



# Computational Imaging

Lecture 09: Imaging Toolbox: Wavefront Analysis and Other Optics



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## Today's Topic

- Wavefront Analysis
  - Point/Line/Edge Spread Function
  - Modulation Transfer Function
  - Wavefront Sensing
- Other Photography Optics
  - Lens Designations.
  - Filters.
  - Prisms.
  - DSLR and Mirrorless Cameras.

# Wavefront Analysis



# Beyond Sphere and Cylinder . . .

- Higher order aberrations have been traditionally ignored clinically
- Now are routinely considered
  - Post lasik increase in higher order aberrations
  - Can be easily measured
  - Wavefront guided correction available
  - Patient expectations



# History of Wavefront Sensing

- DOD in the 1980's to support "star wars"
- Measure the constantly fluctuating refractive power of the atmosphere to improve accuracy of satellite photos and accuracy of weapons
- Led to adaptive optics – real time measurements of refractions using "deformable mirrors" that rapidly
- Astronomers were interested to improve telescope images



Adaptive Optics

No Adaptive Optics

Credit: [www.opt.pacificu.edu](http://www.opt.pacificu.edu); <https://www.eso.org/public/images/eso1824b/>



# Shack-Hartmann Wavefront Sensor

- Hartmann first looked at this a century ago
- Shack elaborated on this in the 1980's working for the US air force
- Liang was the first to use the wavefront sensor to measure the human eye in 1994.
- By the late 1990's commercial development was occurring.



# Airy Disc

An Airy disc shows how a point image is degraded by aberration



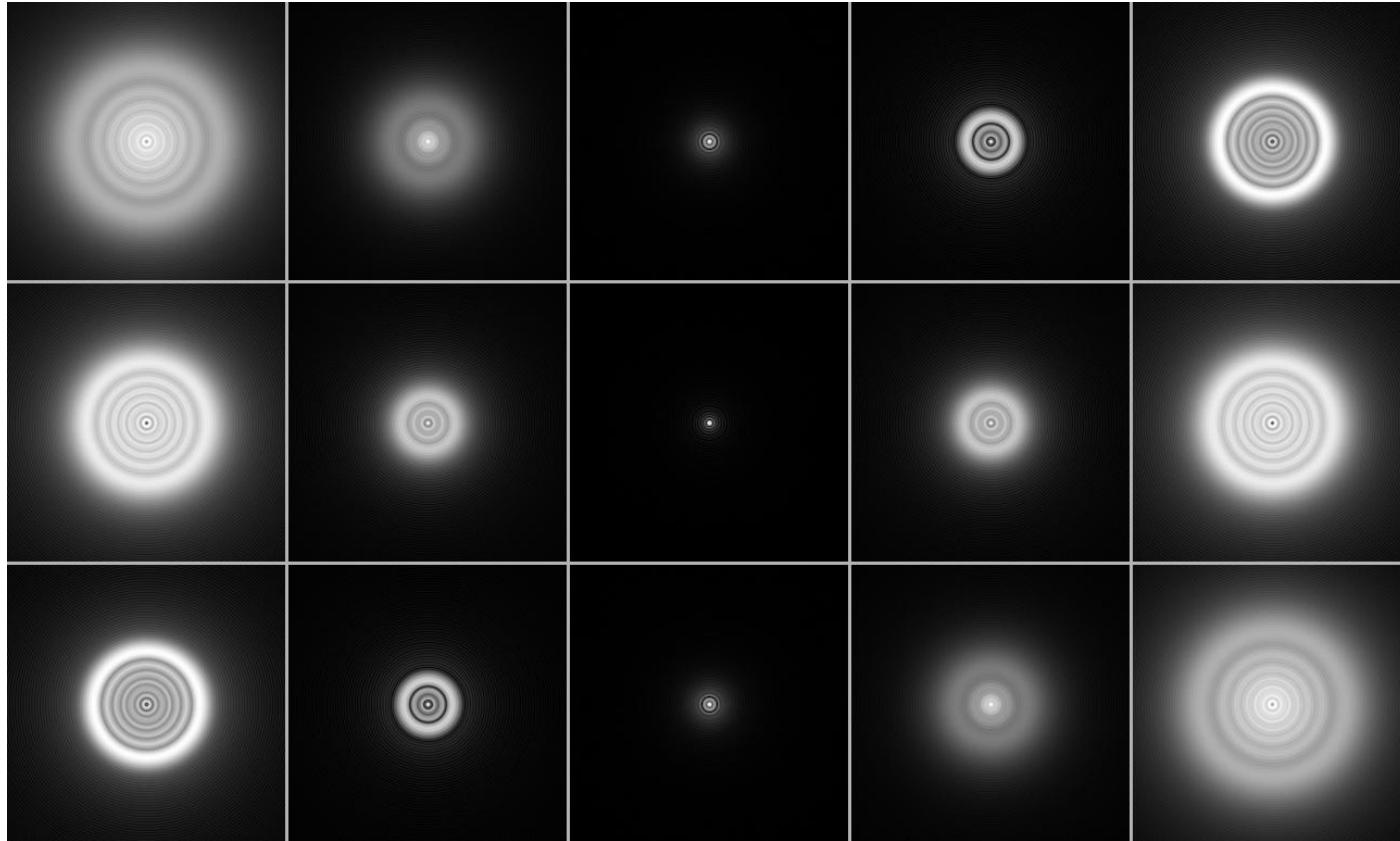
When wave encounters and obstruction, the direction of the wave changes.  
This is called DIFFRACTION



