Computational Photography

Instructor: Sanjeev J. Koppal

MWF

1145am-1235pm

BEN 328

Acknowledgements

Some slides from

Narasimhan (Carnegie Mellon),

Zickler (Harvard),

and

Efros (Berkeley)

Assignment updates

What is an image?

We can think of an **image** as a function, *f*, from R^2 to R:

- $f(x, y)$ gives the **intensity** at position (x, y)
- Realistically, we expect the image only to be defined over a rectangle, with a finite range:
  - $f: [a,b] \times [c,d] \rightarrow [0,1]$

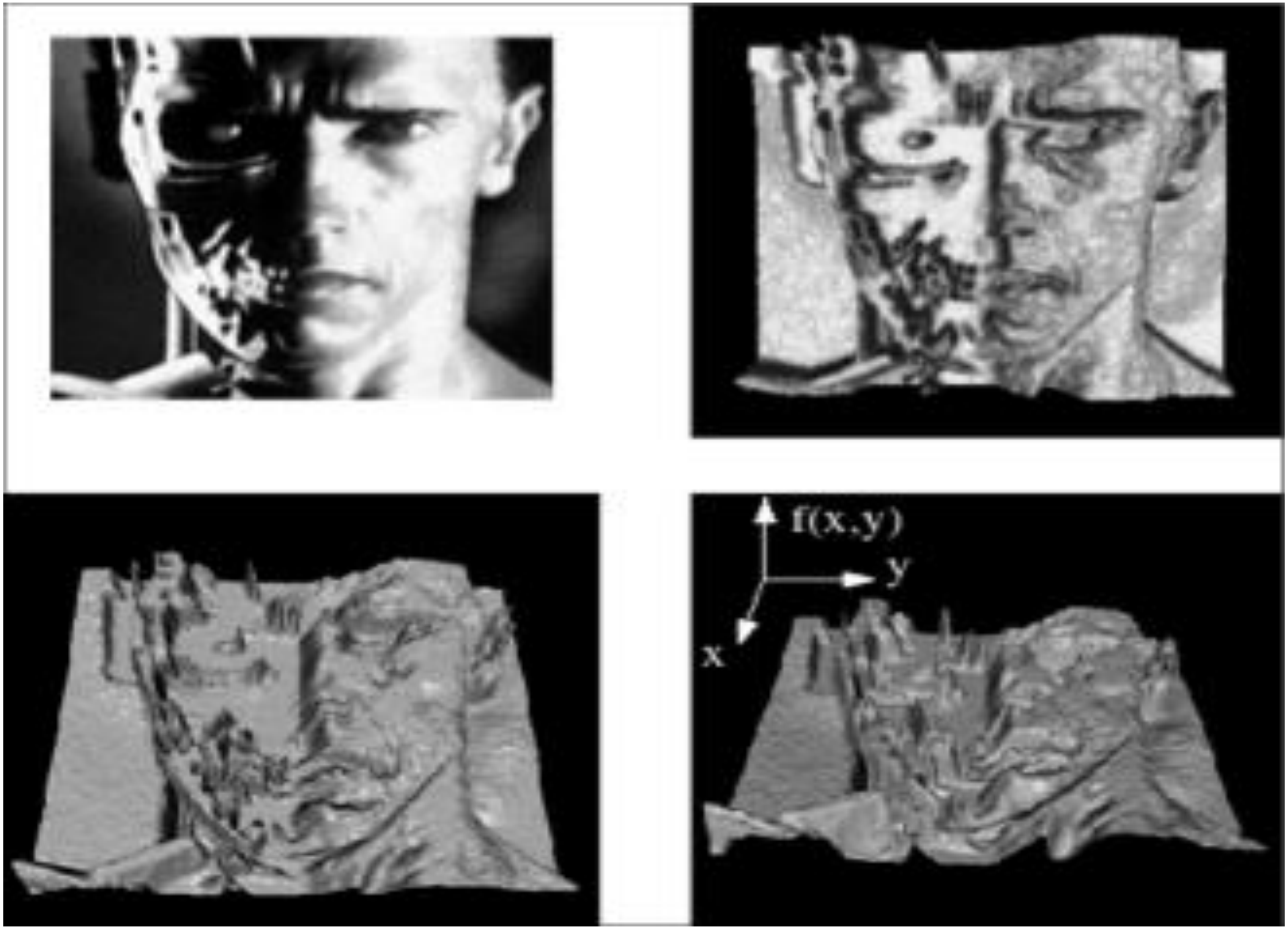
A color image is just three functions pasted together. We can write this as a "vector-valued" function:

$$f(x, y) = \begin{bmatrix} r(x, y) \\ g(x, y) \\ b(x, y) \end{bmatrix}$$

Participation

Can you think of something that would be in a mathematical model for $f(x,y)$?

Images as functions



What is a digital image?

We usually operate on **digital** (**discrete**) images:

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)

If our samples are ⊗ apart, we can write this as:

$f[i\ ,j] = \text{Quantize}\{\ f(i\ \otimes, j\ \otimes)\ \}$

The image can now be represented as a matrix of integer values

$j \longrightarrow$

$i \downarrow$

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

Lesson 1

Images can be treated as functions. Since they are discrete, these discrete functions are represented as matrices.

Image Processing

An **image processing** operation typically defines a new image g in terms of an existing image f.

We can transform either the range of f.

$$g(x, y) = t(f(x, y))$$

Or the domain of *f*:

$$g(x, y) = f(t_x(x, y), t_y(x, y))$$

What kinds of operations can each perform?

Image Processing

image filtering: change ***range*** of image

$$g(x) = h(f(x))$$

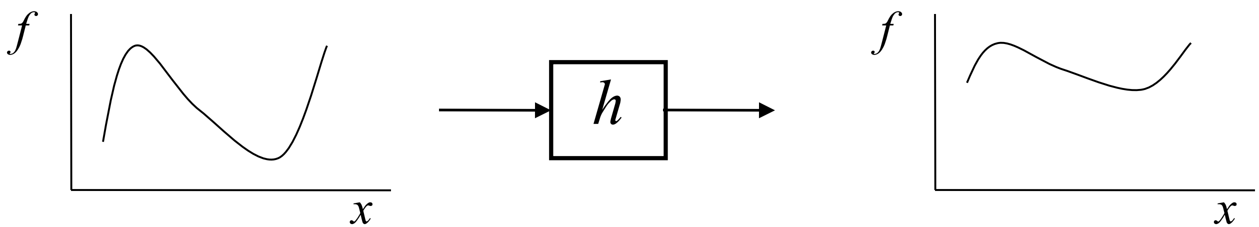


image warping: change ***domain*** of image

$$g(x) = f(h(x))$$

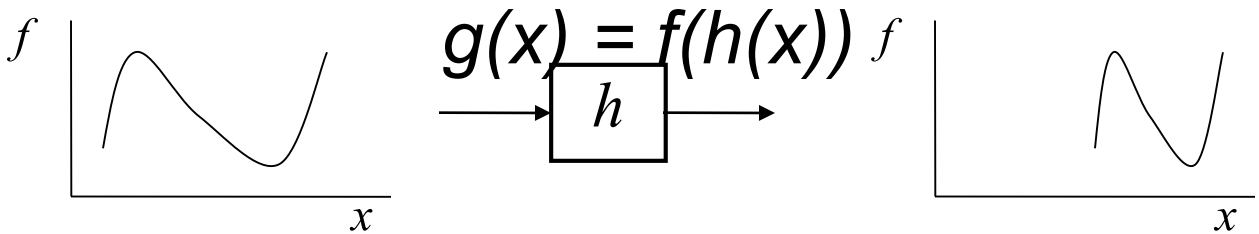
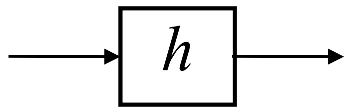


Image Processing

image filtering: change ***range*** of image

$$g(x) = h(f(x))$$

f

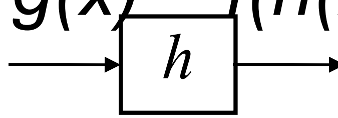


g

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

f

$$g(x) = f(h(x))$$



g

Point Processing

The simplest kind of range transformations are these independent of position x,y:

$$g = t(f)$$

This is called point processing.

What can they do?

What's the form of *t*?

Important: every pixel for himself – spatial information completely lost!

Basic Point Processing

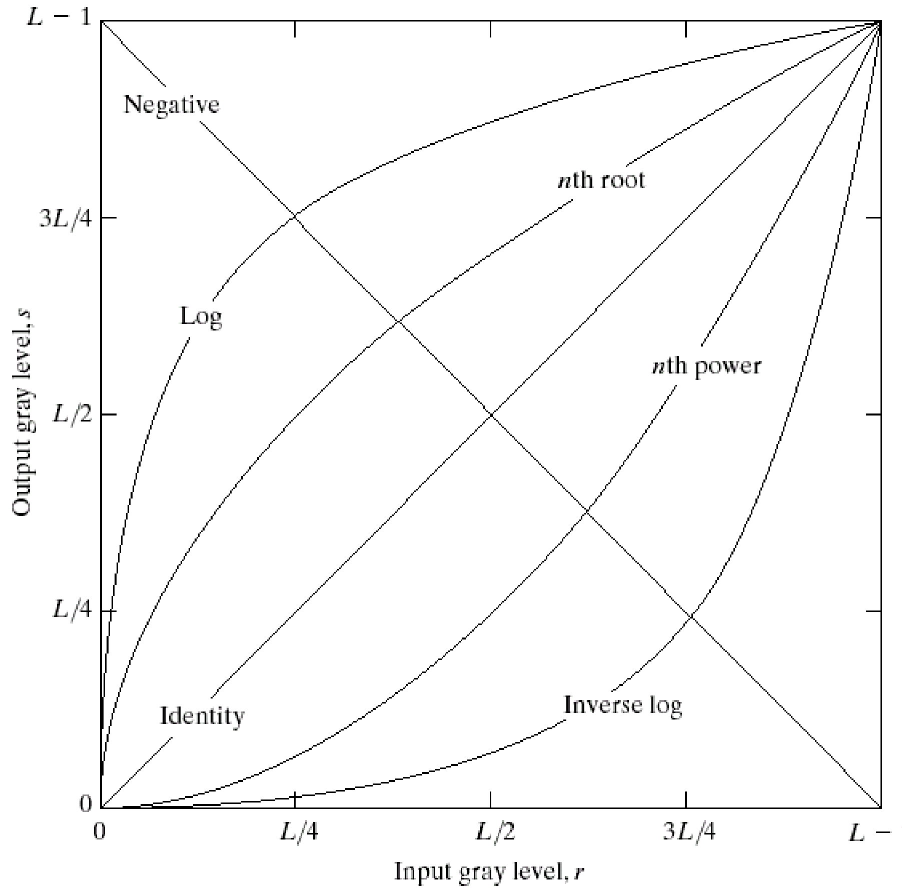


FIGURE 3.3 Some basic gray-level transformation functions used for image enhancement.

Participation

Could there be other curves?

If so, what kinds?

Point processing

Types of point processing

Negative

Log

a b

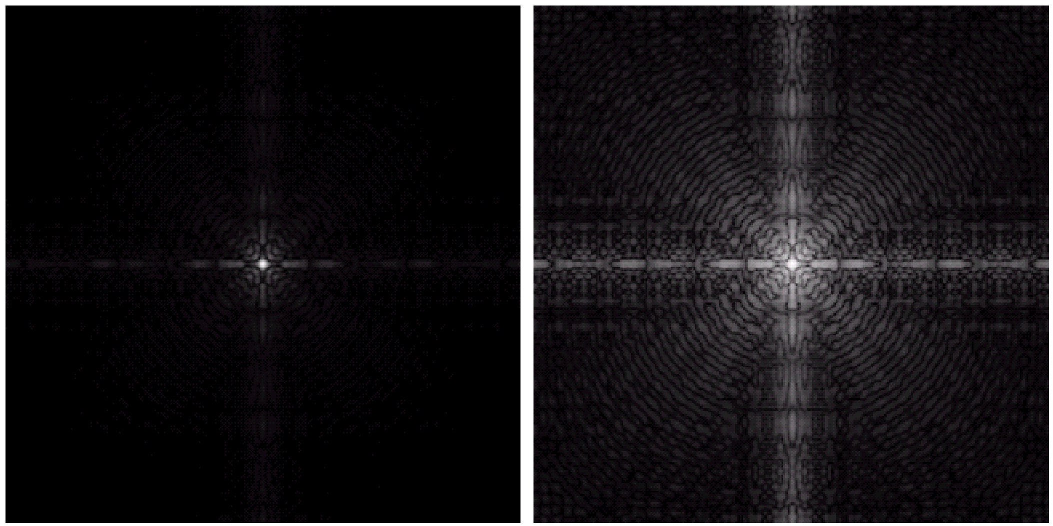


FIGURE 3.5
(a) Fourier spectrum.
(b) Result of applying the log transformation given in Eq. (3.2-2) with $c = 1$.

Power-law transformations

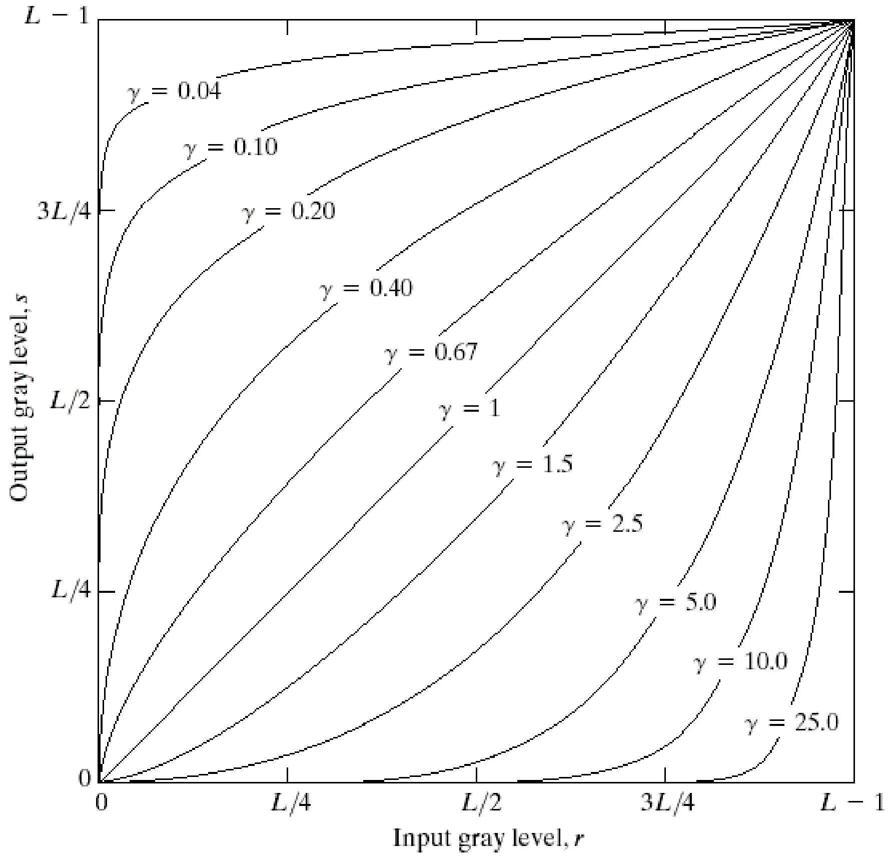


FIGURE 3.6 Plots of the equation $s = cr^{\gamma}$ for various values of γ ($c = 1$ in all cases).

$$s = cr^{\gamma}$$

Image Enhancement

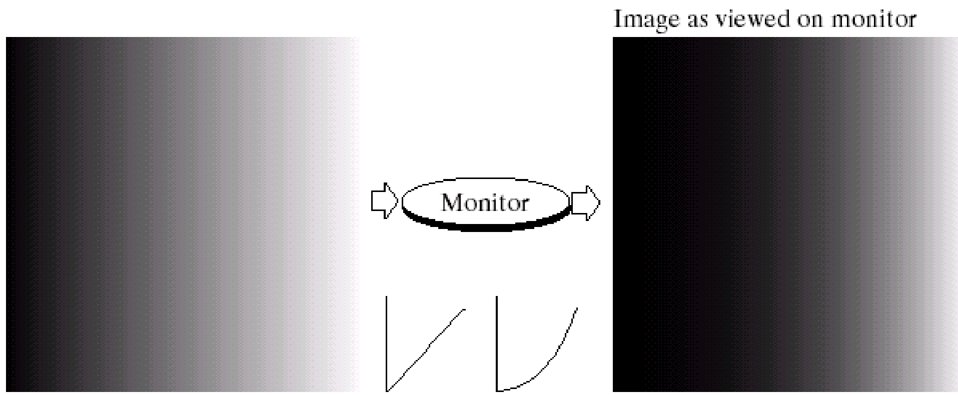
a b
c d

FIGURE 3.9
(a) Aerial image. (b)–(d) Results of applying the transformation in Eq. (3.2-3) with $c = 1$ and $\gamma = 3.0, 4.0$, and 5.0, respectively. (Original image for this example courtesy of NASA.)

