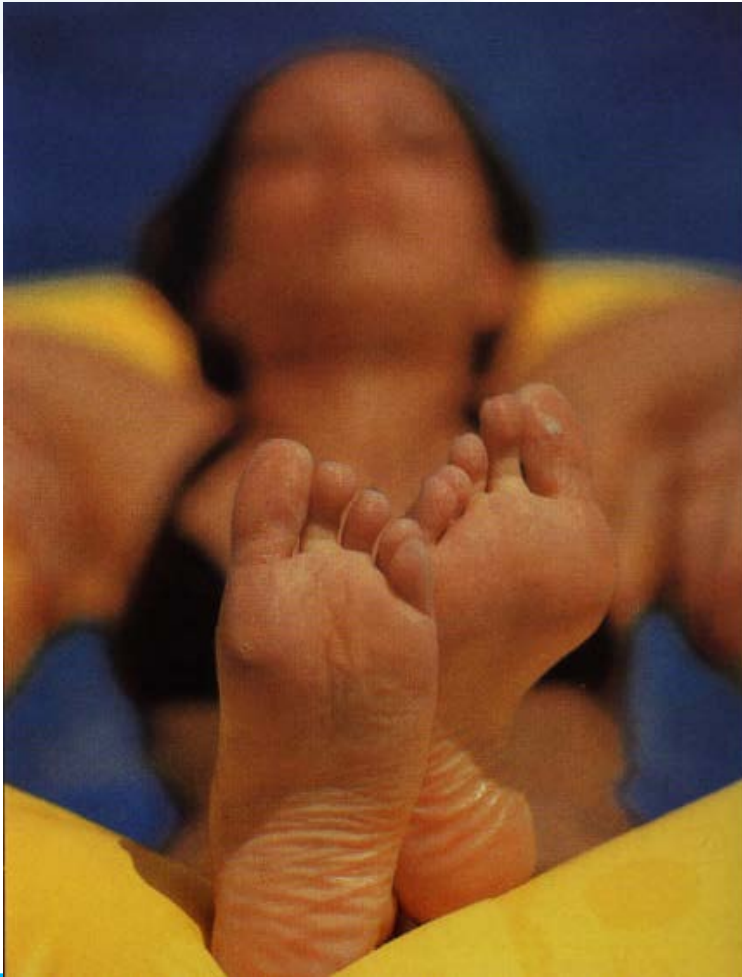


Large aperture = small DOF



Small aperture = large DOF

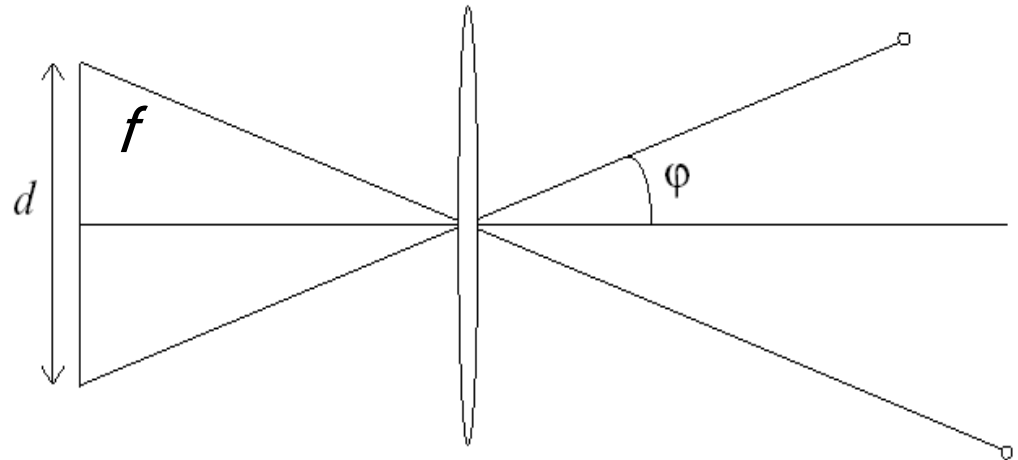
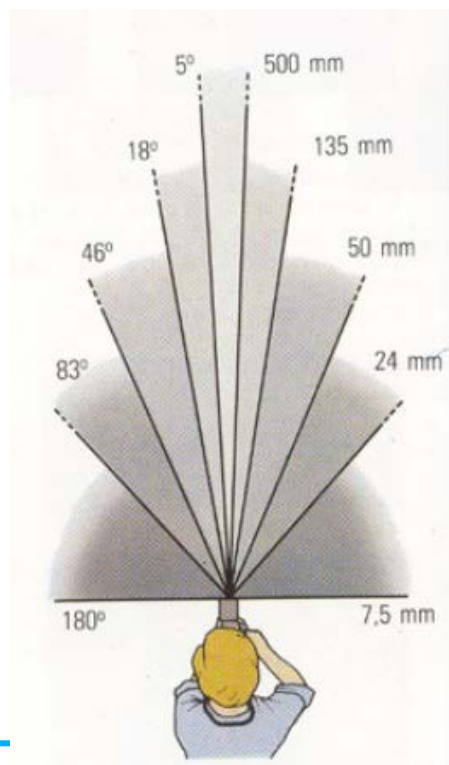
# Another Example



Large aperture = small DOF

# Field of View (Zoom)

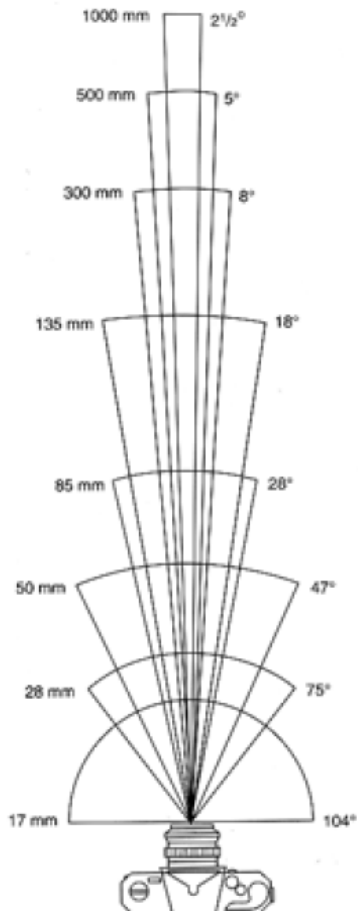
- The cone of viewing directions of the camera.
- Inversely proportional to focal length.



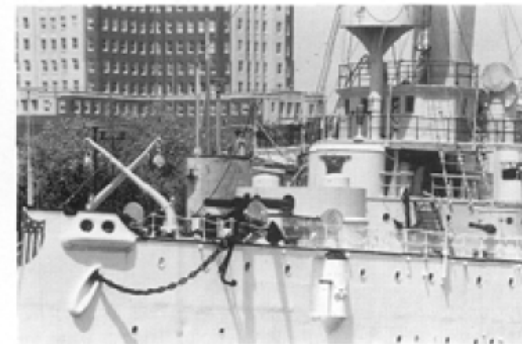
Size of field of view governed by size of the camera retina:

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

# Field of View (Zoom)



135mm



300mm



50mm



28mm

**From London and Upton**

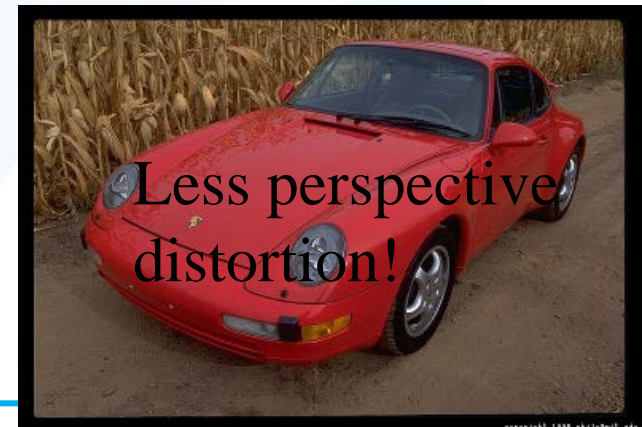


# Reduce Perspective Distortions by varying Distance / Focal Length

Small  $f$  (i.e., large FOV),  
camera **close** to car



Large  $f$  (i.e., small FOV),  
camera **far** from car



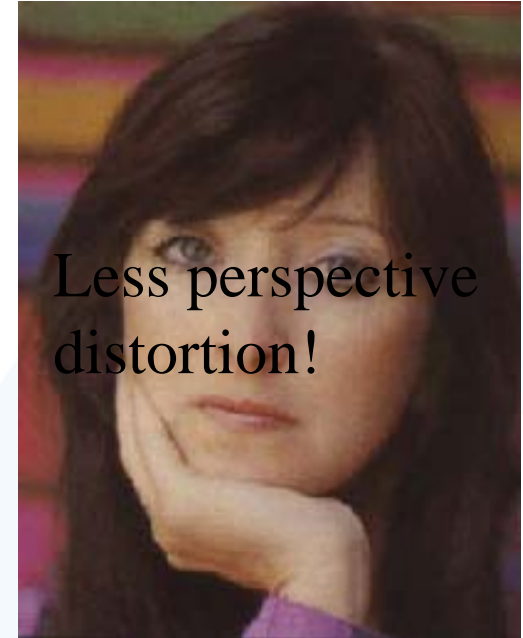
## Same effect for faces



wide-angle



standard

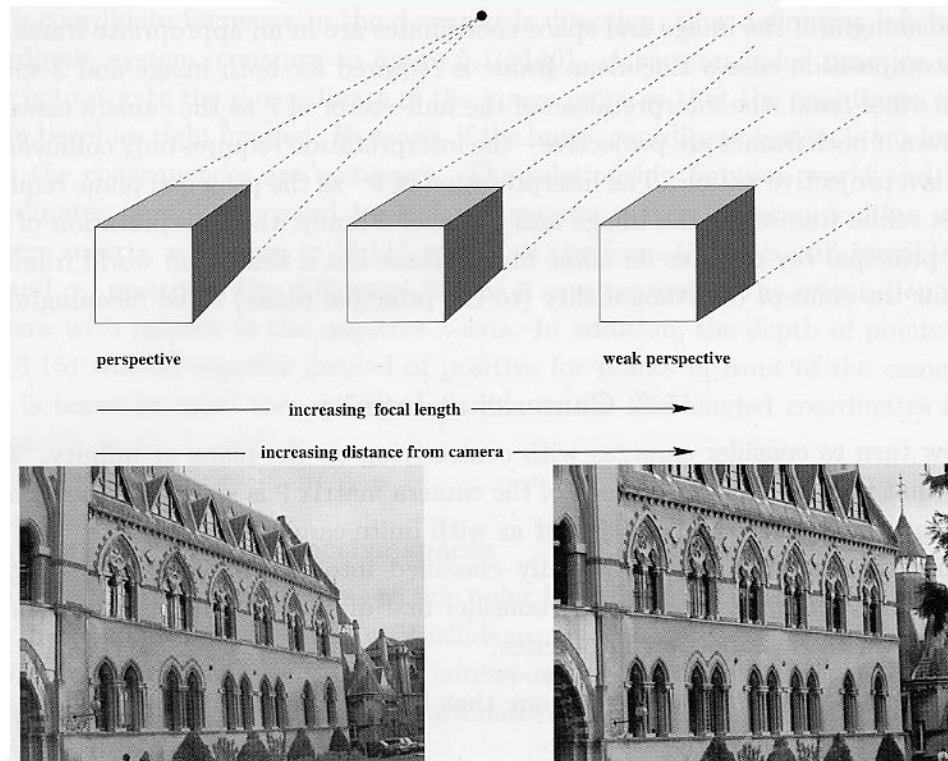


telephoto

Practical significance: we can approximate perspective projection using a simpler model when using telephoto lens to view a distant object that has a relatively small range of depth.