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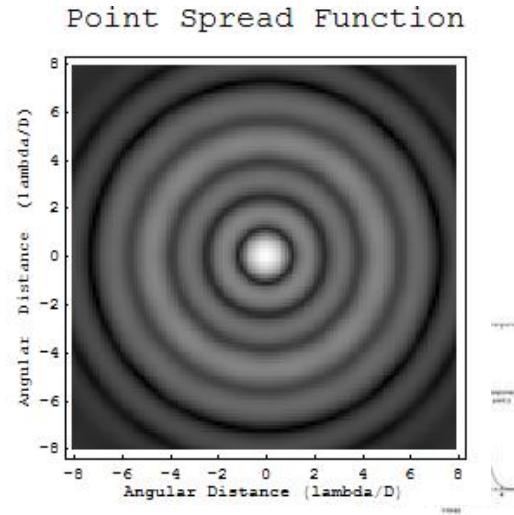
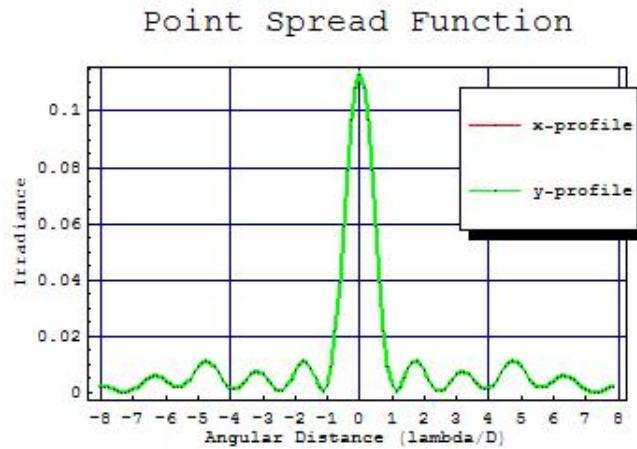
# Point Spread Function (PSF)



# Point Spread Function (PSF)

The image of a perfect point will be at least one point wide.

Normally its image is brightest in the center and progressively darker away from the center. This image function is the point-spread function.





## Point Spread Function (PSF)

- Used to assess the **spatial resolution** of an imaging system.
- The PSF **need not be symmetrical**, so there may be different spatial resolutions in different directions.
- Note that the PSF is, in most cases, a function with significant variation over the **field of view** and **depth**.

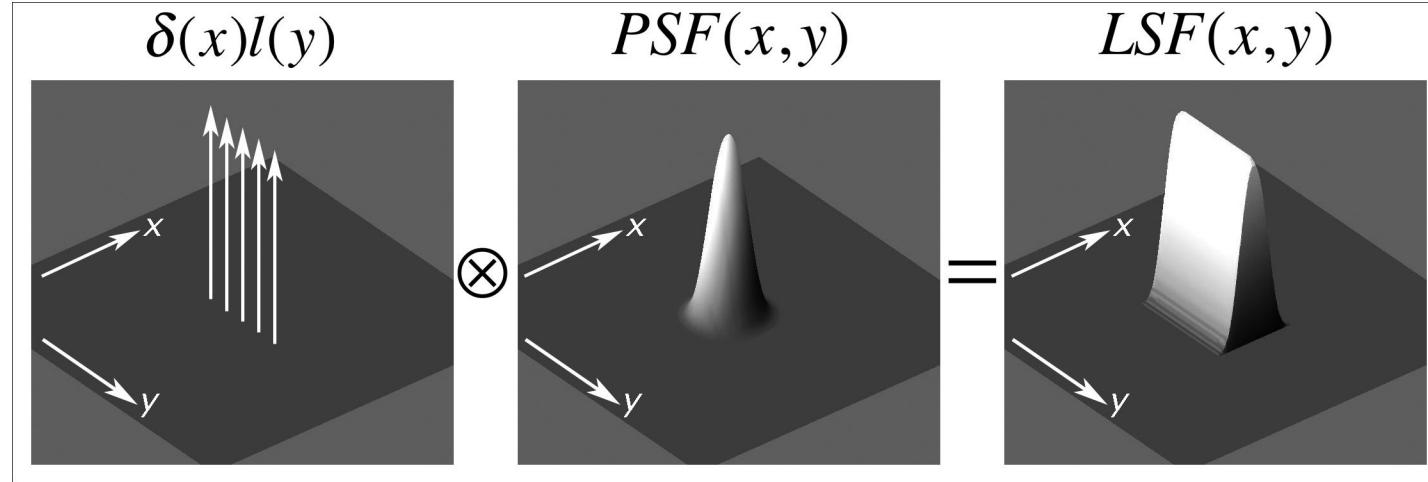
## Modulation Transfer Function (MTF)