Example: Gamma Correction

a b
c d

FIGURE 3.7
(a) Linear-wedge gray-scale image.
(b) Response of monitor to linear wedge.
(c) Gamma-corrected wedge.
(d) Output of monitor.

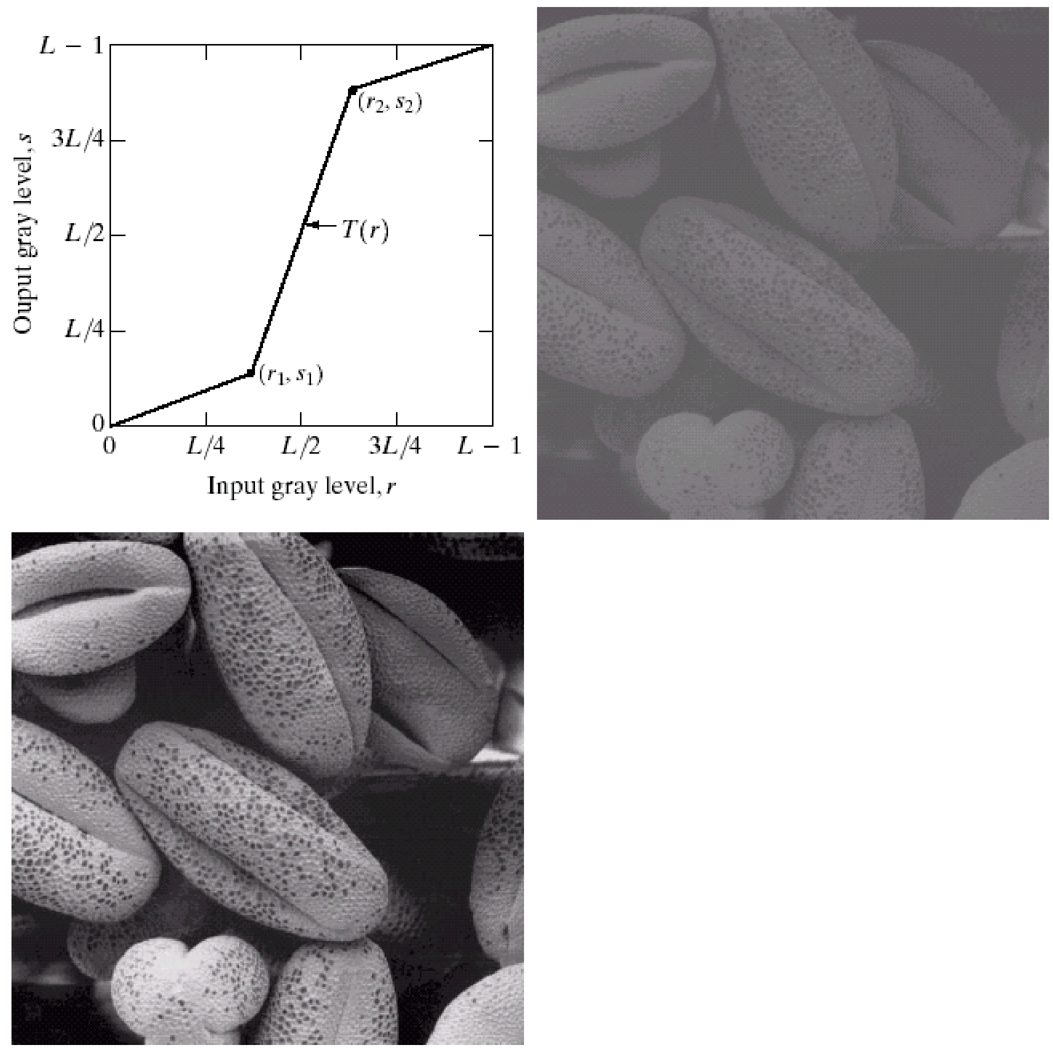


$$s = r^{\gamma}$$

$$e.g. \quad 0.25 = 0.5^{2.0}$$

http://www.cs.berkeley.edu/~efros/java/gamma/gamma.html

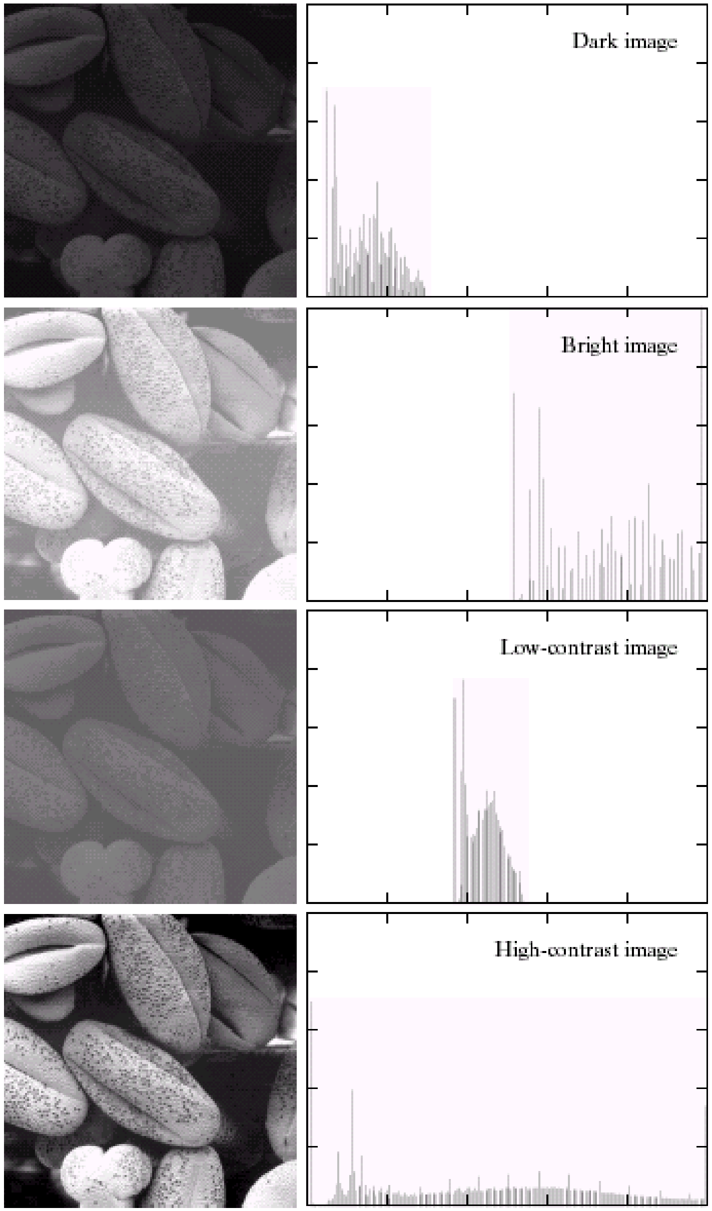
Contrast Stretching

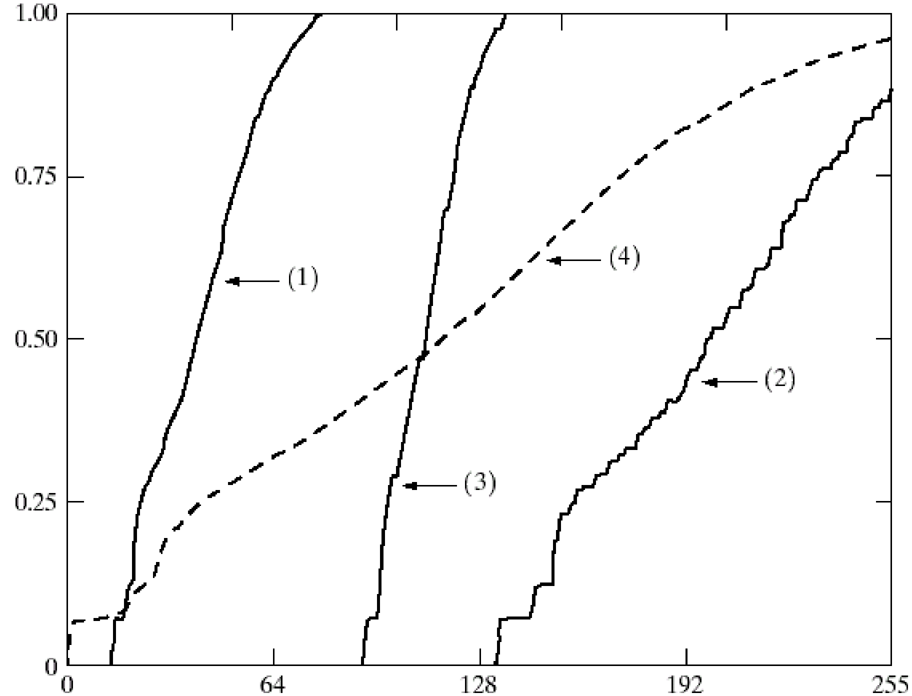


a b
c d

FIGURE 3.10 Contrast stretching. (a) Form of transformation function. (b) A low-contrast image. (c) Result of contrast stretching. (d) Result of thresholding. (Original image courtesy of Dr. Roger Heady, Research School of Biological Sciences, Australian National University, Canberra, Australia.)

Image Histograms





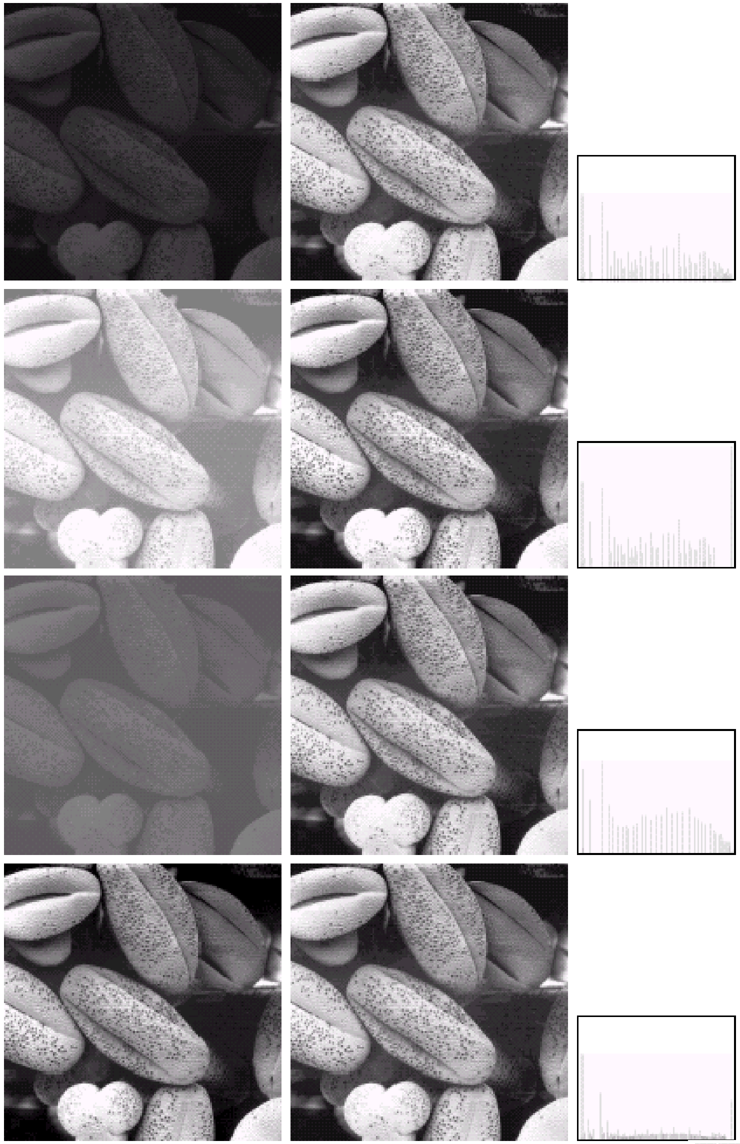
Cumulative Histograms

s = T(r)

a b

FIGURE 3.15 Four basic image types: dark, light, low contrast, high contrast, and their corresponding histograms. (Original image courtesy of Dr. Roger Heady, Research School of Biological Sciences, Australian National University, Canberra, Australia.)

Histogram Equalization

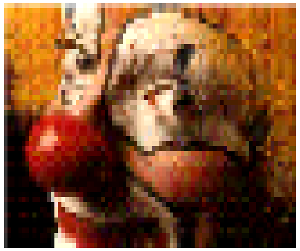


a b c

FIGURE 3.17 (a) Images from Fig. 3.15. (b) Results of histogram equalization. (c) Corresponding histograms.

Neighborhood Processing (filtering)

Q: What happens if I reshuffle all pixels within the image?

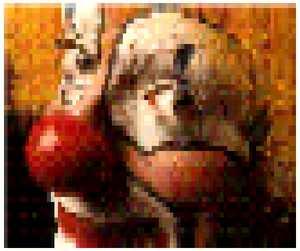


Lesson 2

Always understand if the computation being applied to the image is per pixel, patch-based or global.