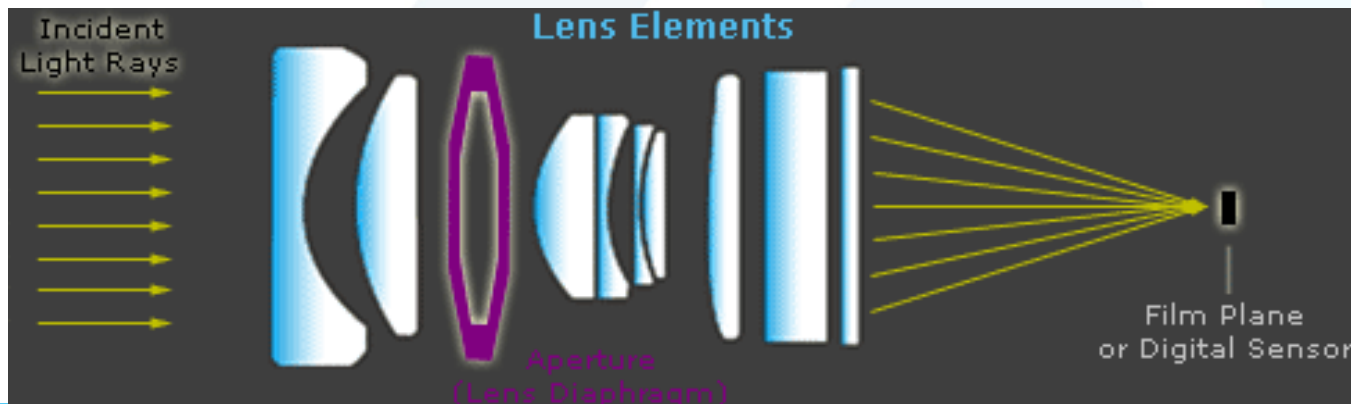
# Approximating an “affine” camera

Center of projection is at infinity!



# Real lenses

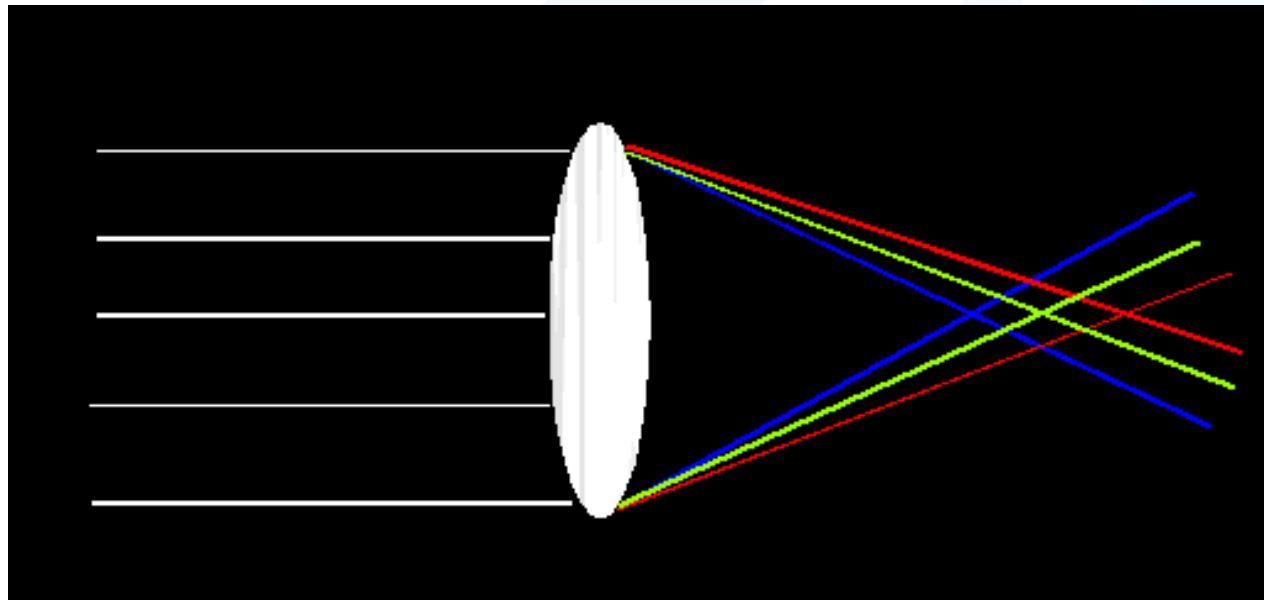
- All but the simplest cameras contain lenses which are actually comprised of several "lens elements."
- Each element aims to direct the path of light rays such that they recreate the image as accurately as possible on the digital sensor.





# Lens Flaws: Chromatic Aberration

- Lens has different refractive indices for different wavelengths.
- Could cause color **fringing**:
  - i.e., lens cannot focus all the colors at the same point.



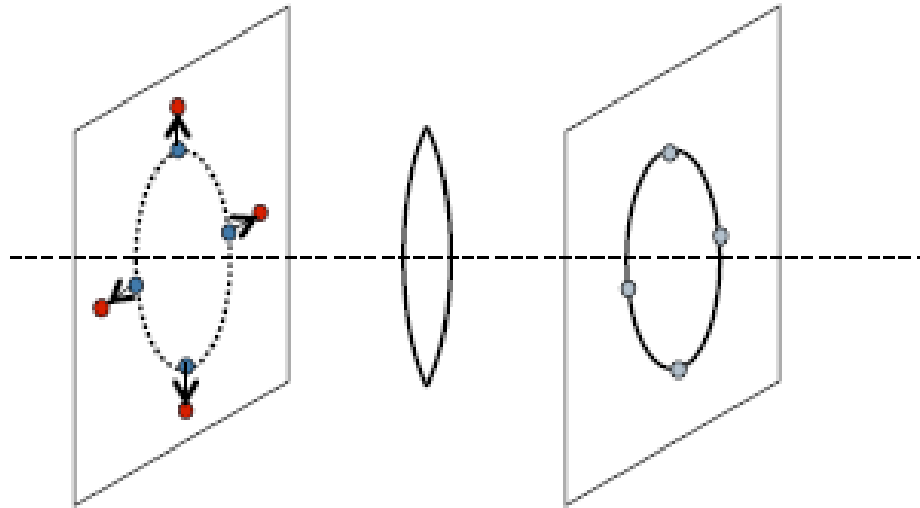


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# Chromatic Aberration - Example



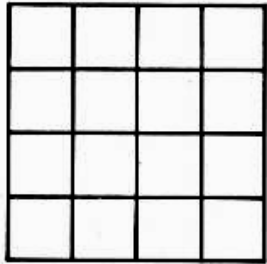
# Lens Flaws: Radial Distortion



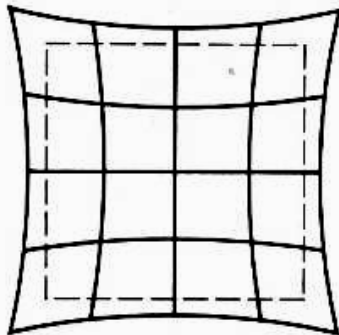
- Straight lines become distorted as we move further away from the center of the image.
- Deviations are most noticeable for rays that pass through the edge of the lens.