- Used to assess the overall spatial resolution of an imaging system. MTF is formally defined as the magnitude of the **Fourier transformed point spread function**.
- The concept of the MTF is to portray how much of the contrast at a specific resolution is maintained by the imaging process.



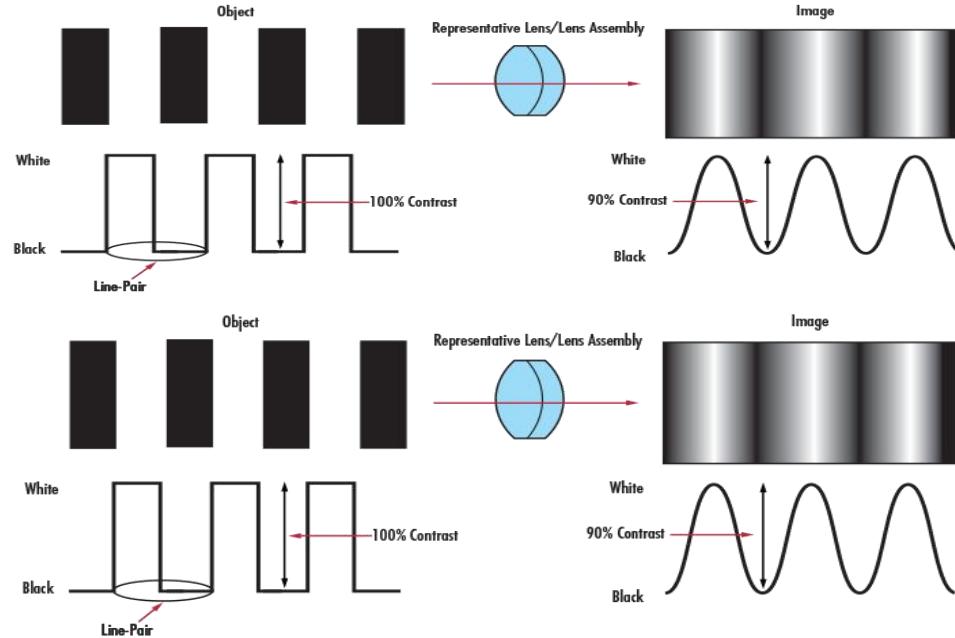
# Line Spread Function (LSF)

➤ The LSF is the two-dimensional convolution of the line source with the system PSF.



# Modulation Transfer Function (MTF)

➤ How can the degradation of an optical system be evaluated?



Perfect Line Edges Before (Left) and After (Right) Passing through a Low Resolution Imaging Lens

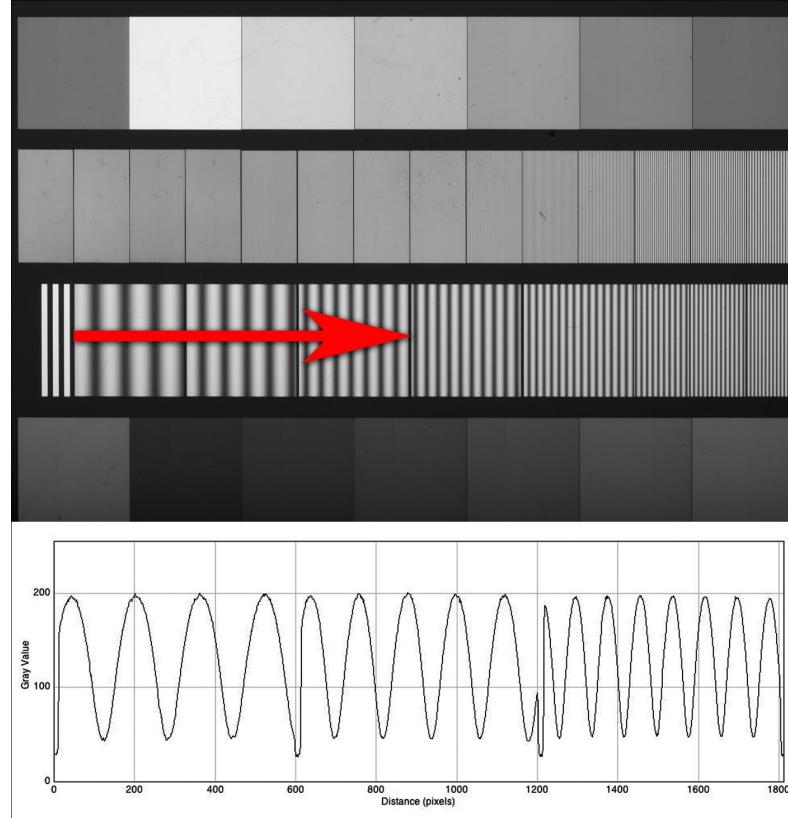
$$M \text{ (Modulation)} = \% \text{ Contrast} = (I_{max} - I_{min}) / (I_{max} + I_{min})$$