Neighborhood Processing (filtering)

- Q: What happens if I reshuffle all pixels within the image?



- A: It’s histogram won’t change. No point processing will be affected…

- Need spatial information to capture this…

Image Filtering

Filtering noise

How can we "smooth" away noise in an image?

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	100	130	110	120	110	0	0
0	0	0	110	90	100	90	100	0	0
0	0	0	130	100	90	130	110	0	0
0	0	0	120	100	130	110	120	0	0
0	0	0	90	110	80	120	100	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Mean filtering

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

Mean filtering

$F[x, y]$

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$G[x, y]$

	0	10	20	30	30	30	20	10	
	0	20	40	60	60	60	40	20	
	0	30	60	90	90	90	60	30	
	0	30	50	80	80	90	60	30	
	0	30	50	80	80	90	60	30	
	0	20	30	50	50	60	40	20	
	10	20	30	30	30	30	20	10	
	10	10	10	0	0	0	0	0	

Cross-correlation filtering

Let's write this down as an equation. Assume the averaging window is (2k+1)x(2k+1):

$$G[i,j] = \frac{1}{(2k+1)^2} \sum_{u=-k}^{k} \sum_{v=-k}^{k} F[i+u, j+v]$$

We can generalize this idea by allowing different weights for different neighboring pixels:

$$G[i,j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u,v] F[i+u, j+v]$$

This is called a **cross-correlation** operation and written:

$$G = H \otimes F$$

H is called the "filter," "kernel," or "mask."

The above allows negative filter indices. When you implement need to use: H[u+k,v+k] instead of H[u,v]

Mean kernel

What’s the kernel for a 3x3 mean filter?

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$F[x, y]$

$H[u, v]$

When can taking an un weighted mean be bad idea?

Gaussian filtering

A Gaussian kernel gives less weight to pixels further from the center of the window

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	90	0	90	90	90	0	0
0	0	0	90	90	90	90	90	0	0
0	0	0	0	0	0	0	0	0	0
0	0	90	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

$F[x, y]$

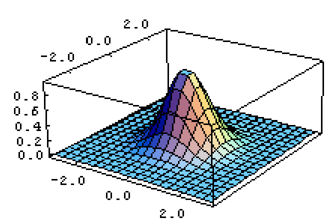
$\frac{1}{16}$

1	2	1
2	4	2
1	2	1

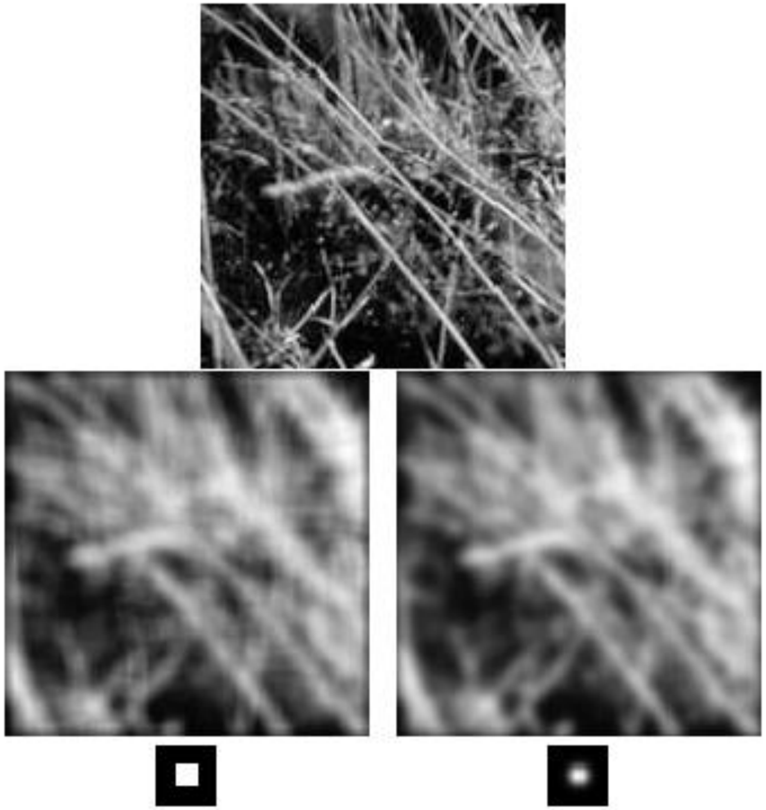
$H[u, v]$

What happens if you increase σ?

$$h(u, v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{\sigma^2}}$$



Mean vs. Gaussian filtering



Fourier transforms and ALL kinds of 2D signal processing is possible on images.

Fourier transforms and ALL kinds of 2D signal processing is possible on images.

For now we will look at how optics can provide some of these image processing functions.

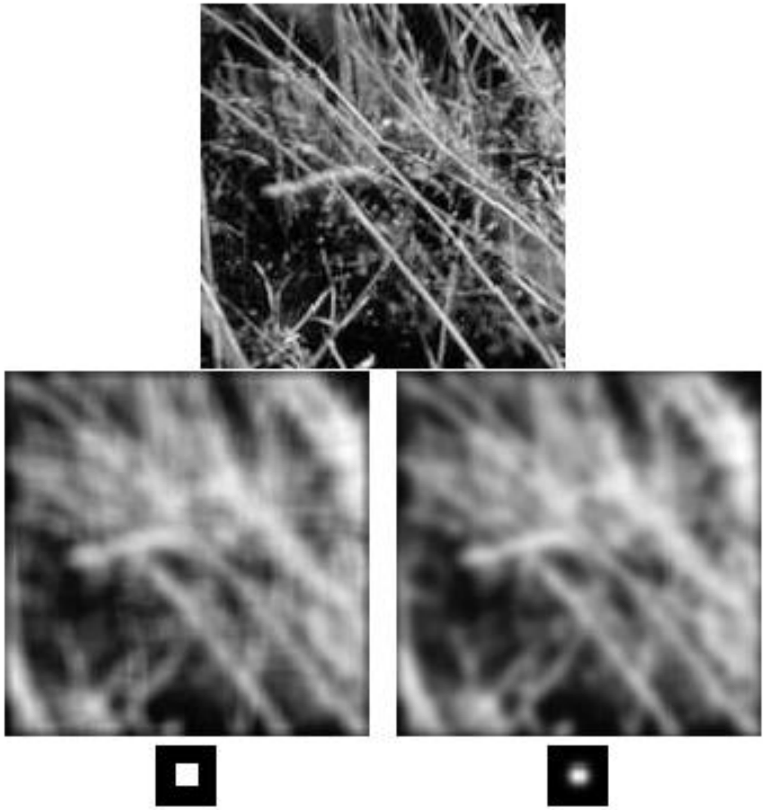
Lenses

Participation

Straightaway, there is one kind of image processing that we can with lenses.

What is it?

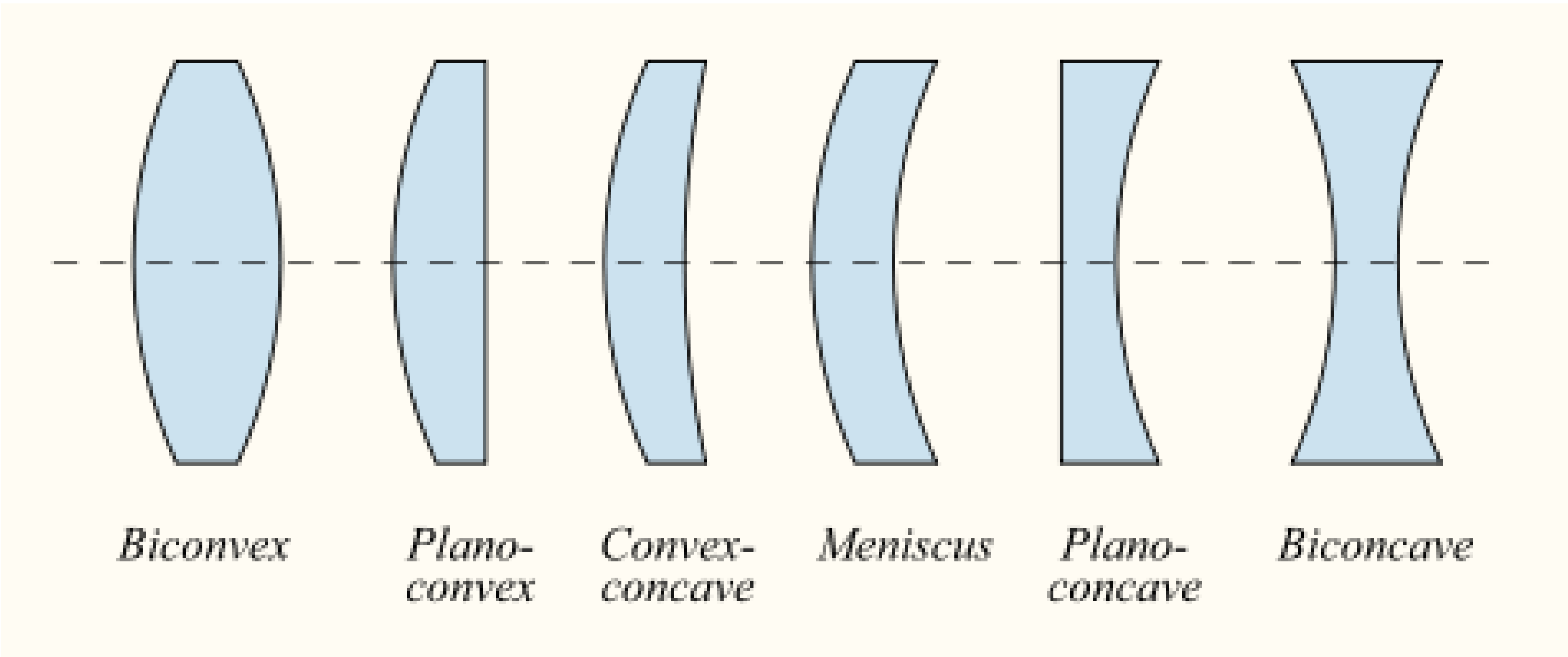
Mean vs. Gaussian filtering



Lesson 3

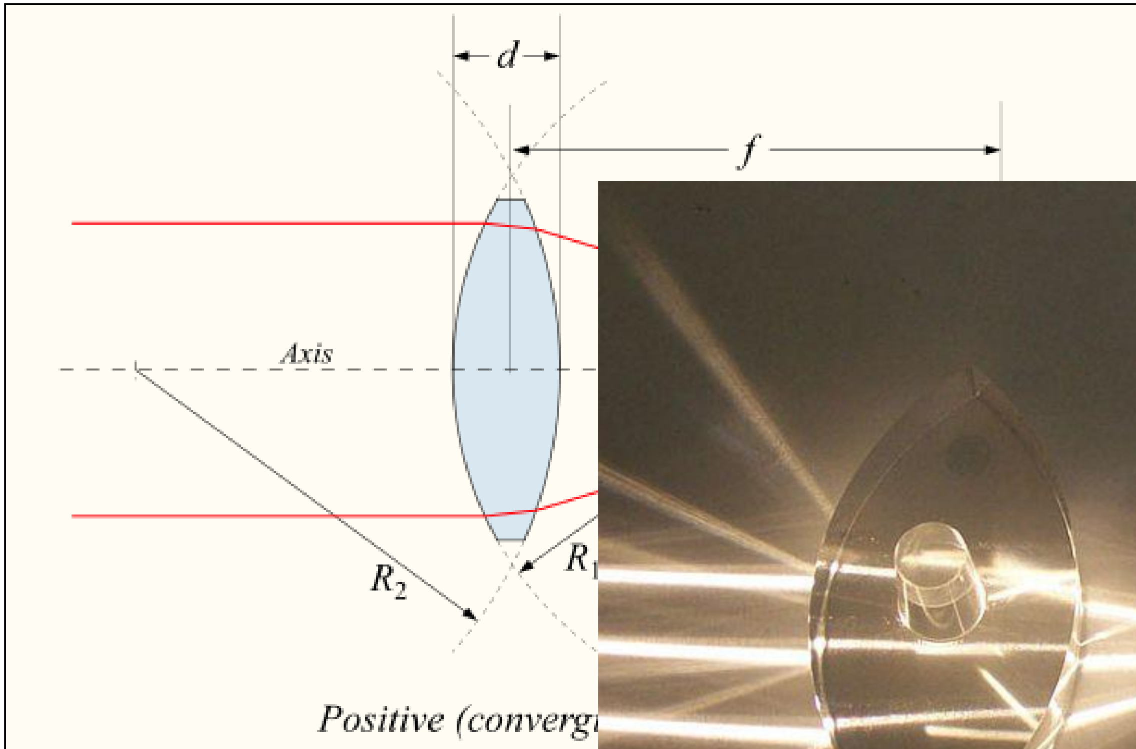
Optics and code can both perform computations on images.

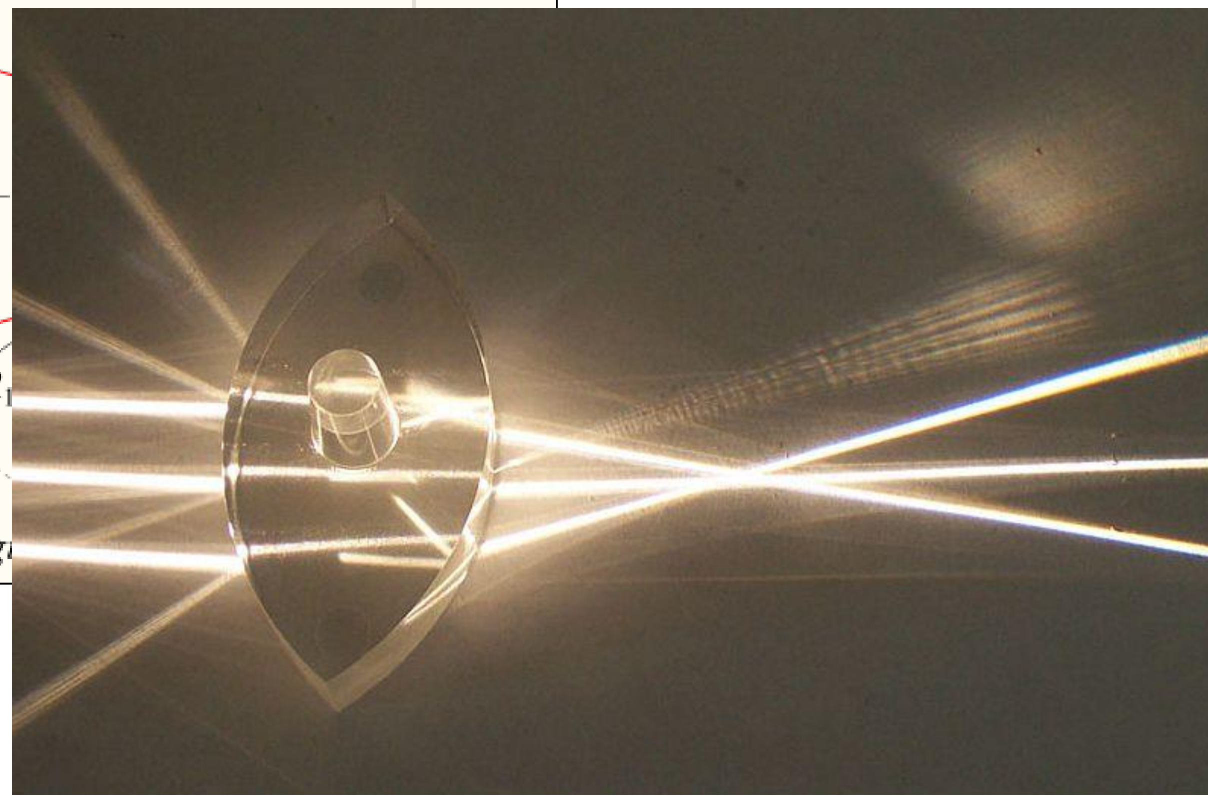
Types of Lenses



[Wikipedia]