# Lens Flaws: Radial Distortion (cont'd)

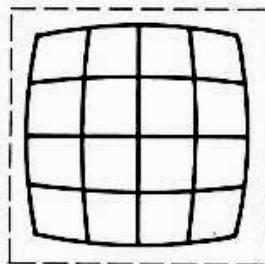
No distortion



Pin cushion

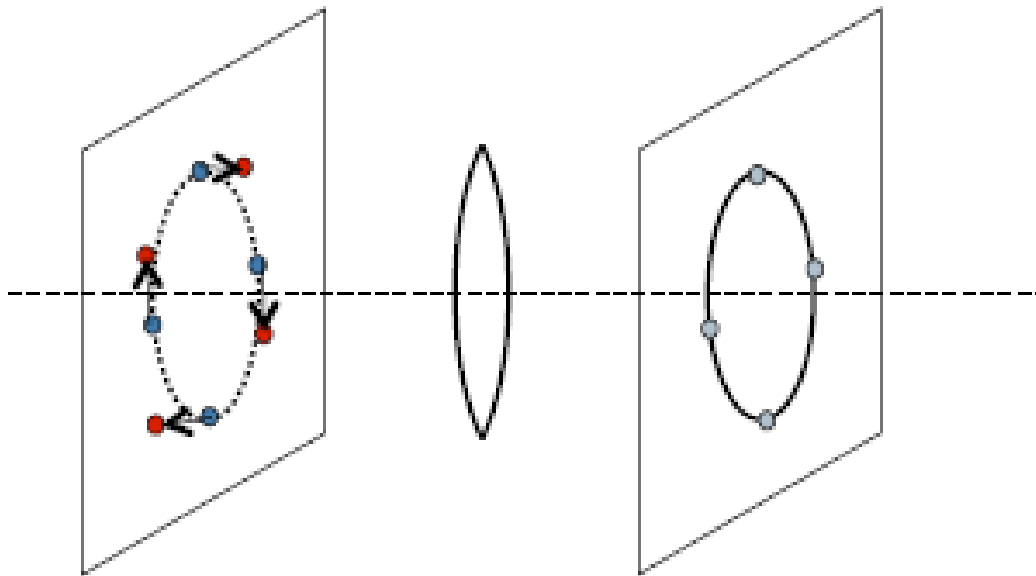


Barrel



# Lens Flaws: Tangential Distortion

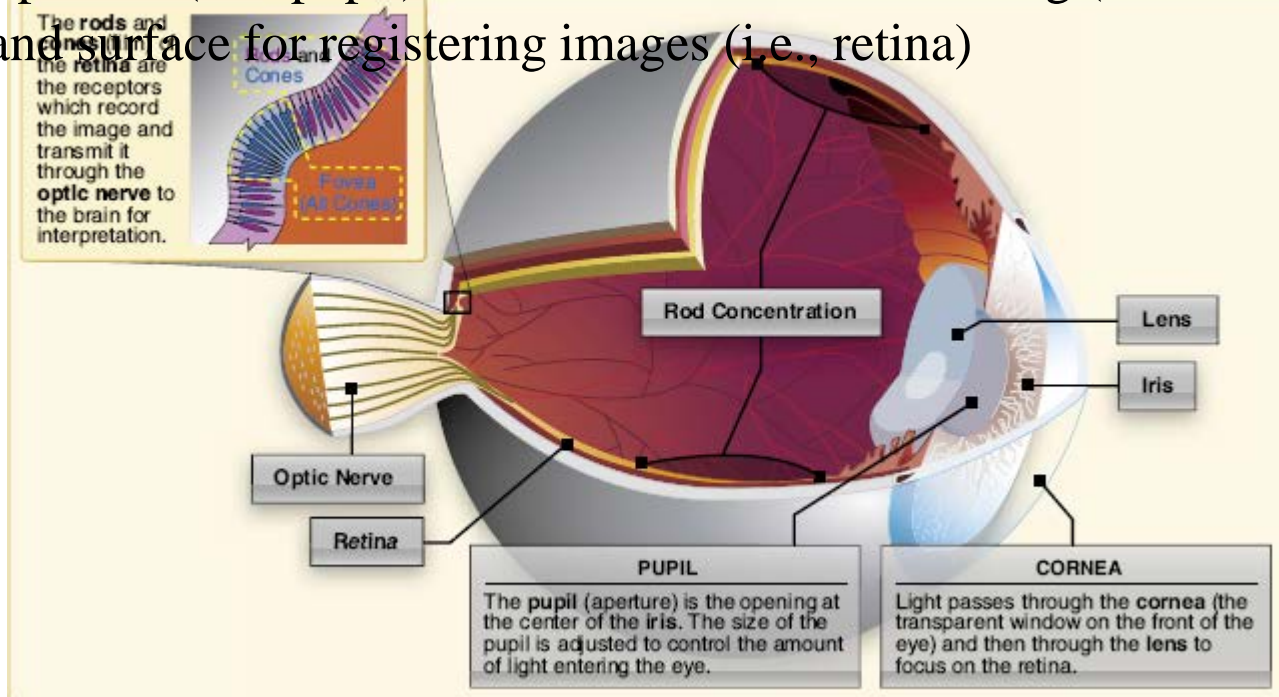
- Lens is not exactly parallel to the imaging plane!



# Human Eye

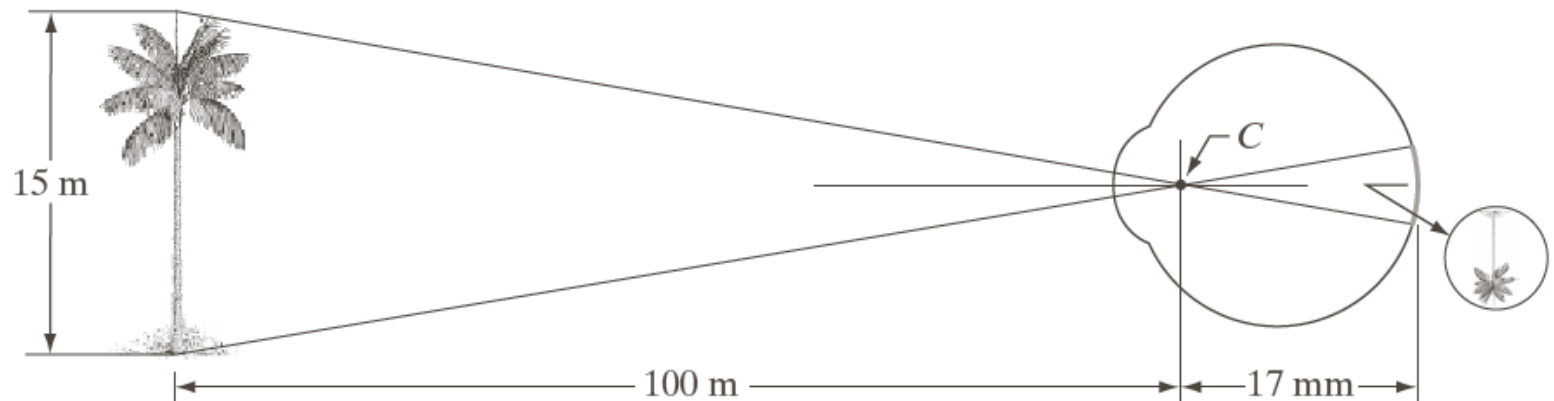
- Functions much like a camera:

aperture (i.e., pupil), lens, mechanism for focusing (zoom in/out) and surface for registering images (i.e., retina)



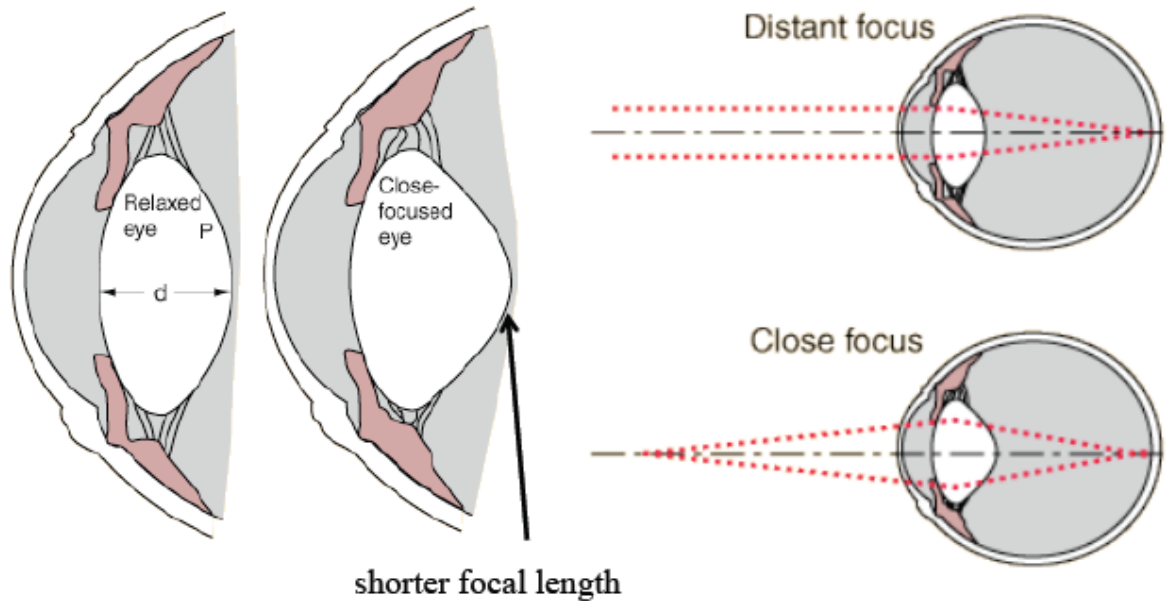
## Human Eye (cont'd)

- In a camera, focusing at various distances is achieved by varying the distance between the lens and the imaging plane.
- In the human eye, the distance between the lens and the retina is fixed (i.e., 14mm to 17mm).



# Human Eye (cont'd)

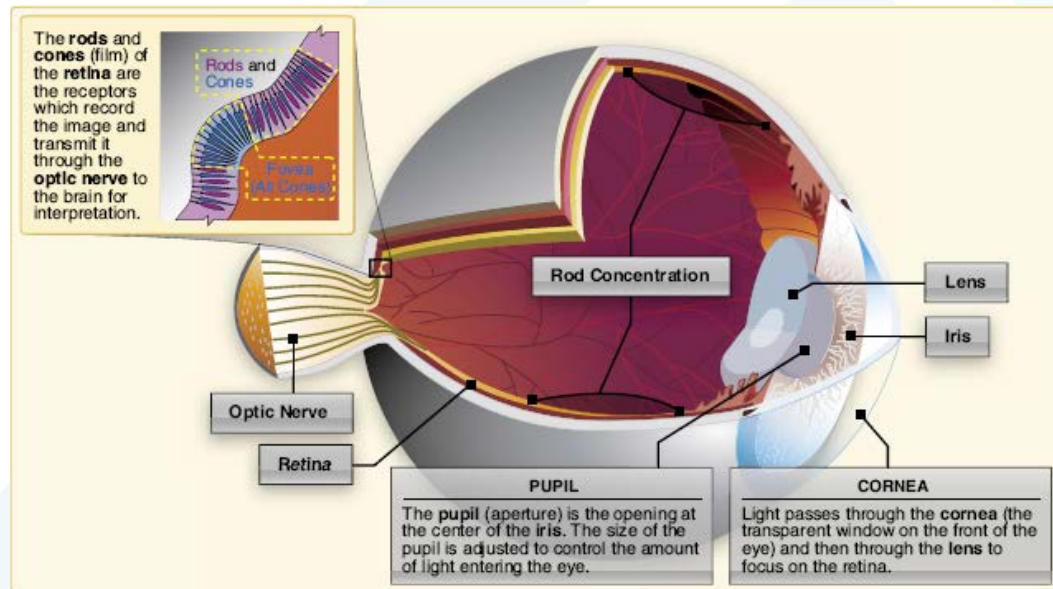
- Focusing is achieved by varying the shape of the lens (i.e., flattening or thickening).





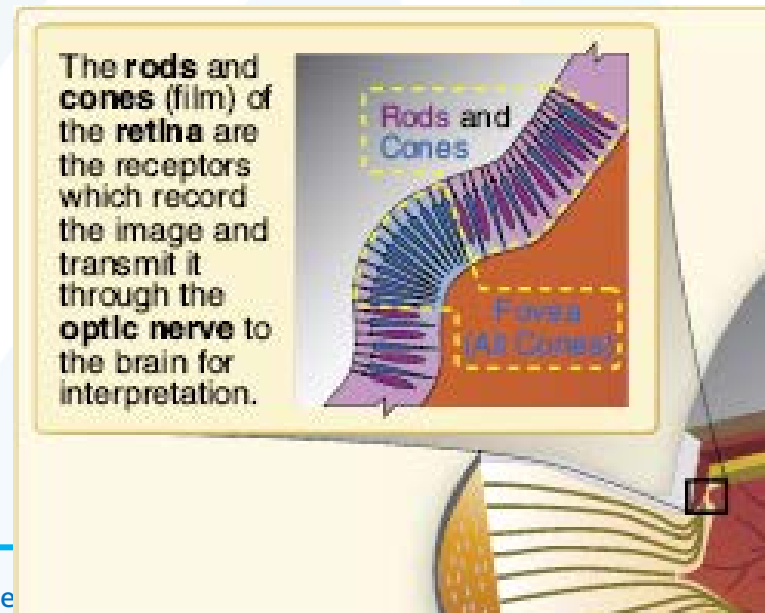
# Human Eye (cont'd)

- Retina contains **light sensitive cells** that convert light energy into **electrical impulses** that travel through nerves to the brain.
- Brain interprets the electrical signals to form images.