Source:edmundoptics



# Modulation Transfer Function (MTF)

- Square wave grating of specific frequency and contrast is passed through an optical system. The MODULATION can then be measured
- $MTF = M_{in}/M_{out}$



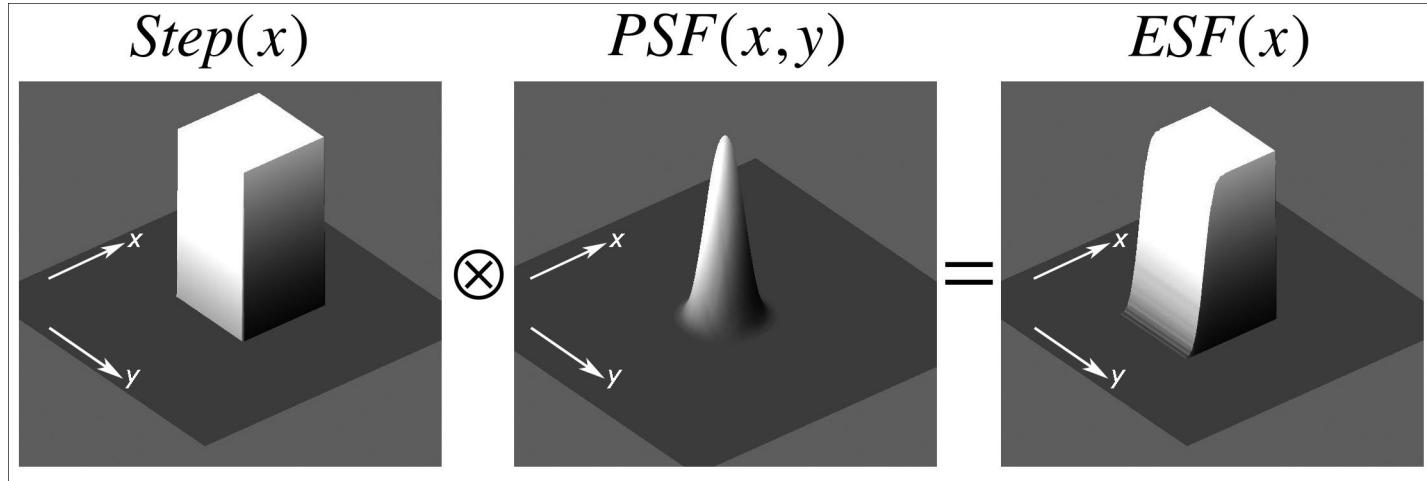
sinusoidal grating

Source:carlesmitja



# Edge Spread Function (ESF)

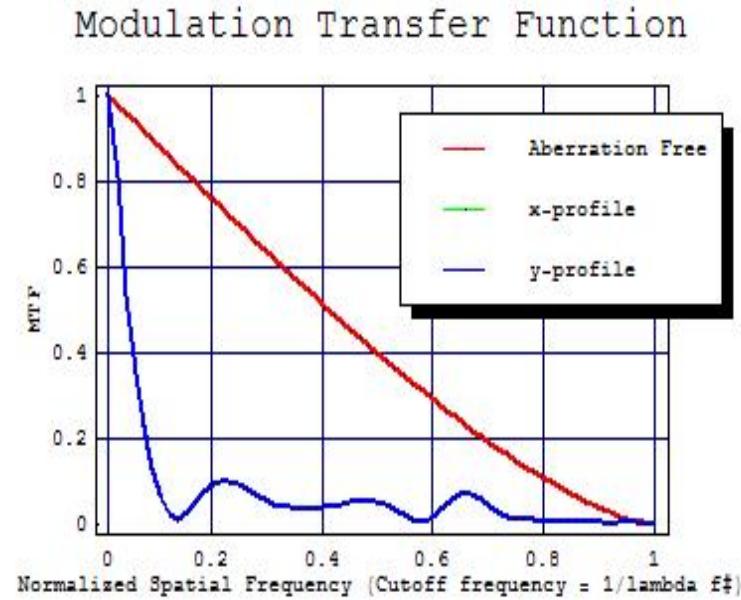
- The ESF is the two-dimensional convolution of the edge source or step function with the system PSF.