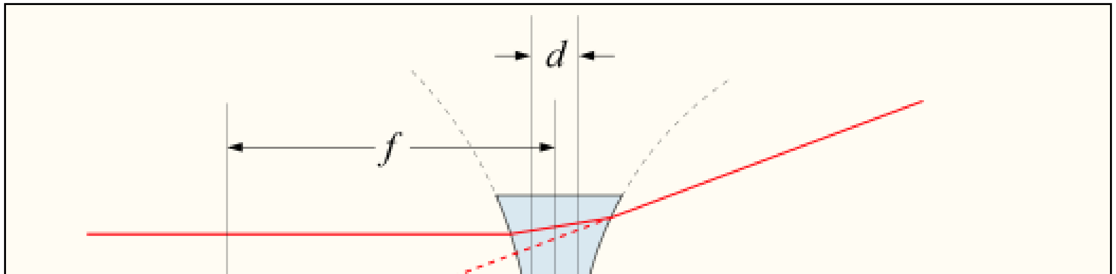
Bi-convex Lens

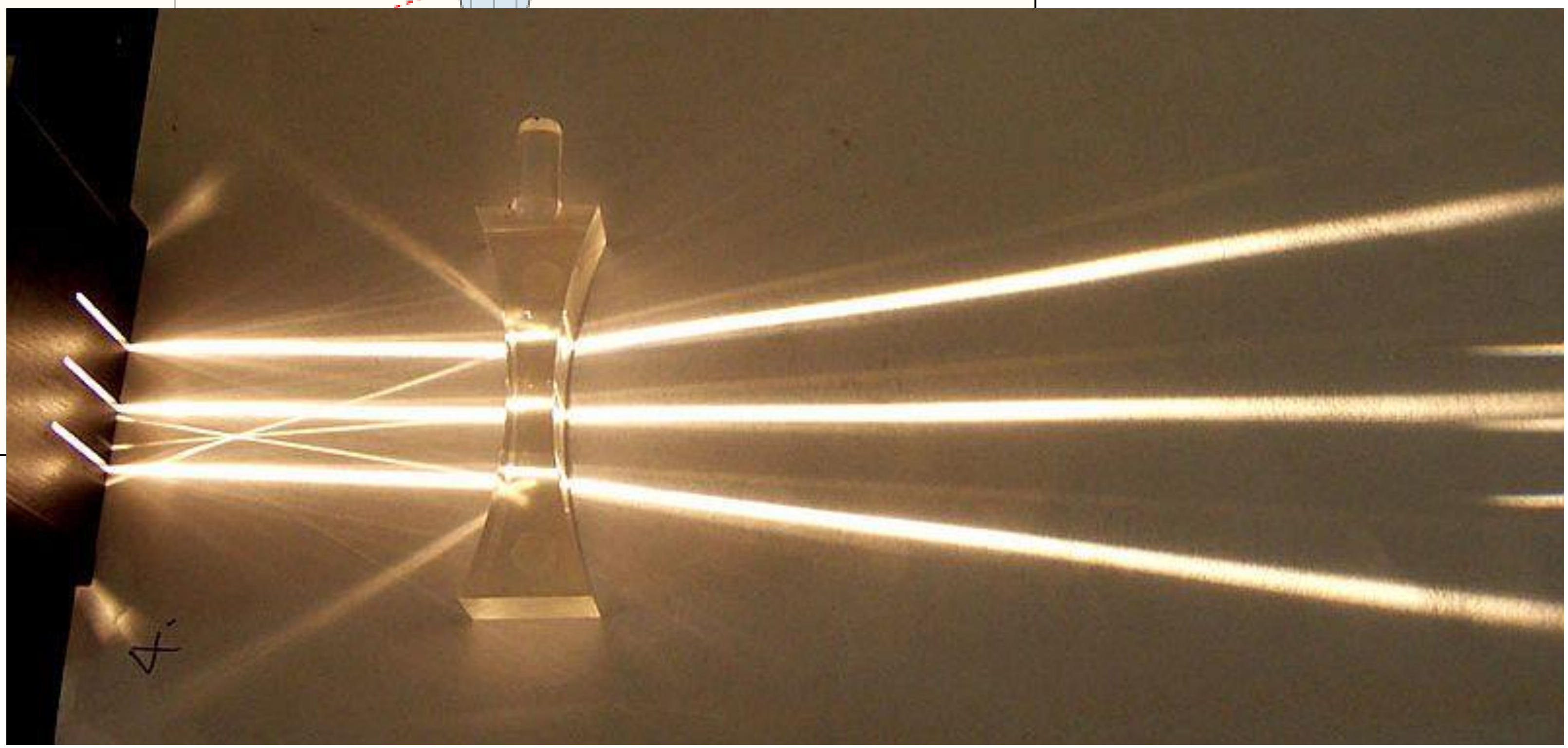




[Wikipedia]

Bi-concave Lens





[Wikipedia]

Lensmaker's Equation

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right],$$

f is the focal length of the lens,

n is the refractive index of the lens material,

R1 is the radius of curvature of the lens surface closest to the light source,

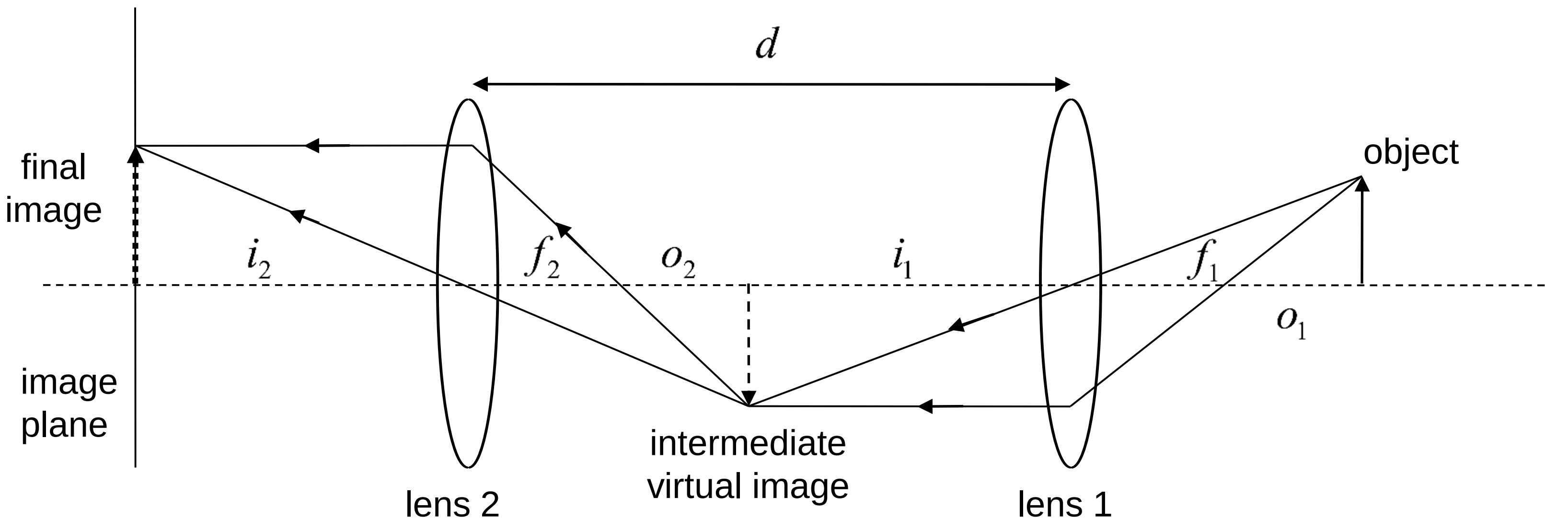
R2 is the radius of curvature of the lens surface farthest from the light source,

d is the thickness of the lens (the distance along the lens axis between the two surface vertices).

Participation

What about plano-convex lenses?

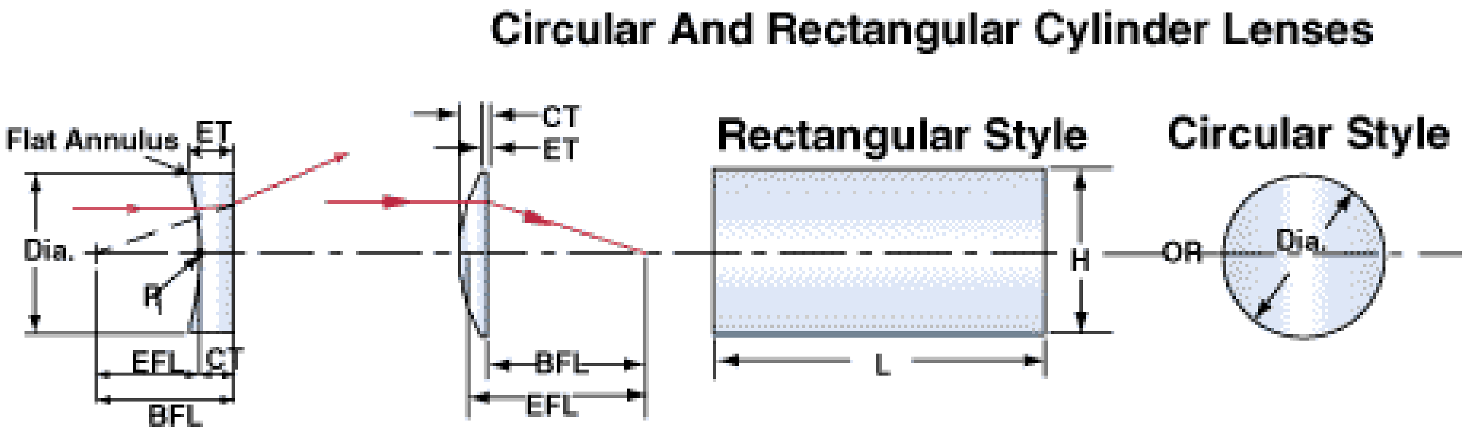
Optics of a Two Lens System

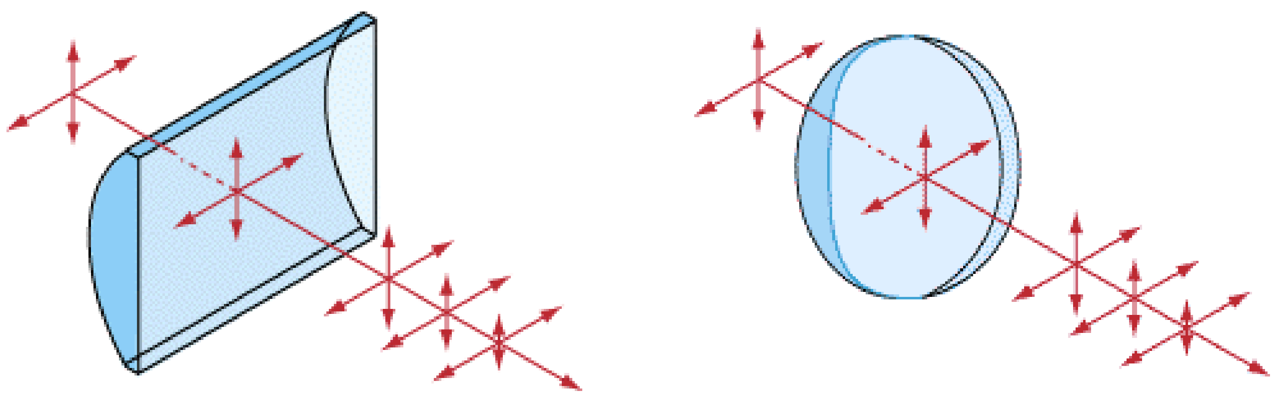


- Rule : Image formed by first lens is the object for the second lens.
- Main Rays : Ray passing through focus emerges parallel to optical axis.
  Ray through optical center passes un-deviated.
- Magnification: $$m = \frac{i_2}{o_2}\frac{i_1}{o_1}$$

Exercises: What is the combined focal length of the system?
What is the combined focal length if d = 0?

Cylindrical Lenses





Participation

What kind of processing can we do with this type of lens?

Image Processing

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

f

$$g(x) = f(h(x))$$

h

g

Suppose we wanted to scale the image?