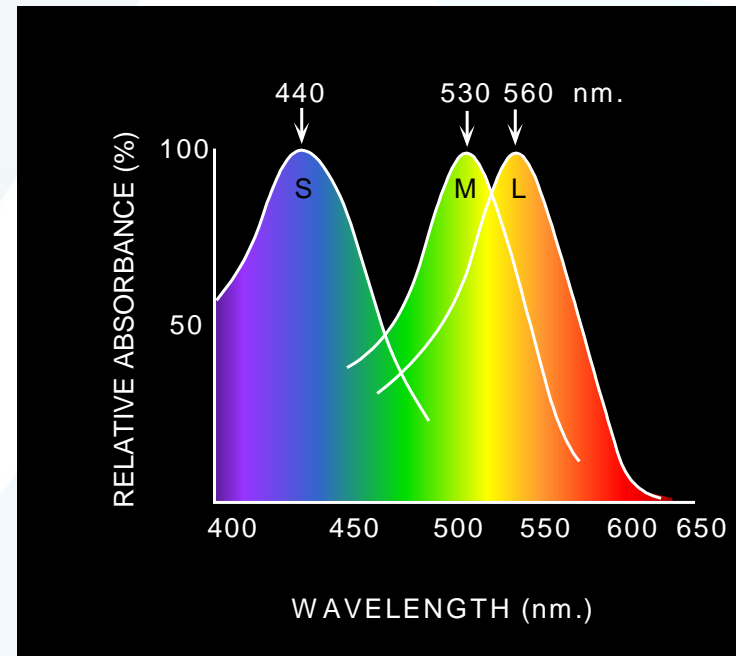
# Human Eye (cont'd)

- Two kinds of light-sensitive cells: **rods** and **cone** (unevenly distributed).
- **Cones** (6 – 7 million) are responsible for all color vision and are present throughout the retina, but are concentrated toward the center of the field of vision at the back of the retina.
- Fovea – special area
  - Mostly cones.
  - Detail, color sensitivity, and resolution are highest.



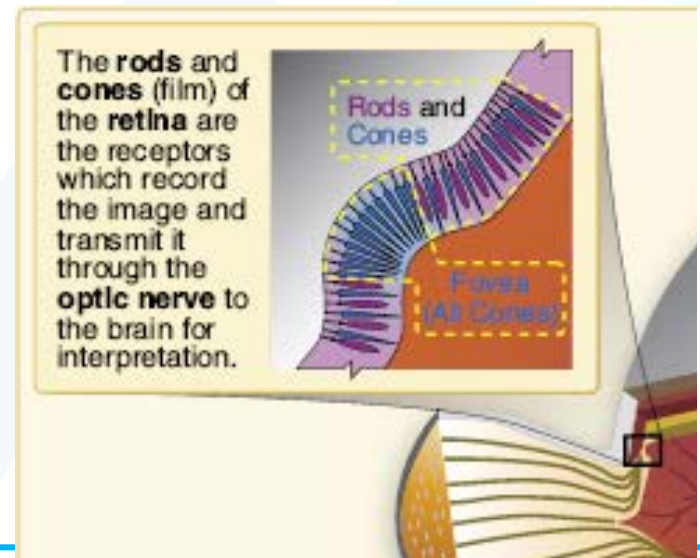
# Human Eye (cont'd)

- Three different types of cones; each type has a special pigment that is sensitive to wavelengths of light in a certain range:
  - Short (S) corresponds to blue
  - Medium (M) corresponds to green
  - Long (L) corresponds to red
- Ratio of L to M to S cones:
  - approx. 10:5:1
- Almost no S cones in the center of the fovea



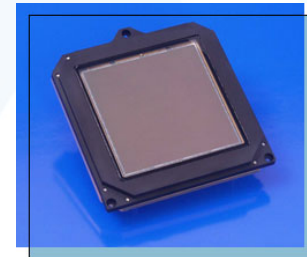
# Human Eye (cont'd)

- **Rods** (120 million) more sensitive to light than cones but cannot discern color.
  - Primary receptors for night vision and detecting motion.
  - Large amount of light overwhelms them, and they take a long time to “reset” and adapt to the dark again.
  - Once fully adapted to darkness, the rods are 10,000 times more sensitive to light than the cones



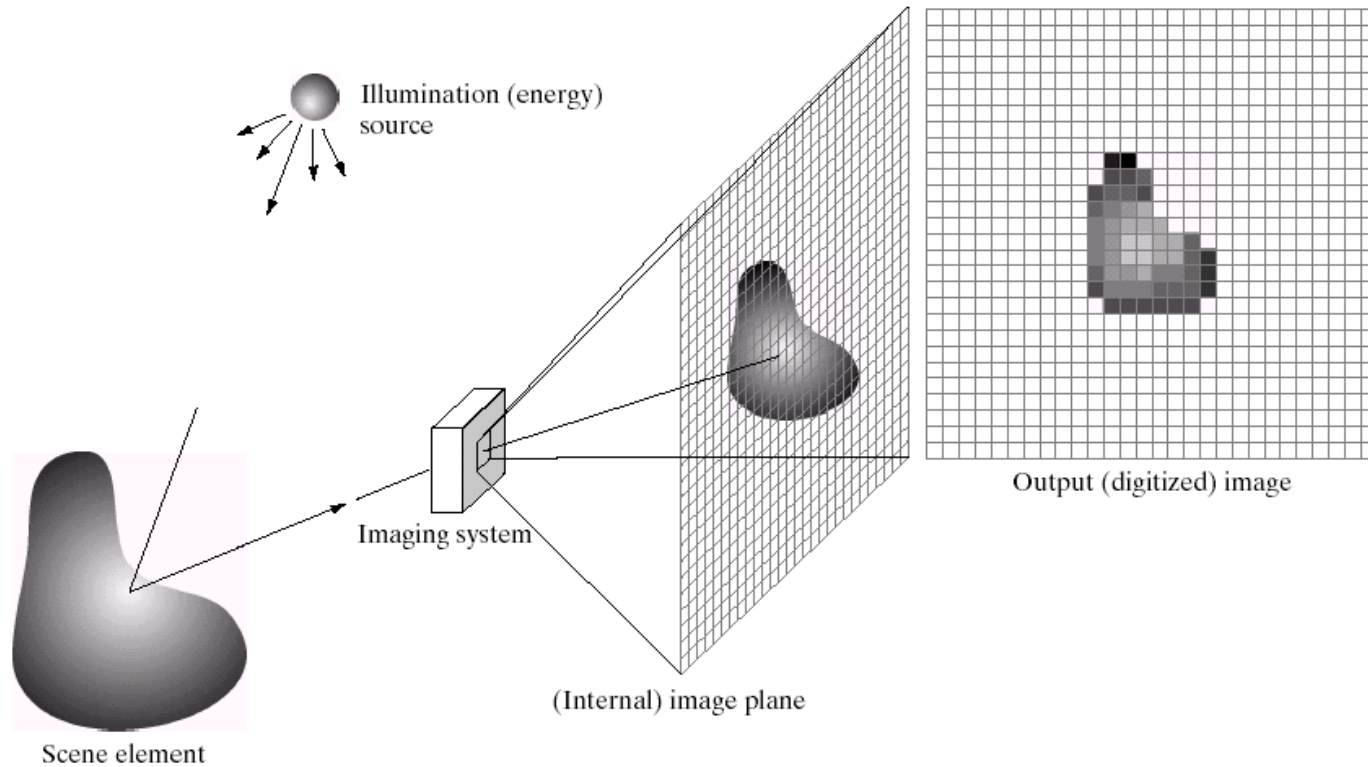
# Digital cameras

- A digital camera replaces film with a sensor array.
  - Each cell in the array is light-sensitive diode that converts **photons** to **electrons**
- Two common types
  - Charge Coupled Device (CCD)
  - Complementary metal oxide semiconductor (CMOS)



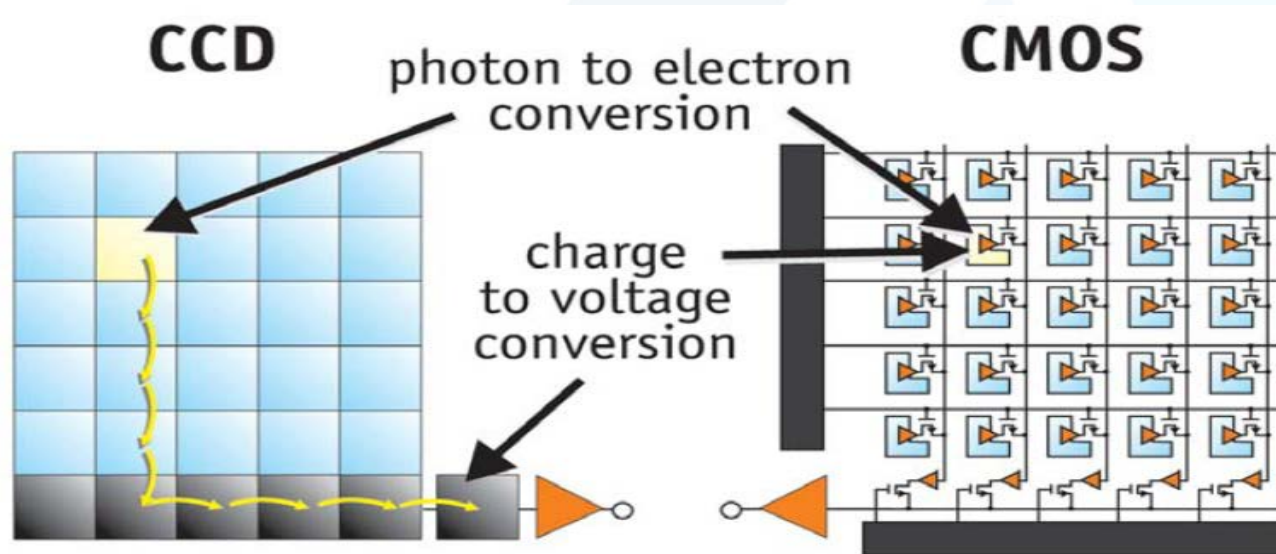
<http://electronics.howstuffworks.com/digital-camera.htm>

# Digital cameras (cont'd)



# CCD Cameras

- CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node.
- An **analog-to-digital converter (ADC)** then turns each pixel's value into a digital value.