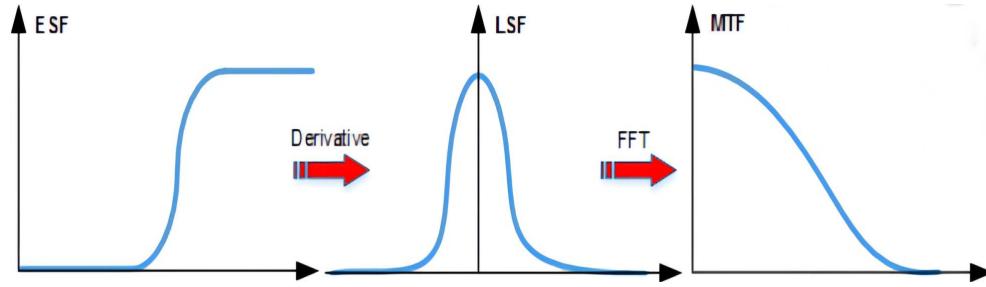
# Modulation Transfer Function (MTF)

- In the optimal case, the MTF value is 1 meaning that object and image contrast are identical.
- MTF usually starts with a value 1 at 0 spatial frequency which represents a homogeneous background. It then drops in a system-specific manner down to zero. By using the MTF, two systems can readily be compared: At each spatial frequency (or 1/resolution) that system with the higher MTF maintains better contrast.





# Slanted Edge Method for MTF



An actual edge image showing the periodicity pattern caused by the slanted position of the test target image over the sampling grid of sensor.



# Wavefront Analysis (Wavescan)

- Light has both **particle** and **wave** characteristics
- Wavefront analysis describes the **wave behavior** of light
- Actual image displacement of the point source from foveola as it passes through the optical system of the eye compared to the ideal image.



# Custom Lasik (Wavefront-LASIK)

Wavescan uses the principles of MTF

- Custom can correct for
  - Myopia or hyperopia
  - Astigmatism
  - Spherical Aberration
  - Coma
  
- Custom does not correct for
  - Chromatic aberration
  - Diffraction





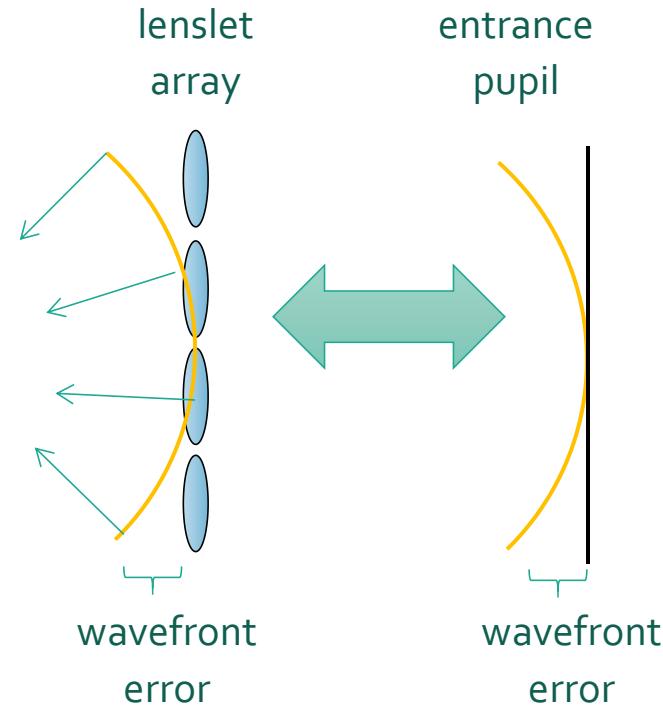
# Hartmann-Shack Aberrometry

- Analyze light that emerges or is reflected from the retina and passes through the optical system of the eye.
- Produces a “fingerprint” of the aberrations for an individual eye.