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

f

$g(x) = f(h(x))$

$\longrightarrow \boxed{h} \longrightarrow$

g

Focusing a Laser beam to a point

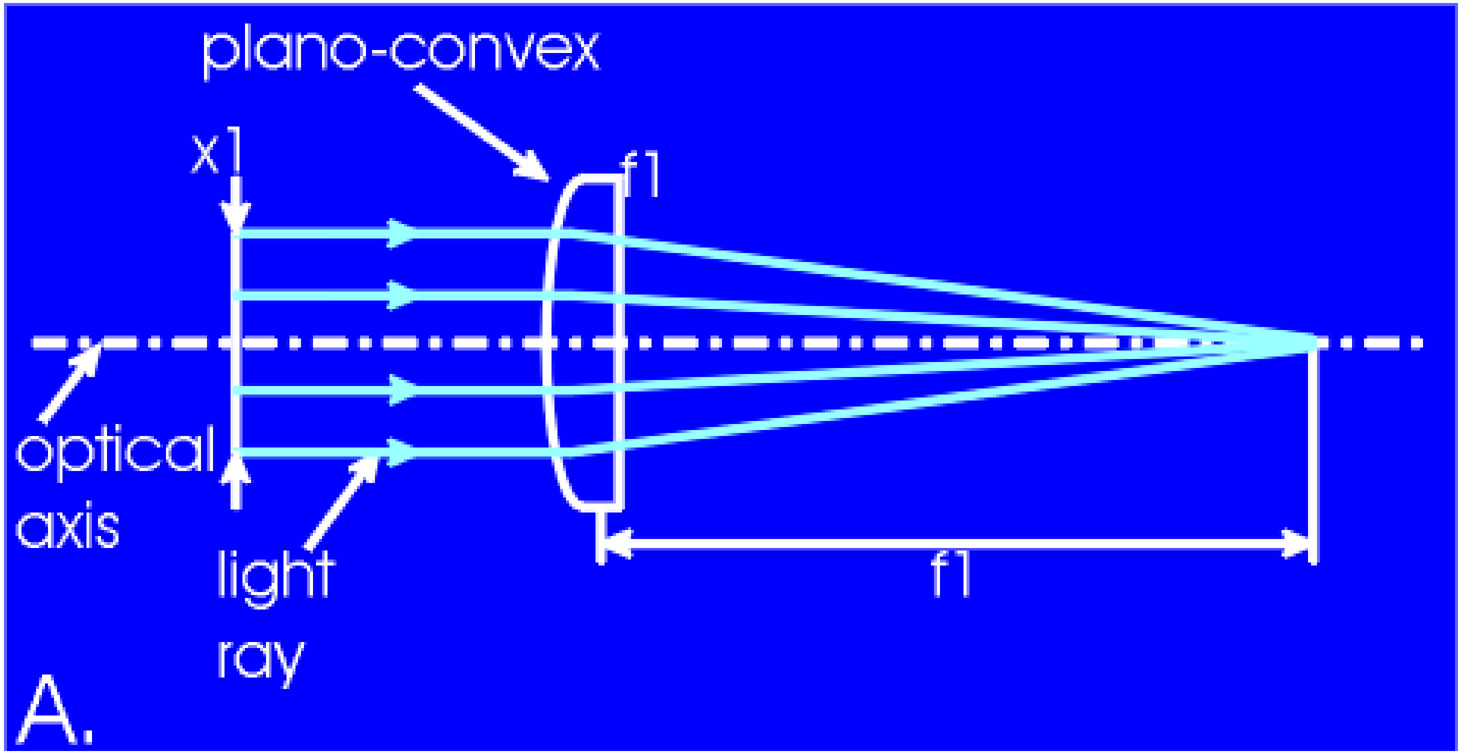


Image Processing

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

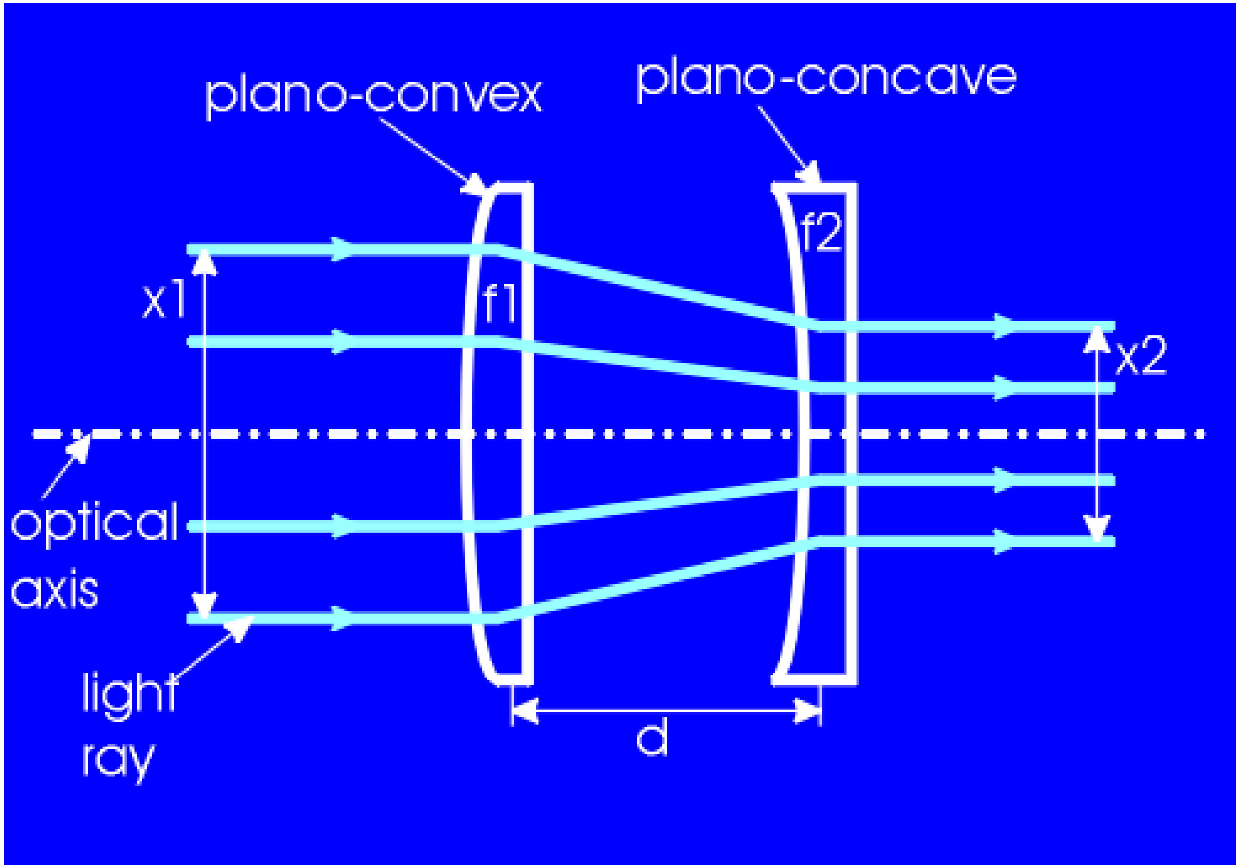
f

$$g(x) = f(h(x))$$

$\xrightarrow{} \boxed{h} \xrightarrow{}$

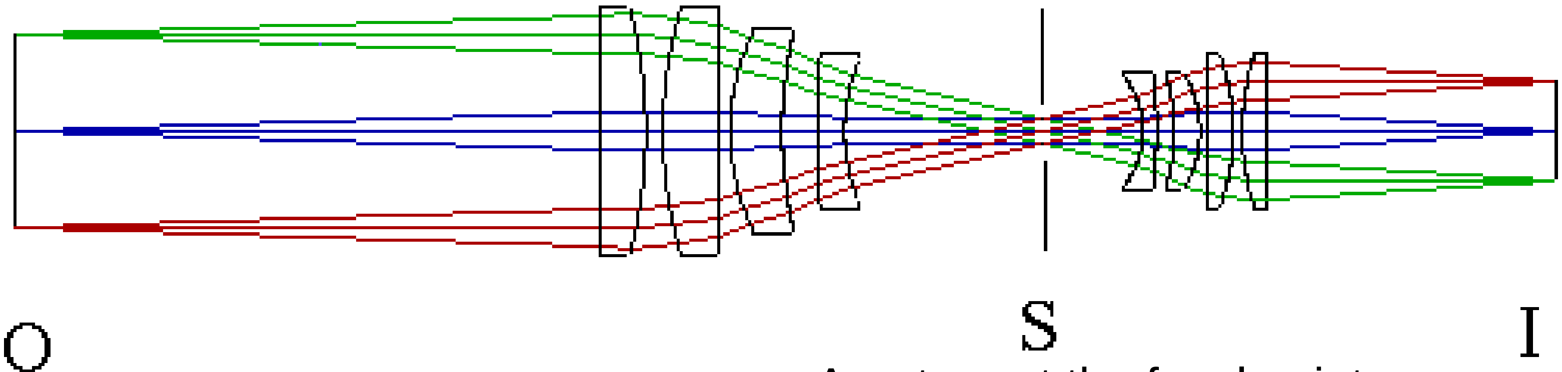
g

Changing Diameter of Collimated Beam



Telecentric Lenses

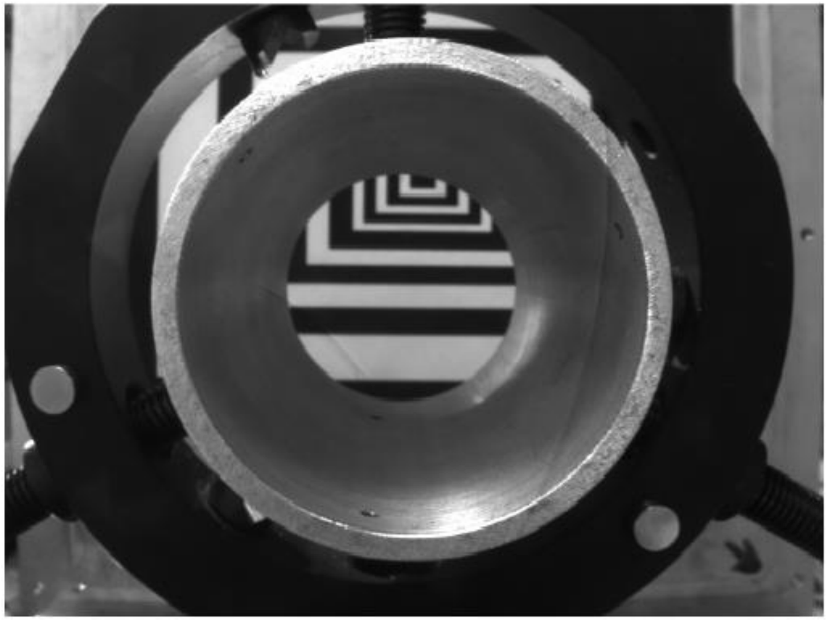
Object-side and Image-side telecentricity:



Aperture at the focal point
of both lens systems

- Sizes of object and image do not change as they are translated.
- However, focus does change as in any lens.