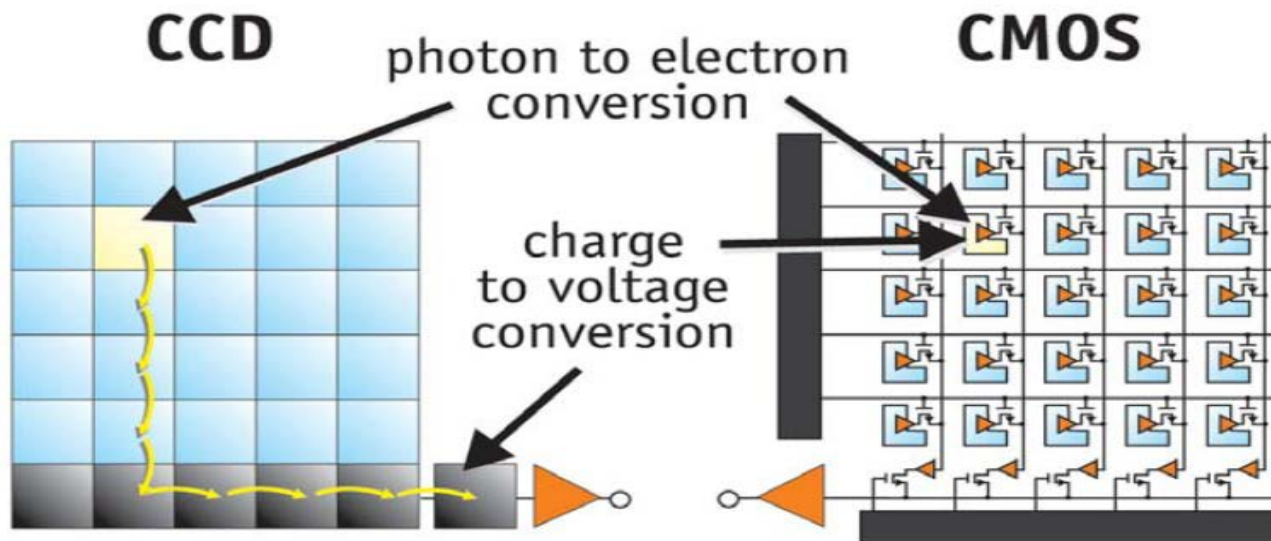


[http://www.dalsa.com/shared/content/pdfs/CCD vs CMOS Litwiller 2005.pdf](http://www.dalsa.com/shared/content/pdfs/CCD_vs_CMOS_Litwiller_2005.pdf)



# CMOS Cameras

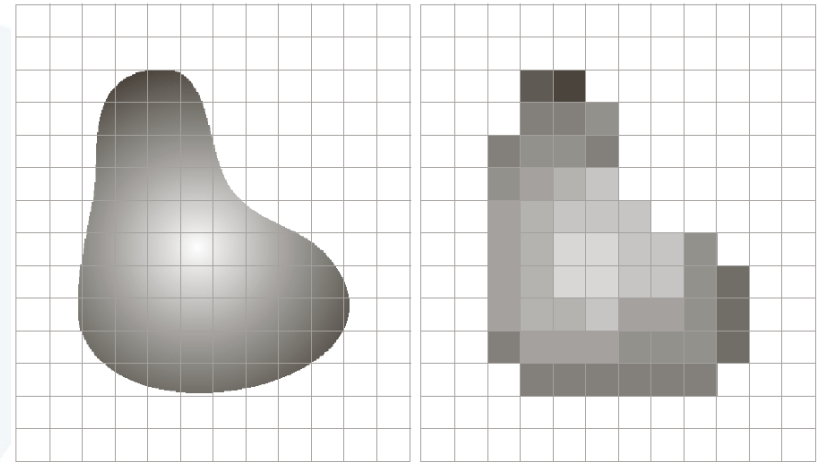
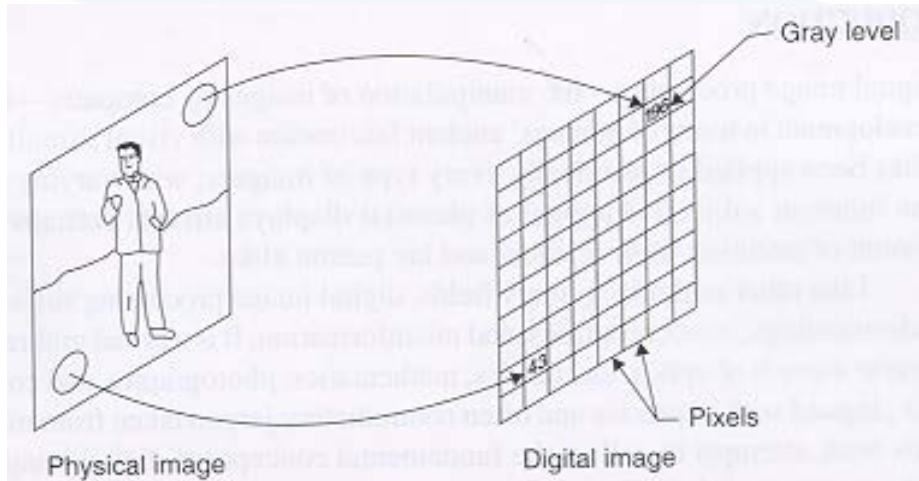
- CMOs convert charge to voltage inside each element.
- Uses several transistors at each pixel to amplify and move the charge using more traditional wires.
- The CMOS signal is digital, so it needs no ADC.



[http://www.dalsa.com/shared/content/pdfs/CCD vs CMOS Litwiller 2005.pdf](http://www.dalsa.com/shared/content/pdfs/CCD_vs_CMOS_Litwiller_2005.pdf)

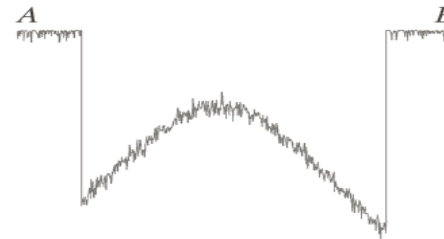
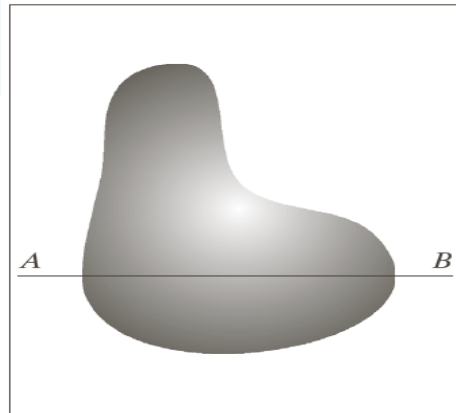


# Image digitization



- **Sampling:** measure the value of an image at a finite number of points.
- **Quantization:** represent measured value (i.e., voltage) at the sampled point by an integer.