# Wavefront Analysis

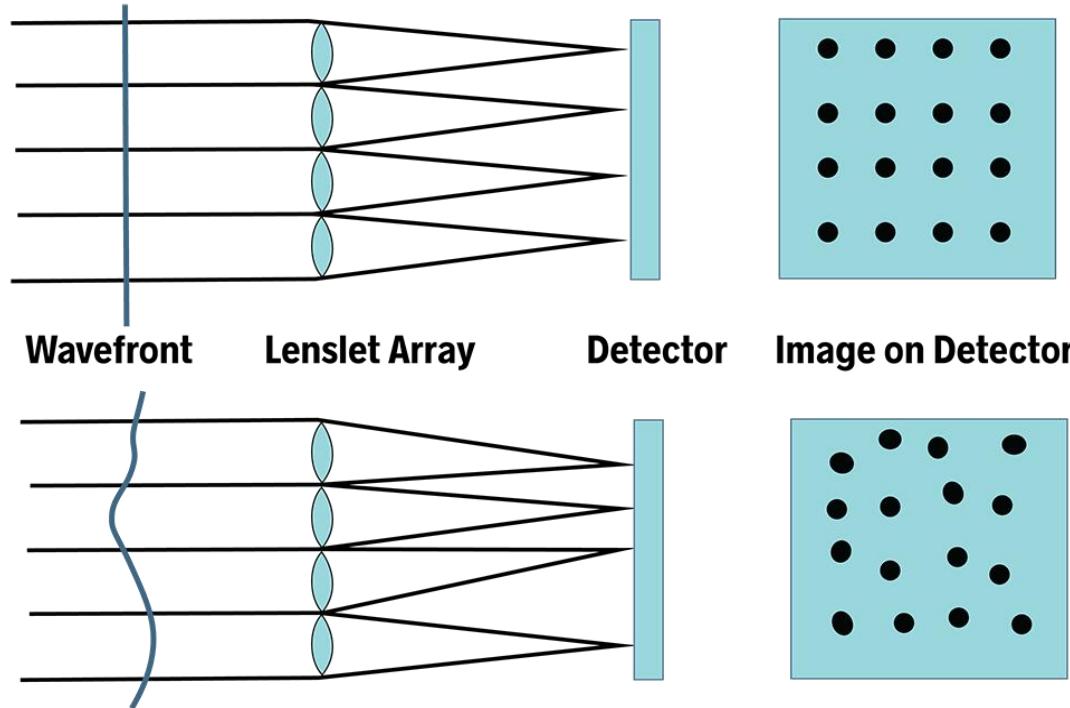
The distance between the wavefront surface and a reference plane



Wavefront exiting the eye.  
Distance from the reference plane  
is measured at many points.



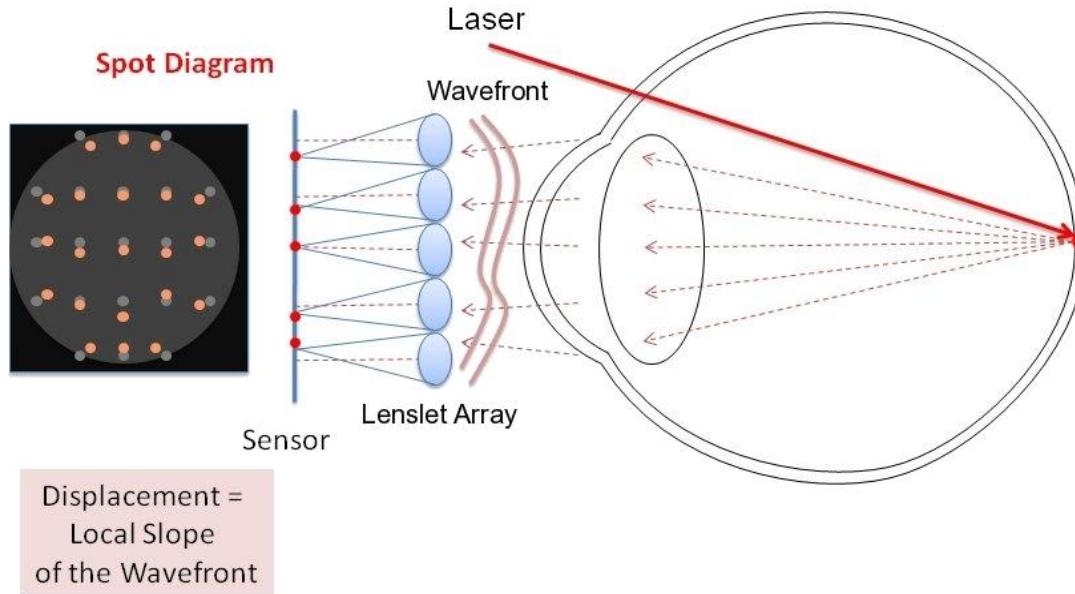
# Wavefront Analysis



Shack–Hartmann sensors are used in astronomy to measure telescopes and in medicine to characterize eyes for corneal treatment of complex refractive errors