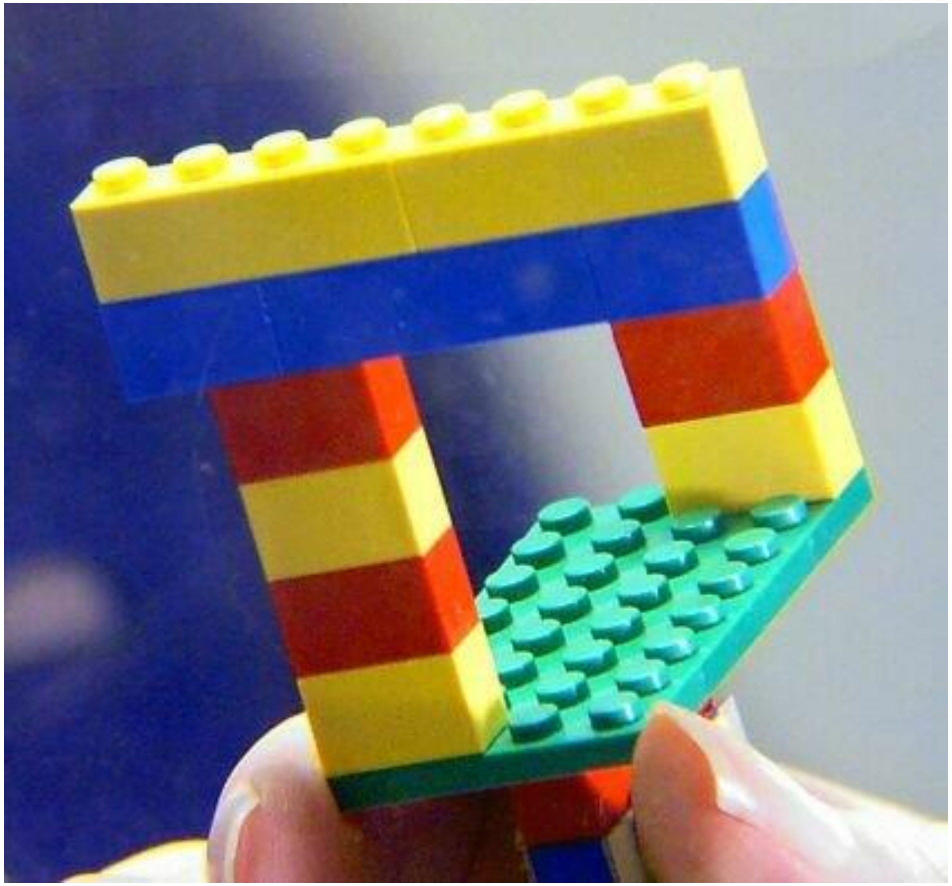
Eliminating Perspective Distortion



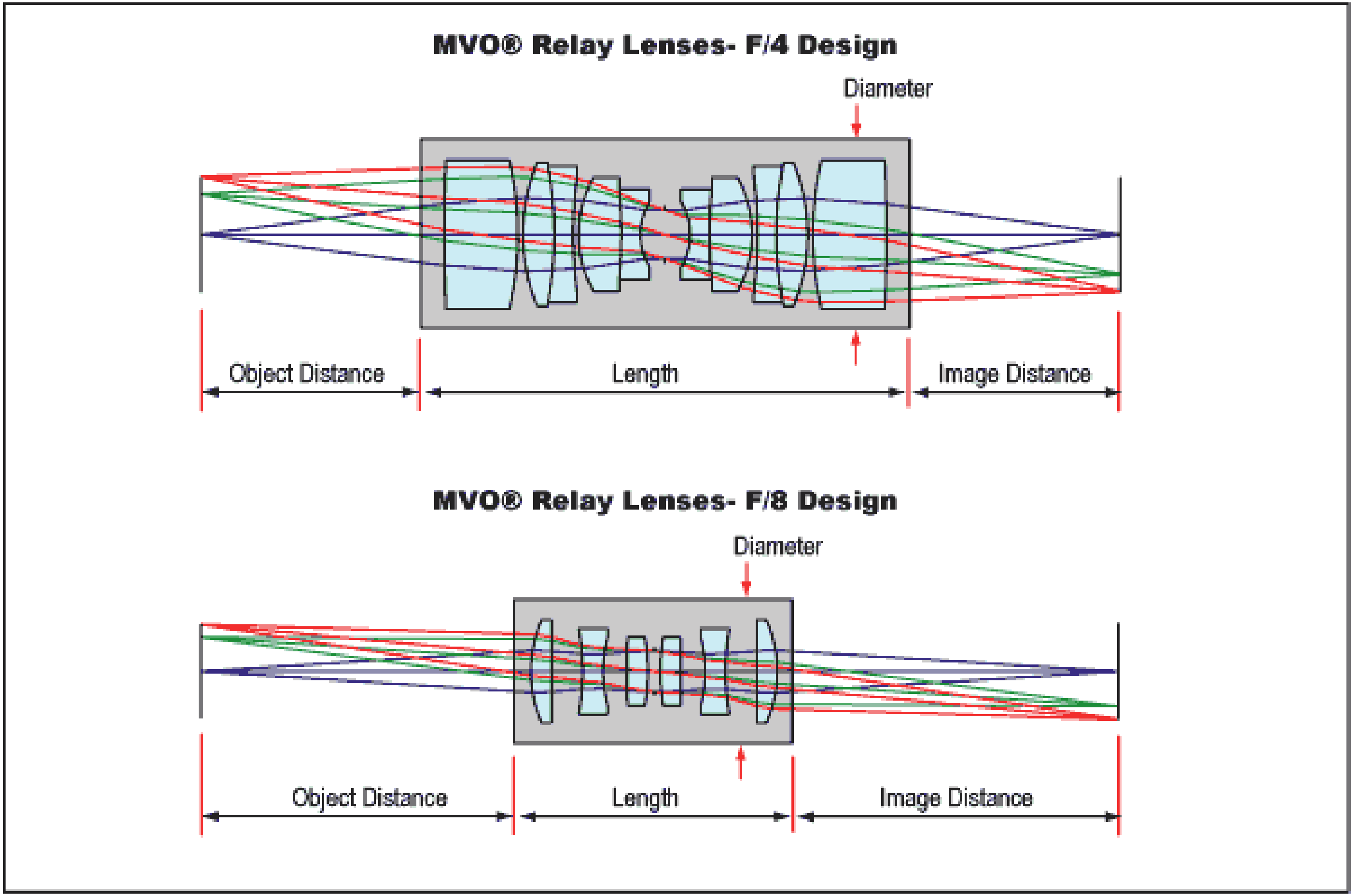
Regular Lens

Telecentric Lens

Illusions with Telecentric Lenses

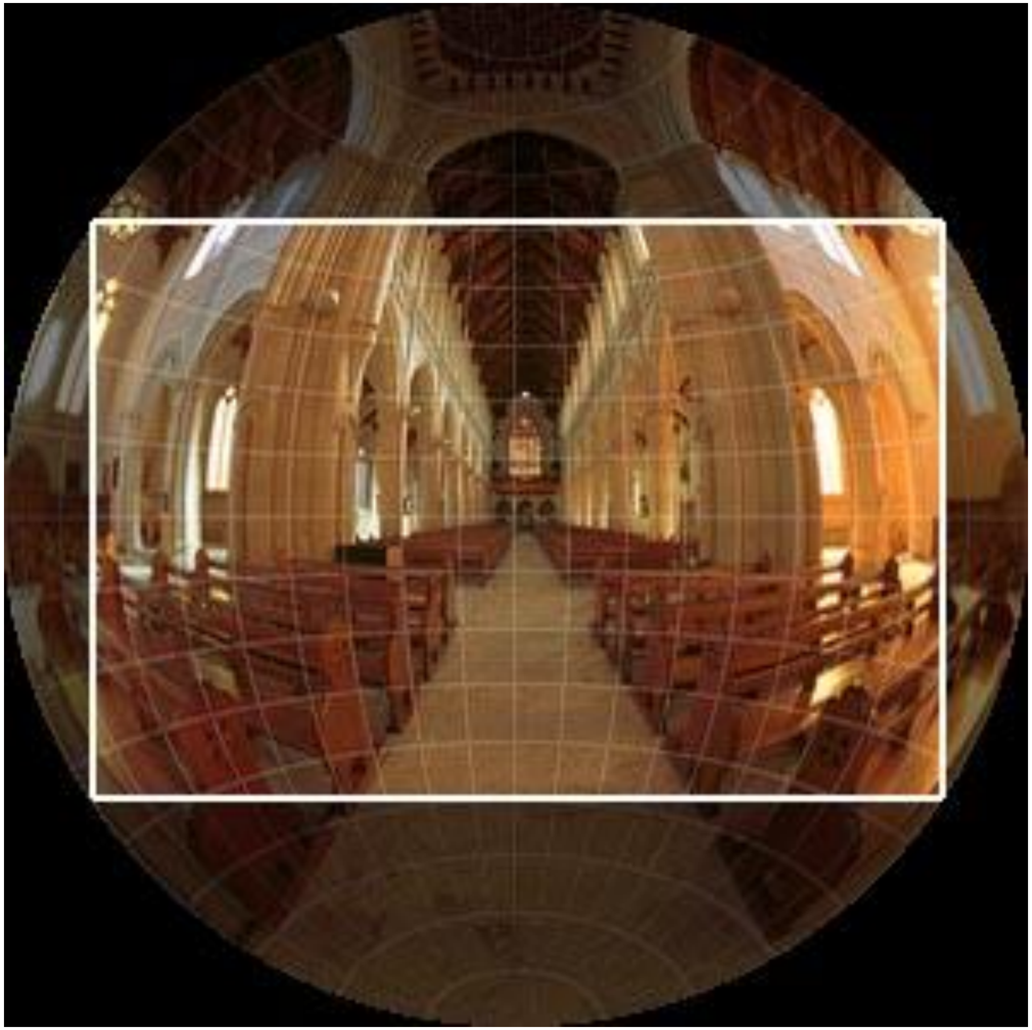


Relay Lenses (1:1 imaging)



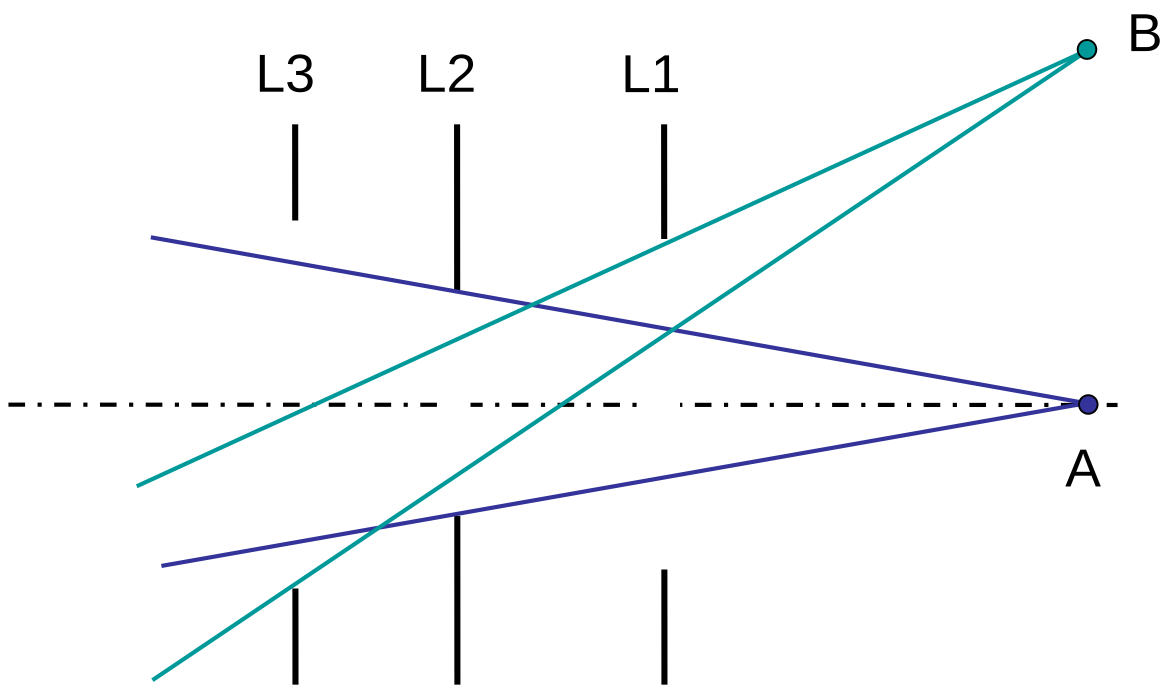
Wide angle Lenses

Circular Fisheye



Full Frame Rectangular Fisheye

Vignetting



More light passes through lens L3 for scene point A than scene point B

Results in spatially non-uniform brightness (in the periphery of the image)

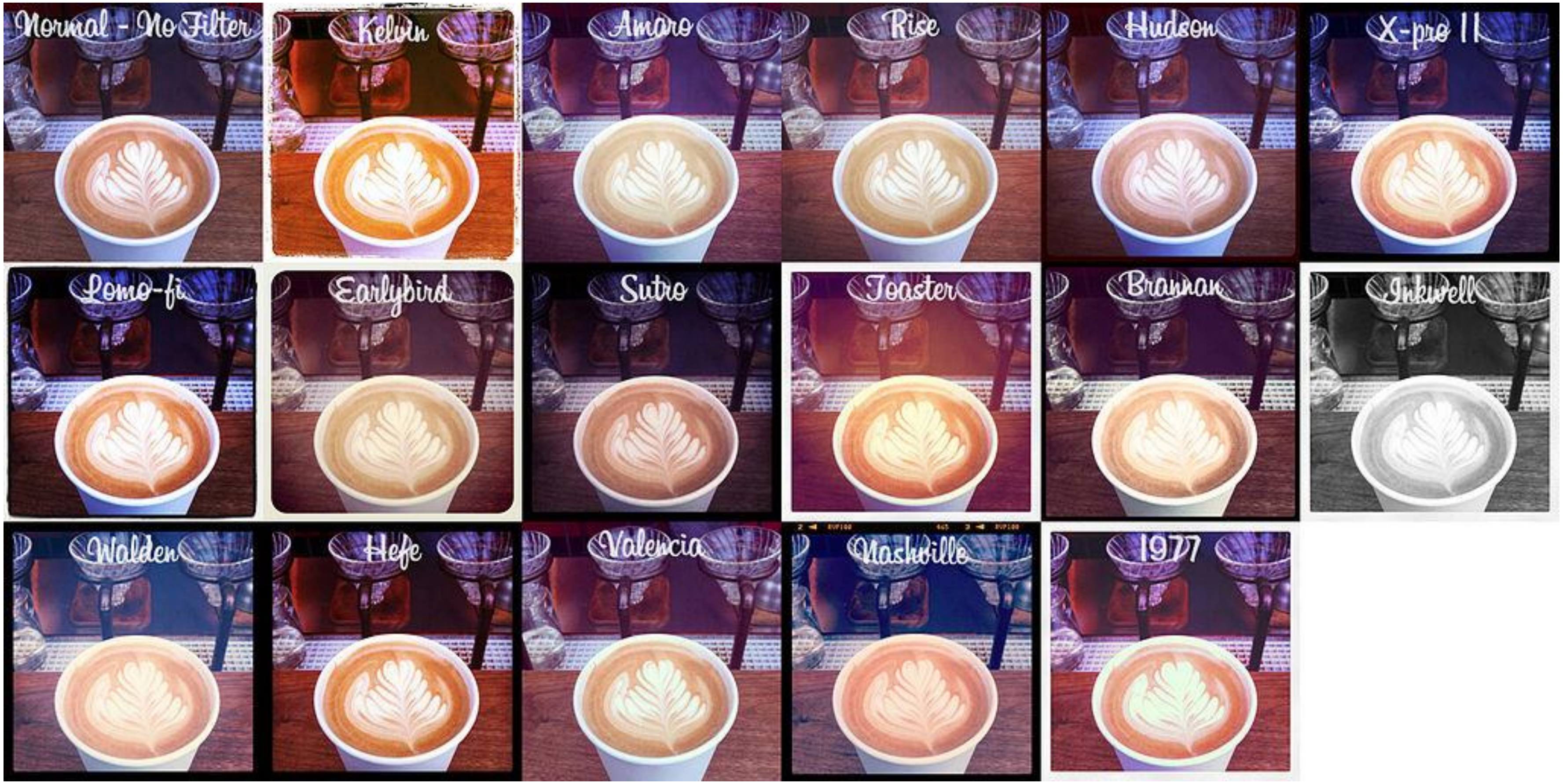
Lens Vignetting

- Usually brighter at the center and darker at the periphery.

Reading: http://www.dpreview.com

Vignetting

photo by Robert Johnes


Normal - No Filter
Kelvin
Amaro
Rise
Hudson
X-pro II
Lomo-fi
Earlybird
Sutro
Toaster
Brannan
Inkwell
Walden
Hefe
Valencia
Nashville
1977

Chromatic Aberrations

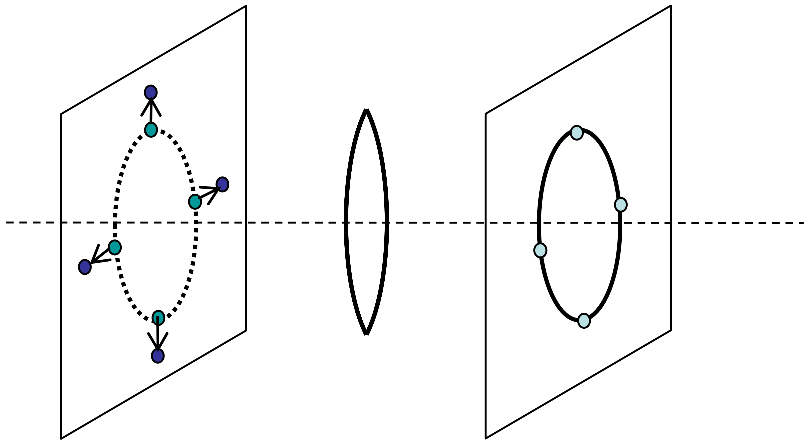
Reading: http://www.dpreview.com

Lens Glare

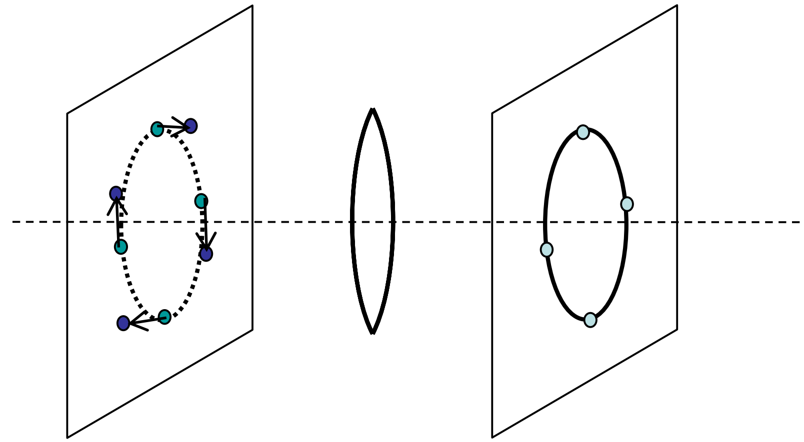
- Stray interreflections of light within the optical lens system.
- Happens when very bright sources are present in the scene.