# Image digitization (cont'd)



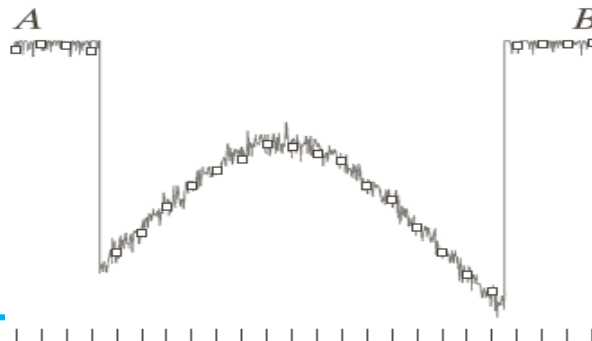
A

B

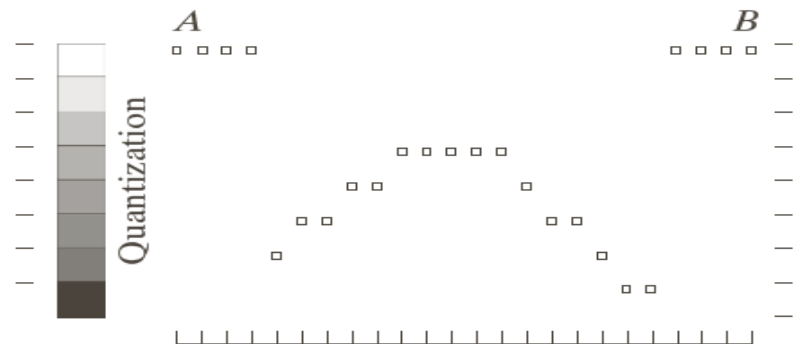
A

B

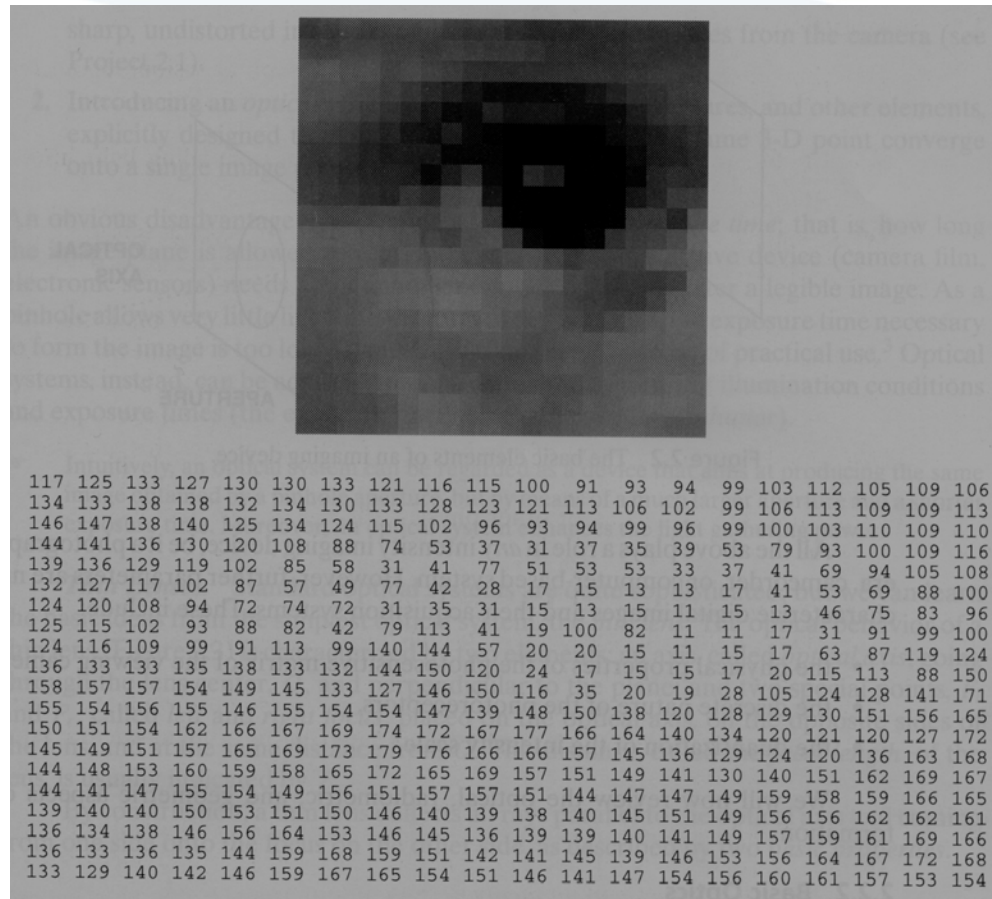
## Sampling



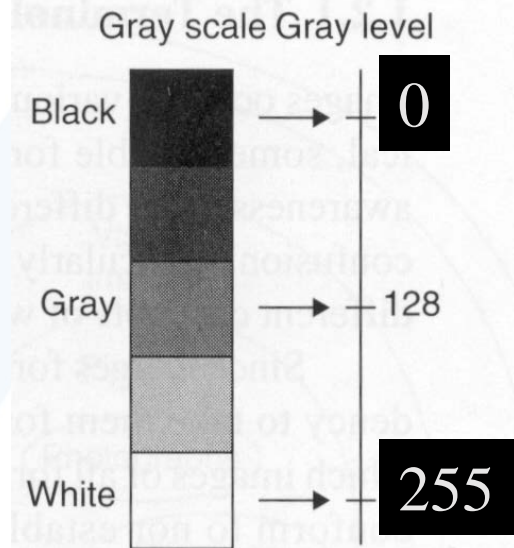
## Quantization



# What is an image?

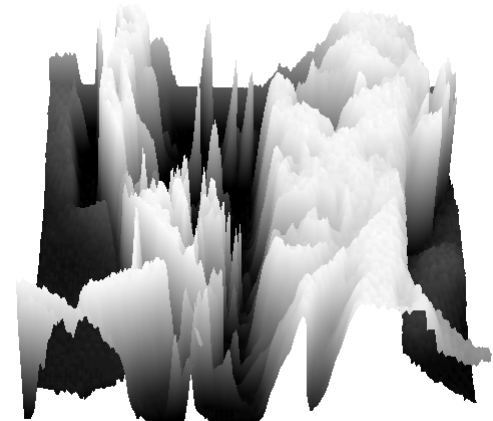
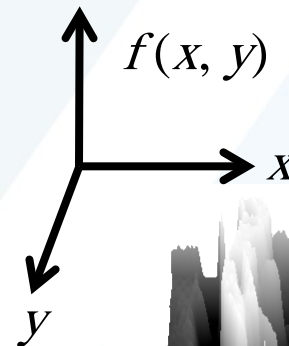


8 bits/pixel



# What is an image? (cont'd)

- We can think of a (grayscale) image as a **function**,  $f$ , from  $\mathbb{R}^2$  to  $\mathbb{R}$  (or a 2D *signal*):
  - $f(x, y)$  gives the **intensity** at position  $(x, y)$



- A **digital image** is a discretized version of a continuous image, quantized



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# Image Sampling - Example

original image



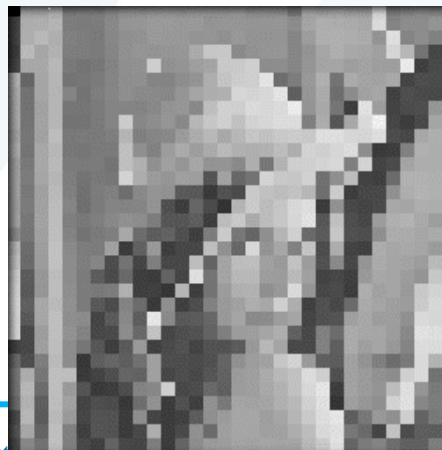
sampled by a factor of 2



sampled by a factor of



sampled by a factor of 8



Images have  
been resized  
for easier  
comparison

# Image Quantization - Example

- 256 gray levels (8bits/pixel)    32 gray levels (5 bits/pixel)    16 gray levels (4 bits/pixel)



- 8 gray



- gray



- gray





# Color Images

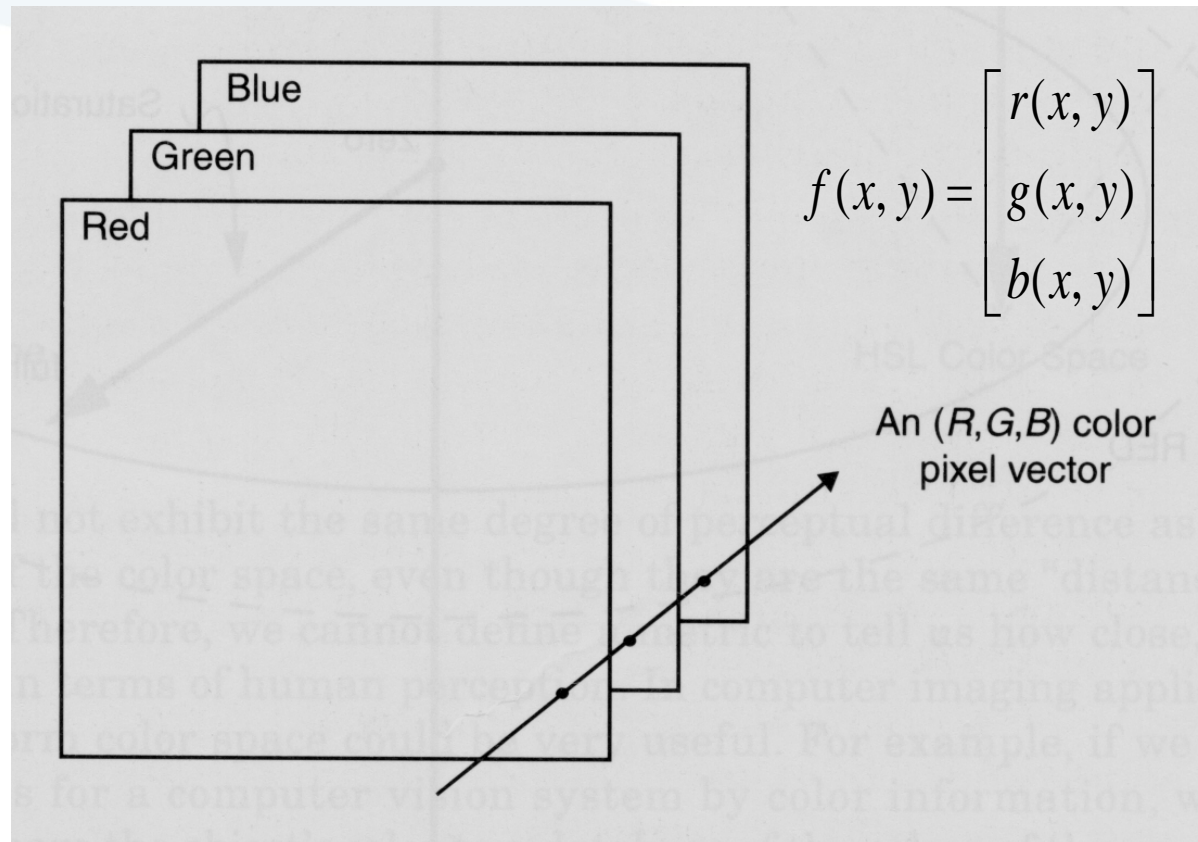
- Color images are comprised of three color channels – **red**, **green**, and, **blue** – which combine to create most of the colors we can see.



=



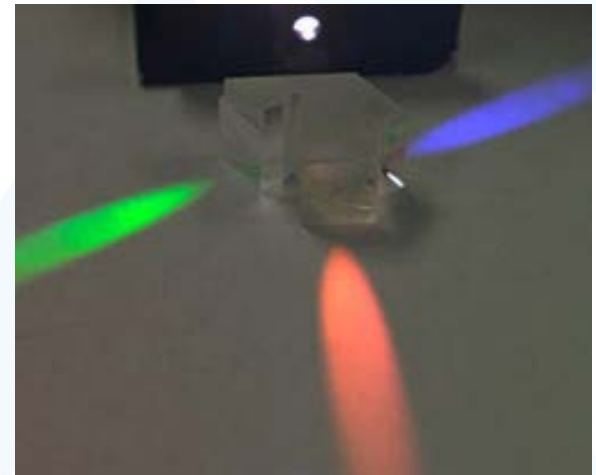
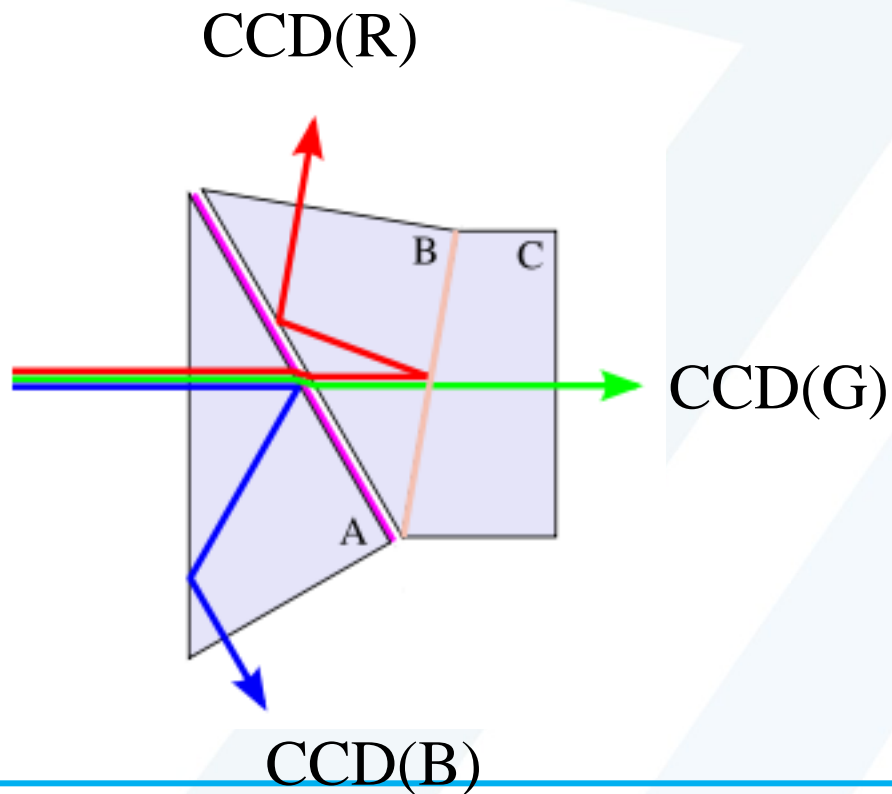
# Color images