# Hartmann Shack Aberrometer

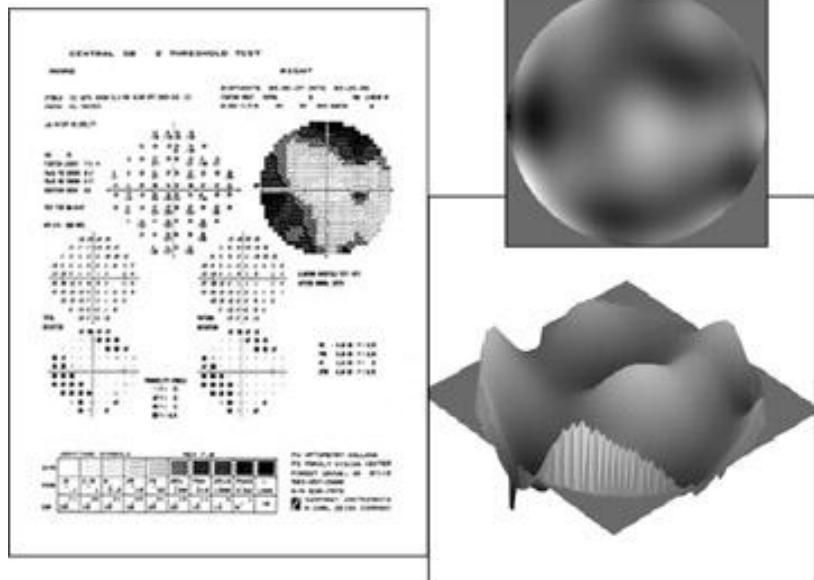


Lenslet Array divides the broad beam of light into many sub-beams for measurement.  
Each lenslet focuses onto the Video sensor. We analyze the position of each spot.

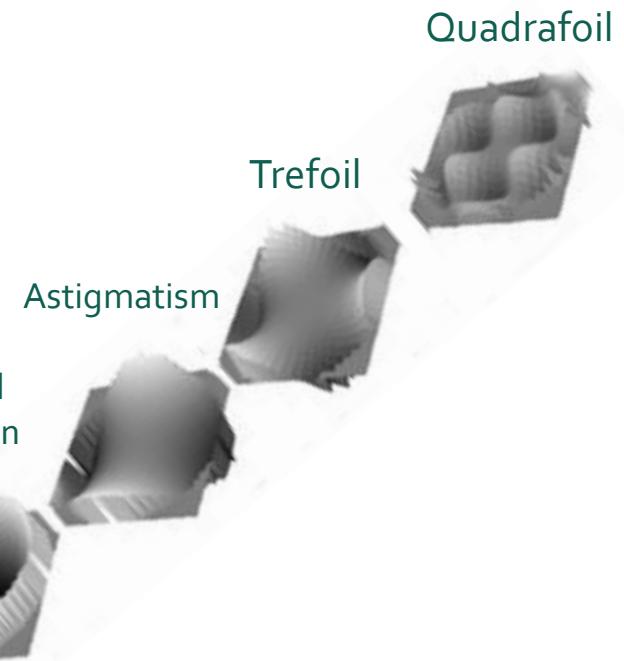
# Wavefront Analysis



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Sometimes it is easier to visualize the wavefront in a 3D surface plot



Quadrafoil

Trefoil

Astigmatism

Spherical  
Aberration



## Wavefront Analysis – Root Mean Square

- Measure of the deviation of an actual image from an ideal image of the source point object
- RMS of ideal system is 0
- RMS of human eye increases from 0.1mm(<40 years old) to 0.25mm (>60 years old).
- Standard LASIK increases RMS especially for large pupils.



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# Lens Designations



# Wide-Angle Lenses

Ultra-wide lenses can get impractically wide...



Fish-eye lens: can produce (near) hemispherical field of view.



# Telephoto Lenses

Lenses with focal length 85 mm or larger.

Technically speaking, “telephoto” refers to a specific lens design, not a focal length range. But that design is mostly useful for long focal lengths, so it has also come to mean any lens with such a focal length.