Reading: http://www.dpreview.com

Geometric Lens Distortions



Radial distortion



Tangential distortion

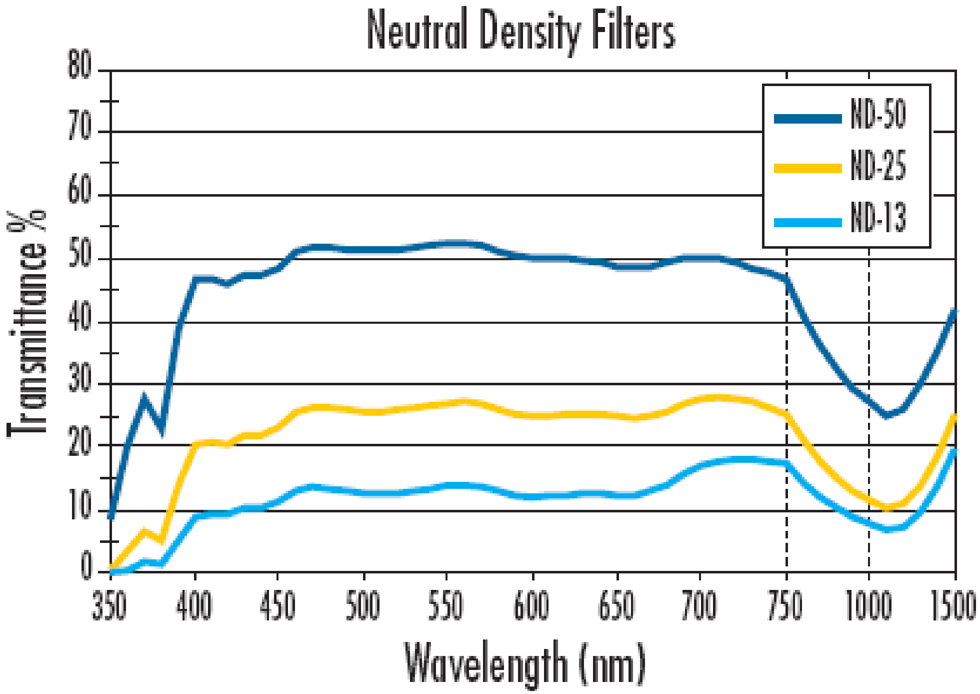
Photo by Helmut Dersch

Both due to lens imperfection

Rectify with geometric camera calibration

Filters

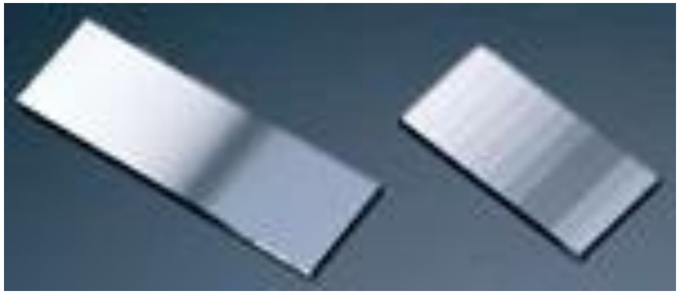
Neutral Density Filters

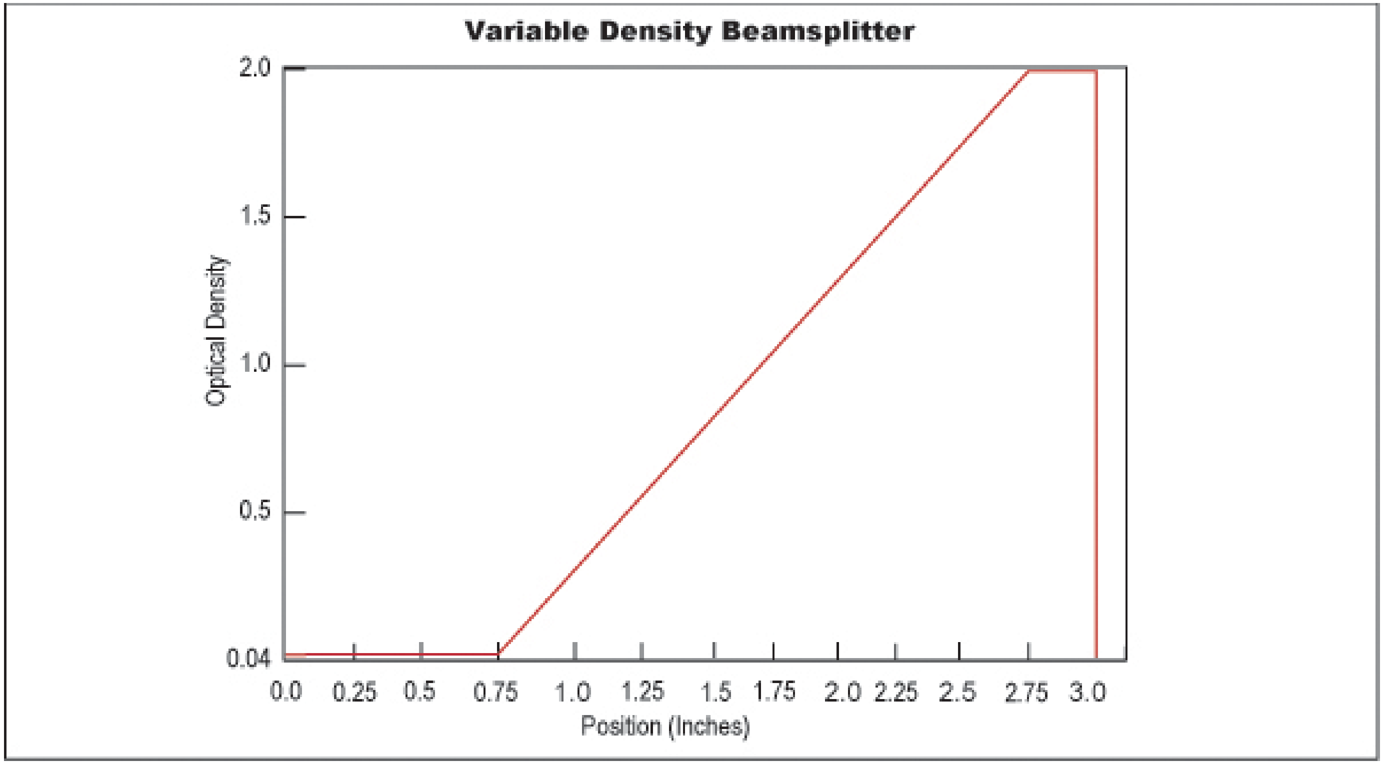


- Spectrally flat from 400-700nm
- Homogeneous Glass: Blocks by absorption or by reflection
- Light/Exposure Control for Imaging

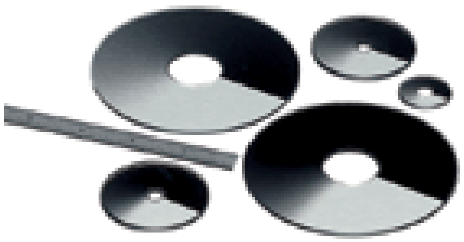
- Transmittance = 10^(-optical density) * 100

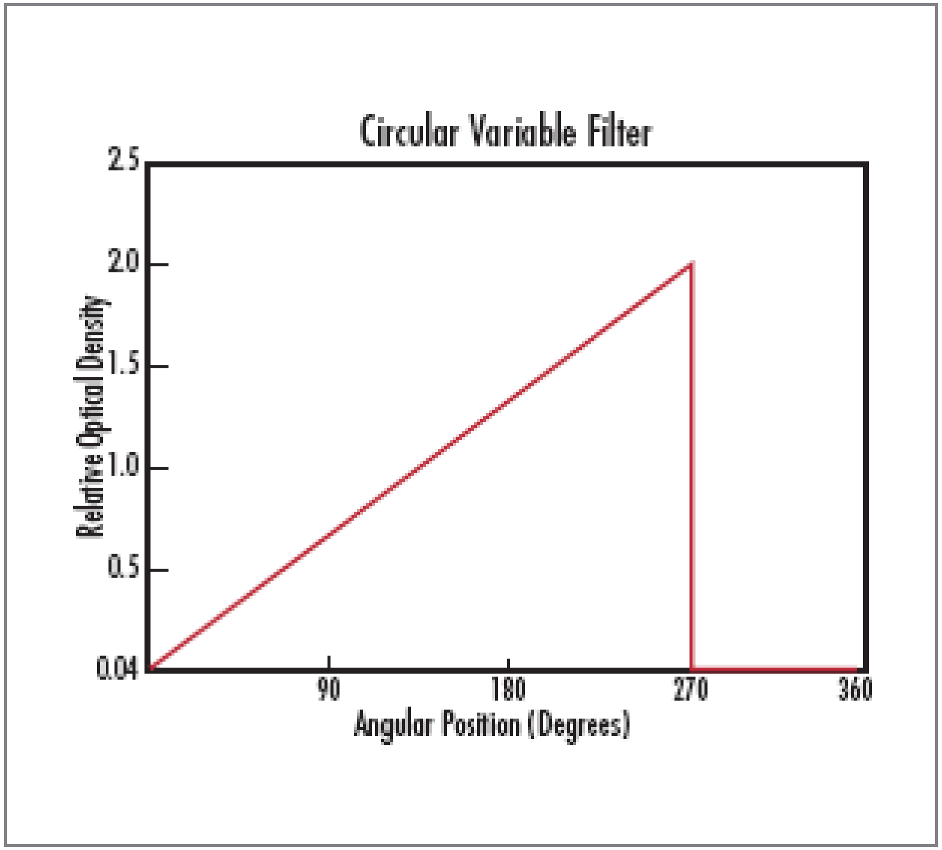
Variable Neutral Density Filters



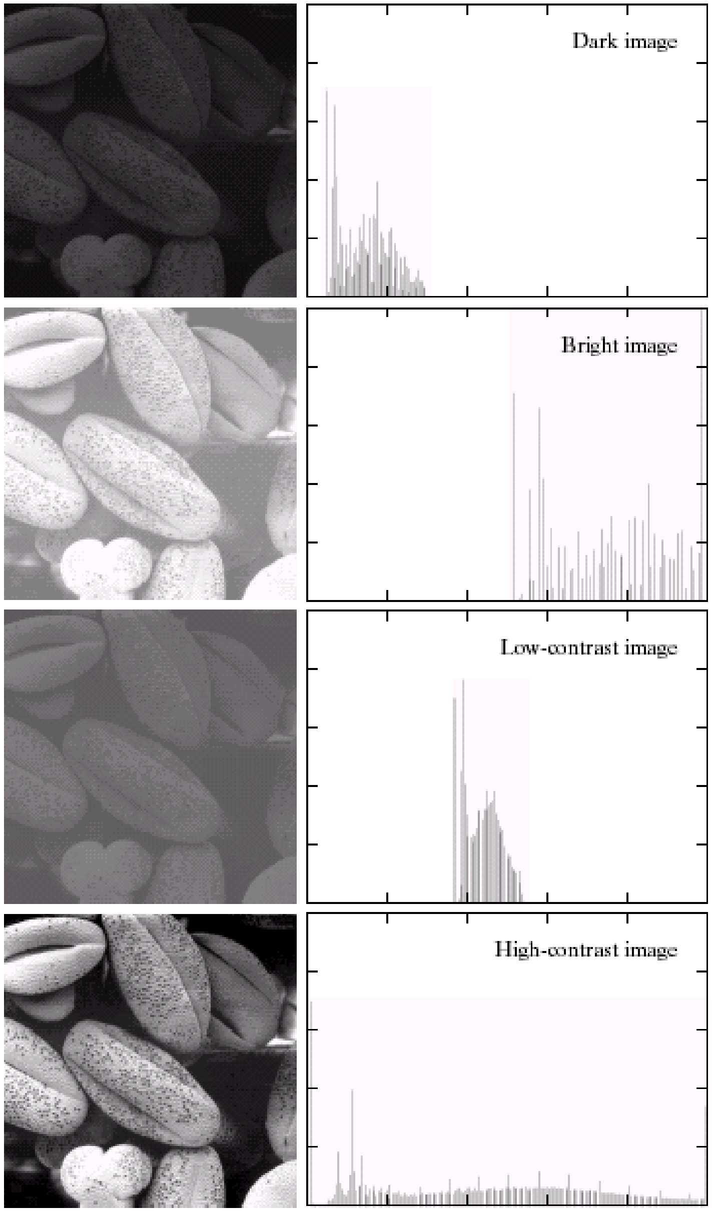


Variable Neutral Density Filters





Can we get these kinds of effects?

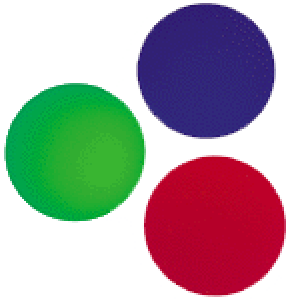


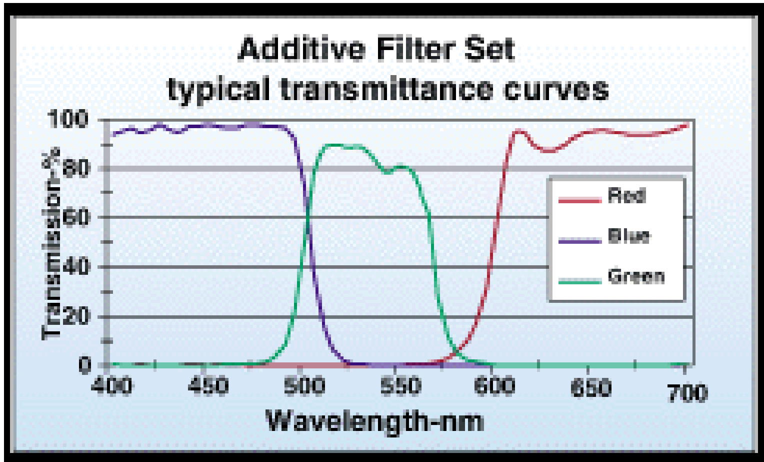
a b

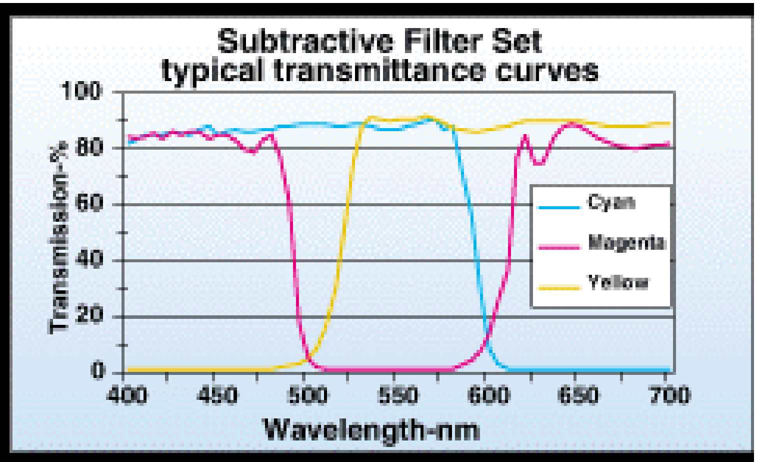
FIGURE 3.15 Four basic image types: dark, light, low contrast, high contrast, and their corresponding histograms. (Original image courtesy of Dr. Roger Heady, Research School of Biological Sciences, Australian National University, Canberra, Australia.)