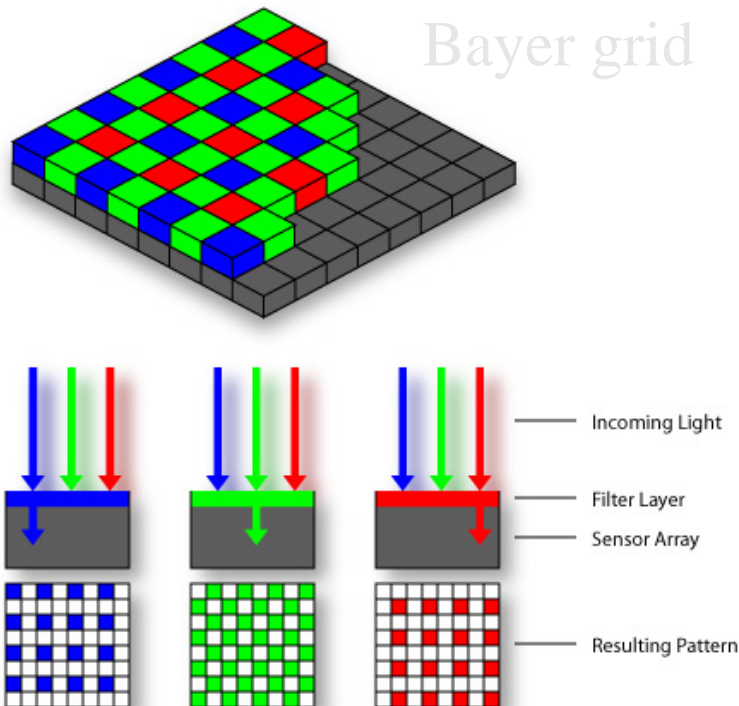
# Color sensing in camera: Prism

- Requires three chips and precise alignment.

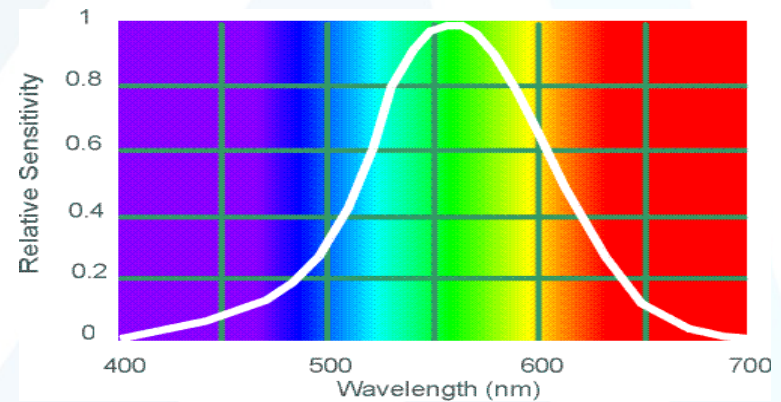


# Color sensing in camera: Color filter array

- In traditional systems, color filters are applied to a single layer of photodetectors in a tiled mosaic pattern.



Why more green?

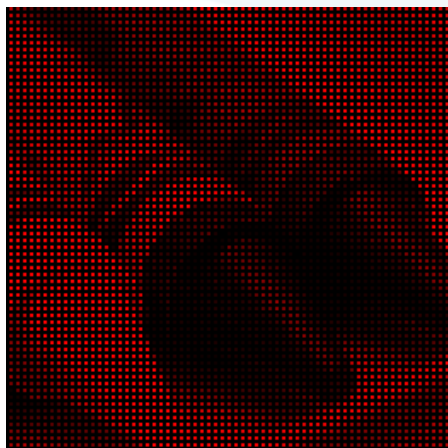


Human Luminance Sensitivity Function

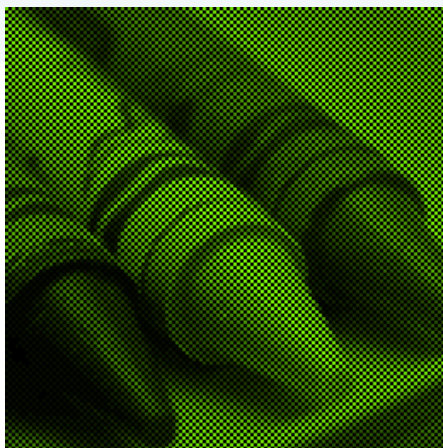


جامعة  
المنارة

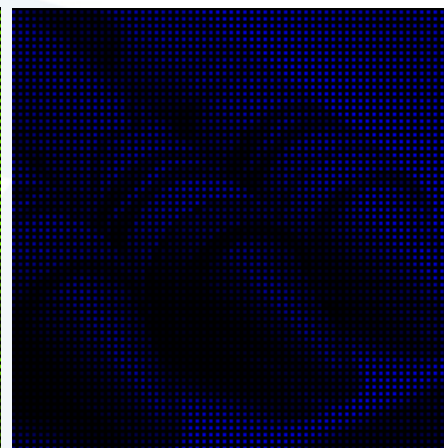
# Color sensing in camera: Color filter array



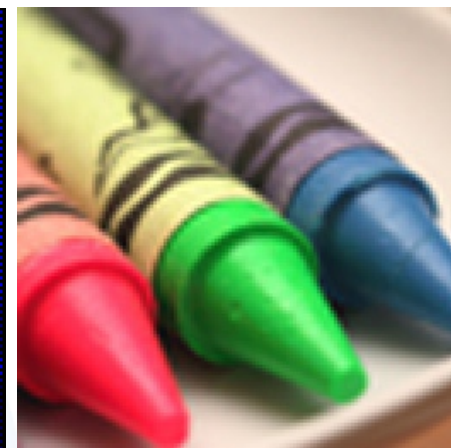
red



green



blue



output

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

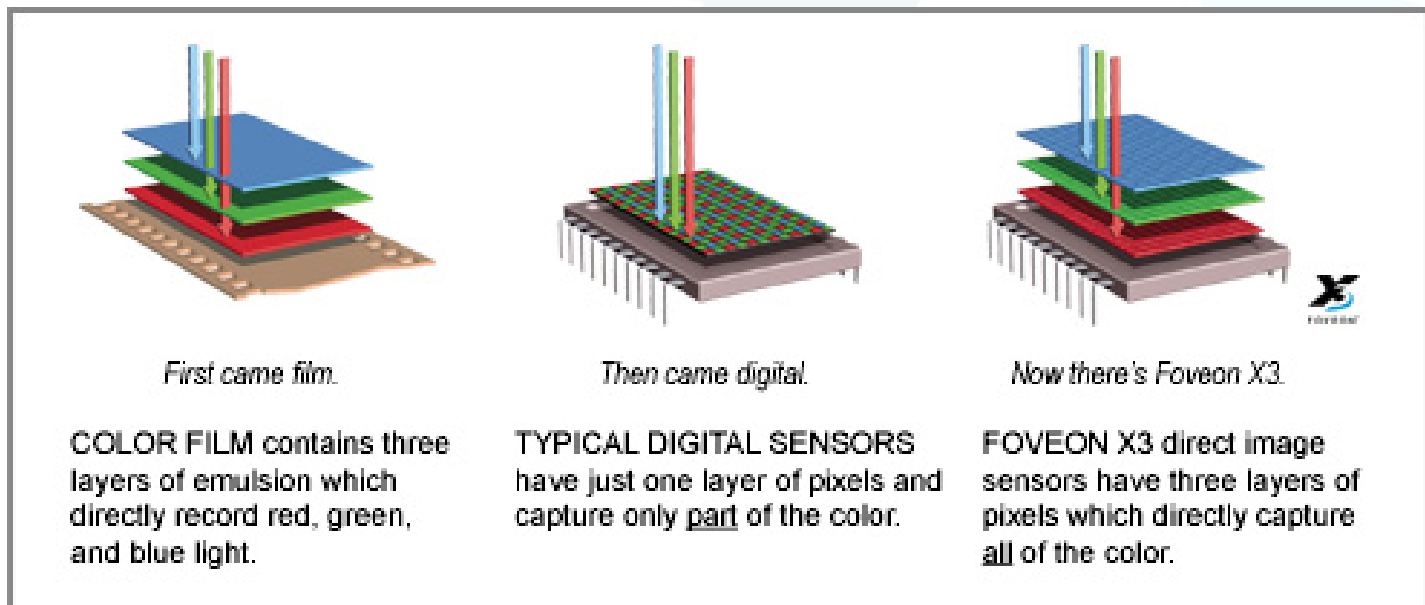
demosaicing  
(interpolation)



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

# Color sensing in camera: Foveon X3

- CMOS sensor; takes advantage of the fact that red, blue and green light pass through silicon to different depths.