Show papers

Color Filters

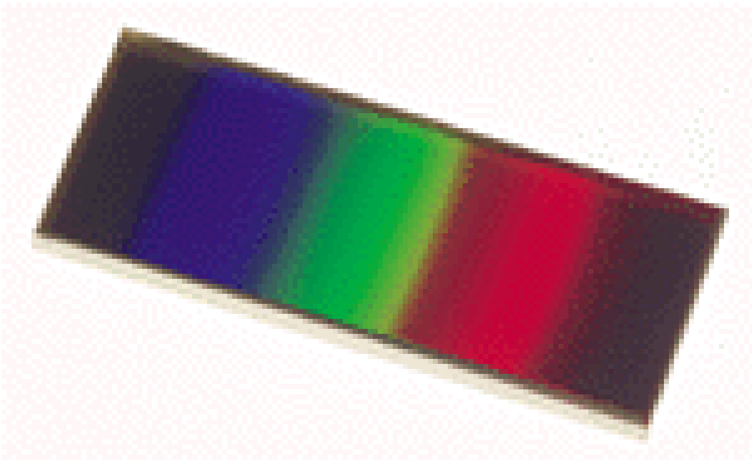


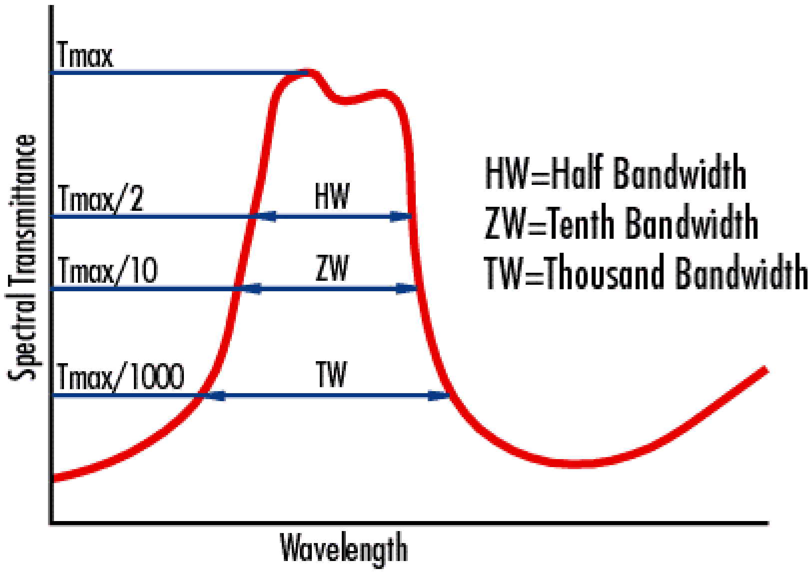


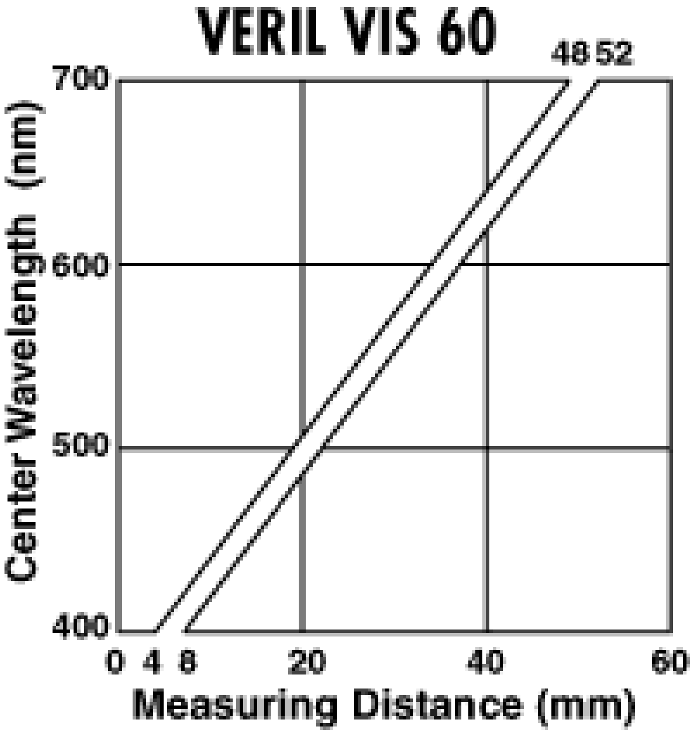


Filter Book

Linear Variable Interference Filters



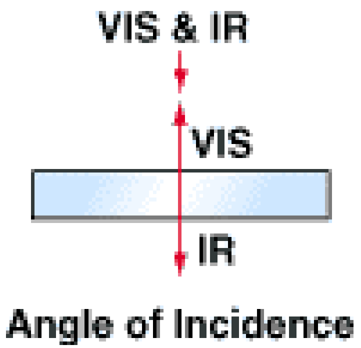


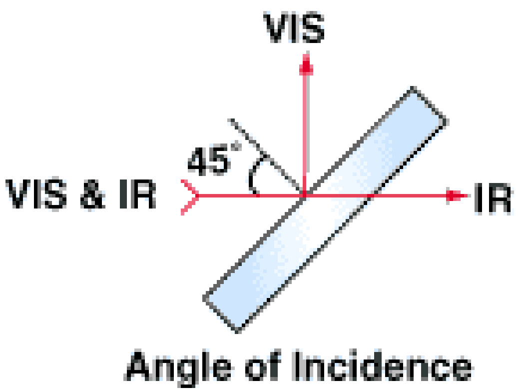


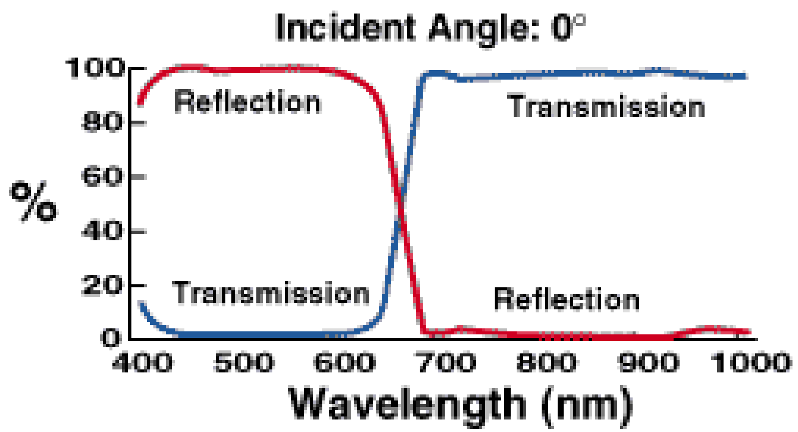
Mirrors

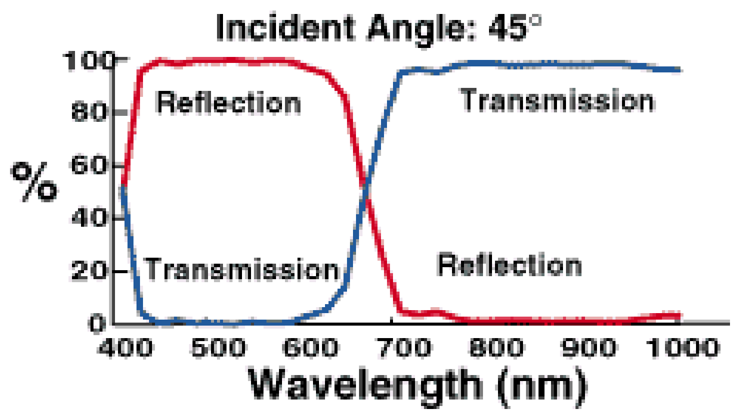
Cold Mirrors

- Reflect VIS
- Transmit IR



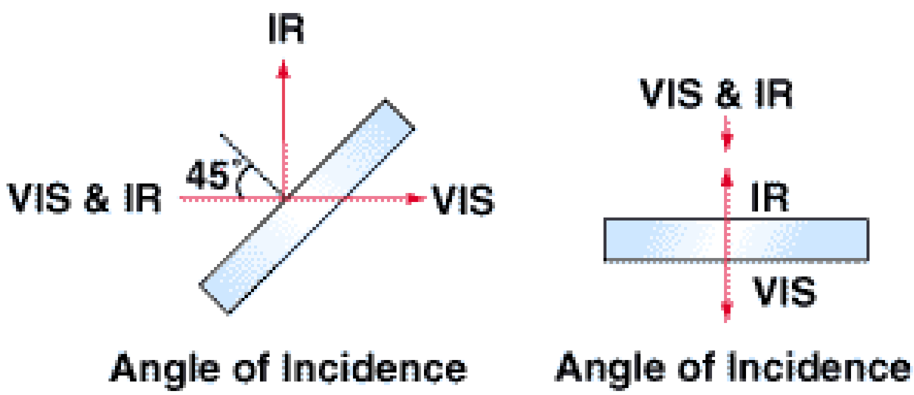


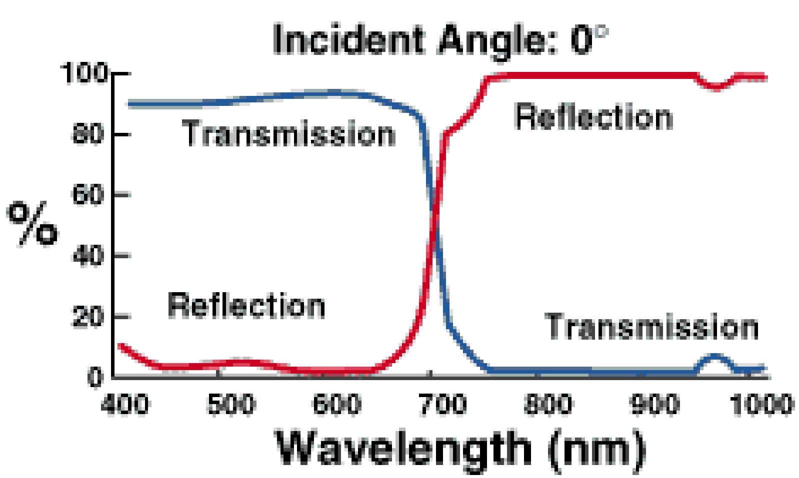


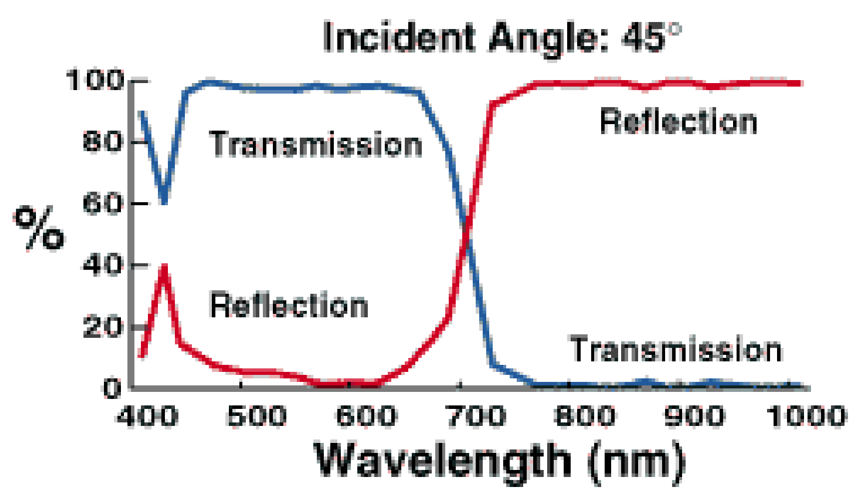


Hot Mirrors

- Reflect IR
- Transmit VIS





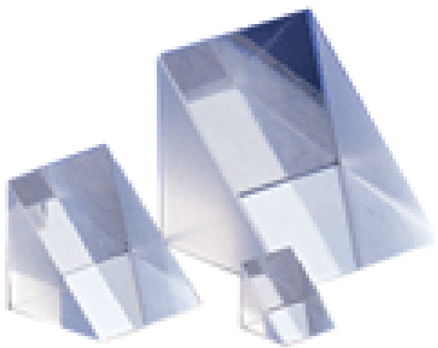


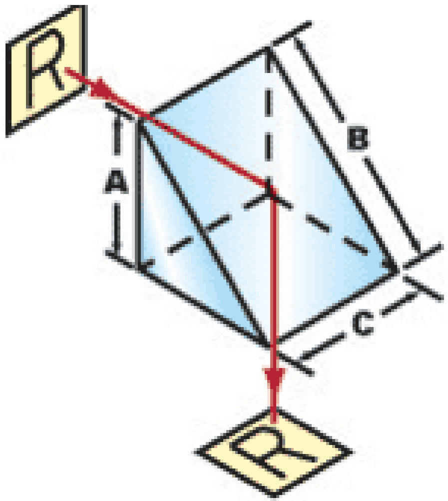
Mirrors and Color Filters

Show papers

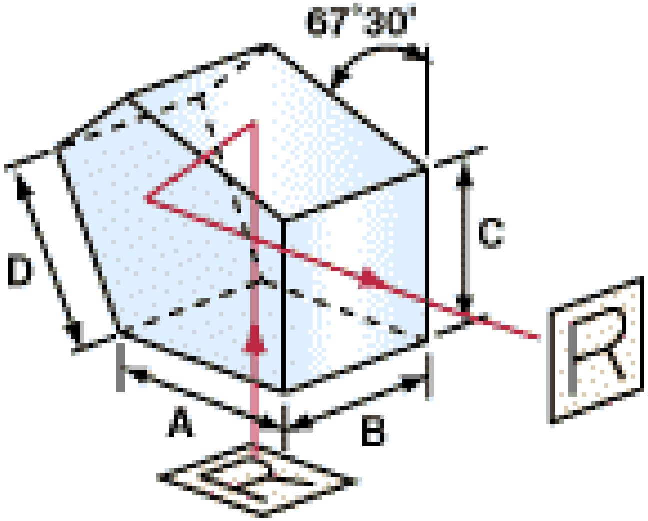
Prisms can rotate images

Image Reflection





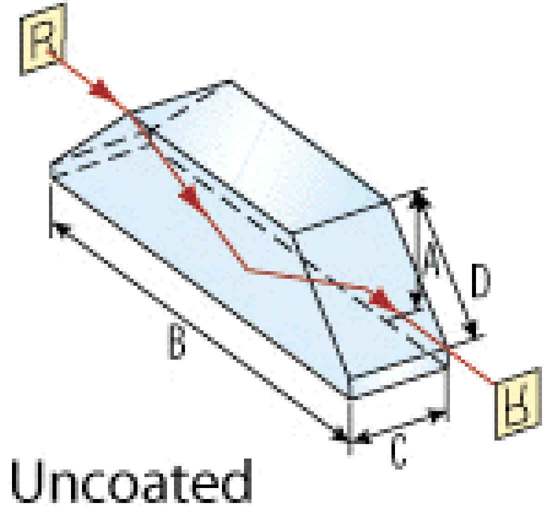
Right Angle Prism

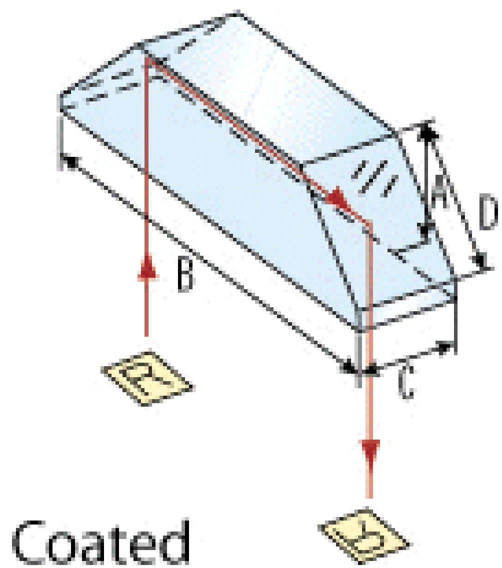


Penta Prism

Image Rotation

Dove Prism





What can we *not* do with optics (at least non-exotic optics):

- negative numbers

- histograms (counting and taking max/mins)

- what else?

Thank you

Lesson summary:

1. Images are discrete functions that are represented by matrices.

2. Always understand if the computation applied on an image is per pixel, patch-based or global.

3. Optics and code can both perform functions on images