<http://www.foveon.com/article.php?a=67>

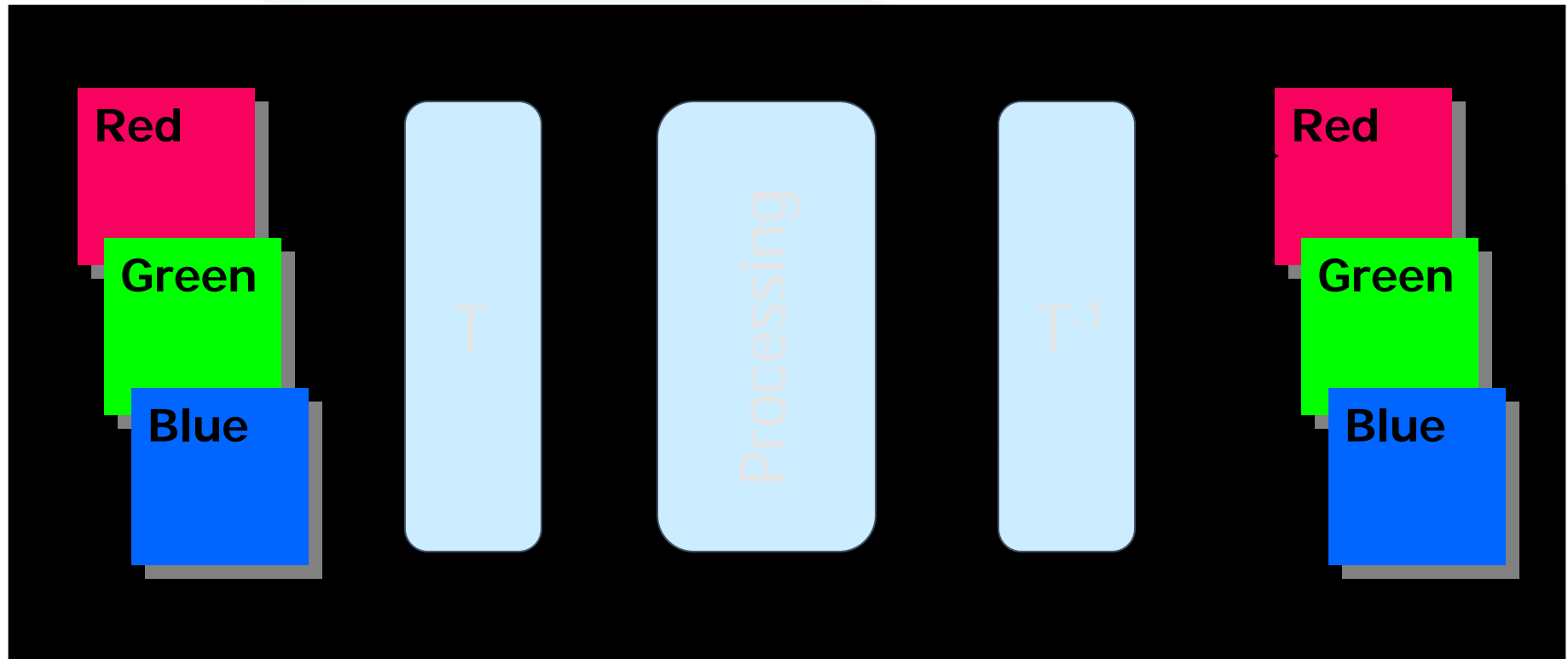
# Alternative Color Spaces

- Various other color representations can be computed from RGB.
- This can be done for:
  - Decorrelating the color channels:
    - principal components.
  - Bringing color information to the fore:
    - Hue, saturation and brightness.
  - Perceptual uniformity:
    - CIE Luv, CIE Lab, ...

# Alternative Color spaces

- RGB (CIE), RnGnBn (TV - National Television Standard Committee)
- XYZ (CIE)
- UVW (UCS de la CIE),  $U^*V^*W^*$  (UCS modified by the CIE)
- YUV, YIQ, YCbCr
- YDbDr
- DSH, HSV, HLS, IHS
- Munsel color space (cylindrical representation)
- CIELuv
- CIELab
- SMPTE-C RGB
- YES (Xerox)
- Kodak Photo CD, YCC, YPbPr, ...

# Processing Strategy



# Color Transformation Examples

$$H = \arccos \frac{\frac{1}{2}((R-G) + (R-B))}{\sqrt{((R-G)^2 + (R-B)(G-B))}}$$

$$S = 1 - 3 \frac{\min(R, G, B)}{R + G + B}$$

$$V = \frac{1}{3}(R + G + B)$$

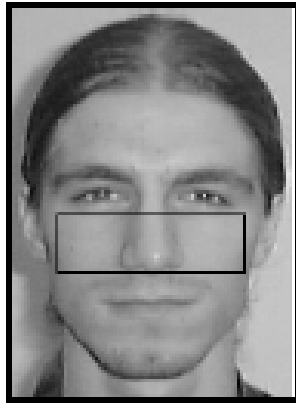
$$Y = 0.299R + 0.587G + 0.114B$$

$$C_r = R - Y$$

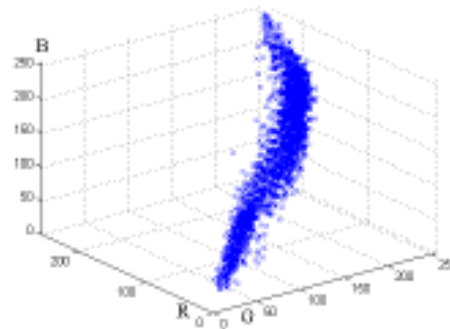
$$C_b = B - Y$$



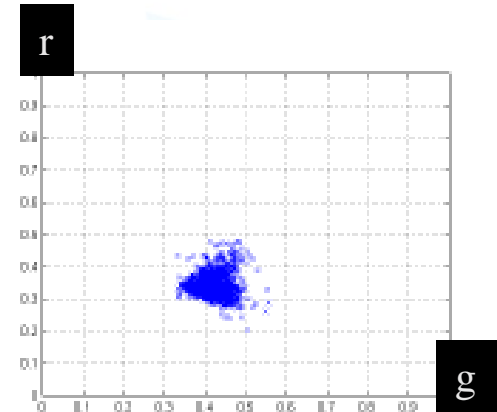
# Skin color



RGB

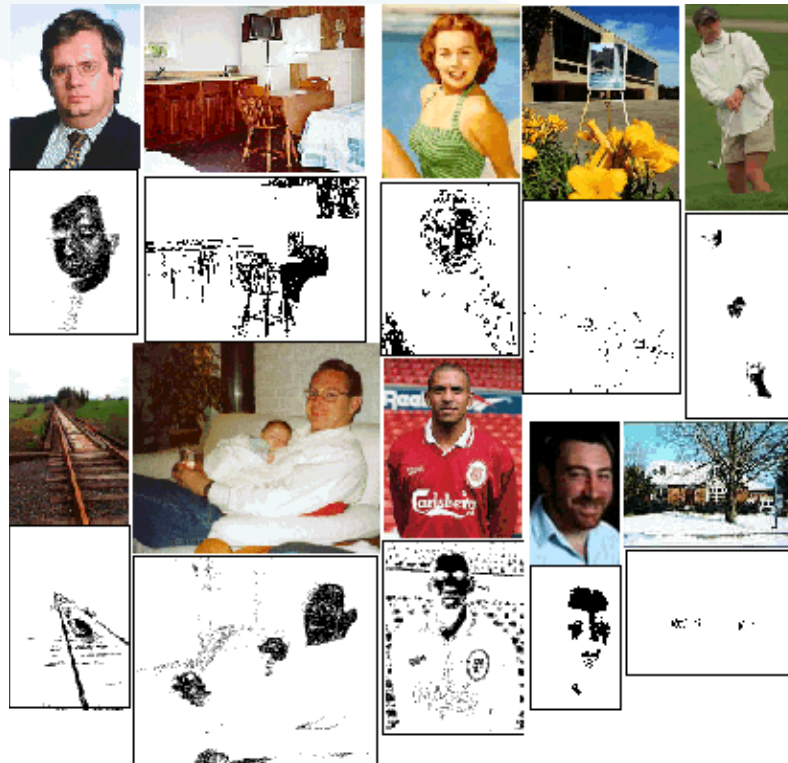


rg



$$r = \frac{R}{R+G+B} \quad g = \frac{G}{R+G+B} \quad b = \frac{B}{R+G+B}$$

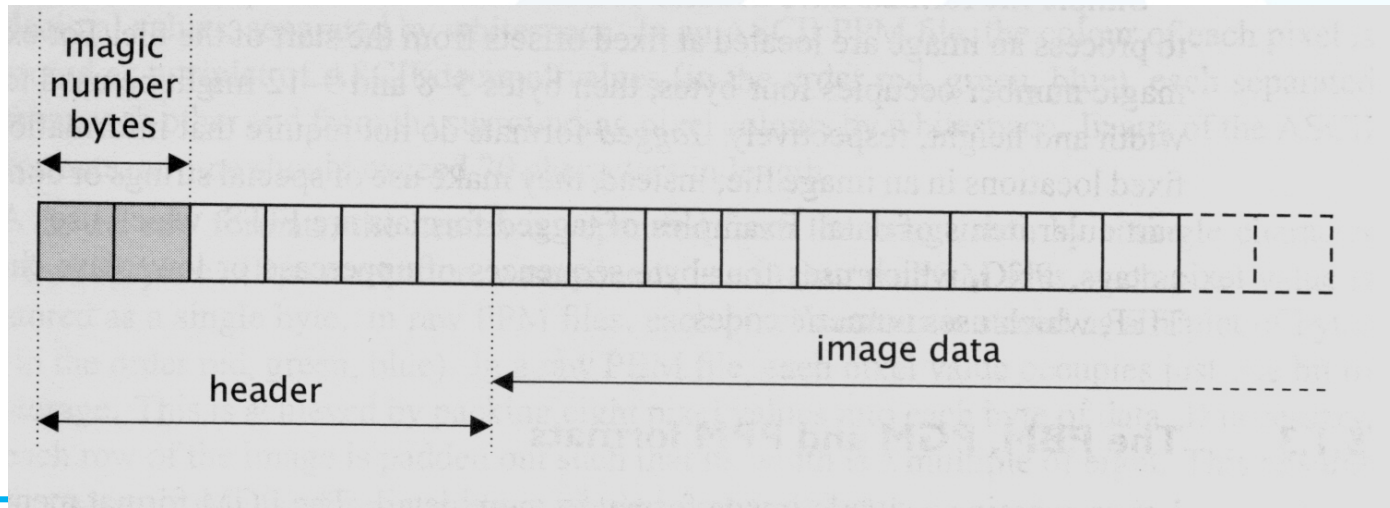
# Skin detection



M. Jones and J. Rehg, [Statistical Color Models with Application to Skin Detection](#), International Journal of Computer Vision, 2002.  
<https://mansoura.edu.sy/>

# Image file formats

- Many image formats adhere to the simple model shown below (line by line, no breaks between lines).
- The header contains at least the width and height of the image.
- Most headers begin with a **signature** or “magic number” (i.e., a short sequence of bytes for identifying the file format)



# Common image file formats

- GIF (Graphic Interchange Format) -
- PNG (Portable Network Graphics)
- JPEG (Joint Photographic Experts Group)
- TIFF (Tagged Image File Format)
- PGM (Portable Gray Map)
- FITS (Flexible Image Transport System)

# PBM/PGM/PPM format

- A popular format for grayscale images (8 bits/pixel)
- Closely-related formats are:
  - PBM (Portable Bitmap), for binary images (1 bit/pixel)
  - PPM (Portable Pixmap), for color images (24 bits/pixel)

ASCII or binary (raw) storage

ASCII

```
P2
# a simple PGM image
7 7 255
120 120 120 120 120 120 120
120 120 120 33 120 120 120
120 120 120 33 120 120 120
120 33 33 33 33 33 120
120 120 120 33 120 120 120
120 120 120 33 120 120 120
120 120 120 120 120 120 120
```

Binary

```
P5
# a simple PGM image
7 7 255
xxxxxxxxxx!xxxxxx!xxxx!!!!xxxx!xxxxxx!xxxxxxxxxx
```

Signatures of the various PBM, PGM and PPM image formats.

Signature	Image type	Storage type
P1	binary	ASCII
P2	greyscale	ASCII
P3	RGB	ASCII
P4	binary	raw bytes
P5	greyscale	raw bytes
P6	RGB	raw bytes