800mm f5.6 L IS



600mm f4 L IS II



200-400mm f4 L IS



500mm f4 L IS II



400mm f2.8 L IS II



300mm f2.8 L IS II



# Prime vs Zoom Lenses

focus ring:  
changes focus  
distance

single focal  
length



Prime lens: fixed focal length

available  
focal length  
range



focus ring:  
changes focus  
distance

zoom ring:  
changes focal  
length

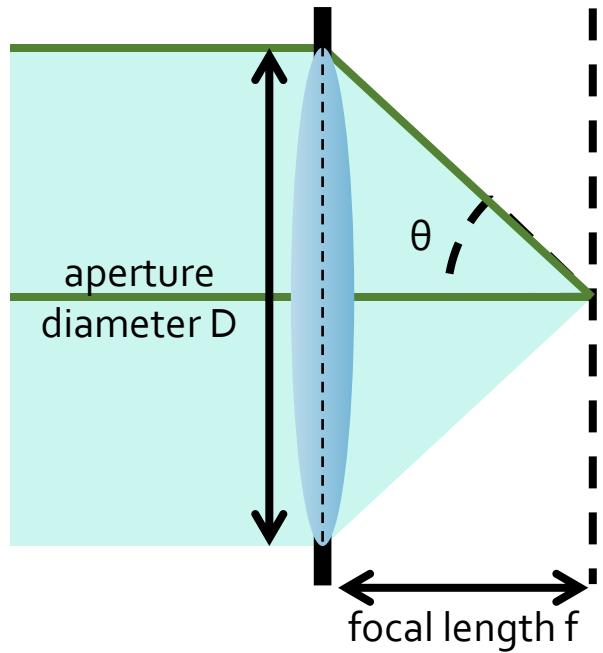
Zoom lens: variable focal length

Why use prime lenses and not always use the more versatile zoom lenses?

Zoom lenses have **larger aberrations** due to the need to cover multiple focal lengths.



# Numerical aperture and f-number



*Numerical aperture (NA):* sine of half-angle of entering light cone.

- Varies with focus settings, we consider NA at infinity focus.
- A larger NA means a larger aperture.

$$NA \equiv \sin \theta$$

*F-number (f/):* ratio of focal length and aperture diameter.

- Independent of focus setting (at least for ideal lenses).
- A larger f/ means a smaller aperture.

$$f/ \equiv \frac{f}{D}$$

How are the two related under paraxial approximation?

$$NA = \sin \theta \approx \tan \theta = \frac{D}{2f} = \frac{1}{2f/}$$



# Aperture Size

Most lenses have variable aperture size.

- F-number notation: “f/1.4” means  $f/ = 1.4$ .
- Usually aperture sizes available at steps of one-half or one-third stops.
- Older lenses have separate manual aperture ring.
- Modern lenses control the aperture through a dial on the camera body (“gilded” lenses).



f/1.4



f/2.8



f/4



f/8



f/16

Note: A “stop” is a change in camera settings that changes amount of light by a factor of 2.

- If the current aperture is at f/4, what is the f-number one stop up and one stop down?



# Lens Speed

- A *fast* lens is one that has a **large maximum aperture**, or a small **minimum f-number**.
- The “speed” of a lens is its minimum f-number.



Why does this zoom lens has more than one lens speeds?

- The max aperture size varies as the focal length (zoom) varies.



# Fastest Possible Lenses

What is the speed of the fastest possible lens?

- From paraxial approximation, fastest lens is f/0.5.
- In consumer photography, fastest lenses are f/0.9 – f/0.95.



Leica Noctilux 50mm f/0.95 (price tag: > \$10,000)  
Fast lenses tend to be bulky and expensive.



Zeiss 50 mm f / 0.7 Planar lens  
Originally developed for NASA's Apollo missions.



# Other Lens Designations

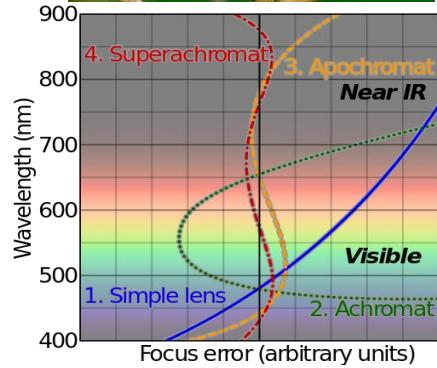
Macro lens: very large magnifications (typically at least 1:1).

- Lens body allows effective lens plane to be placed far away from sensor.
- Macro photography: extremely close-up photography.



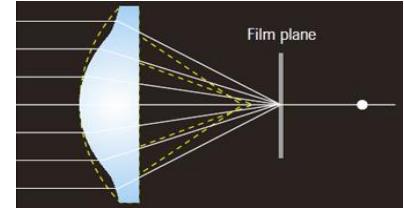
Achromatic or apochromatic lens: corrected for chromatic aberration.

- Achromatic: two wavelengths have same focus.
- Apochromatic (better): three wavelengths have same focus.
- Often done by inserting elements made from low-dispersion glass.
- Expensive.



Aspherical lens: reduces aberrations.

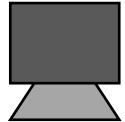
- Expensive, often only 1-2 elements in a compound lens are aspherical.



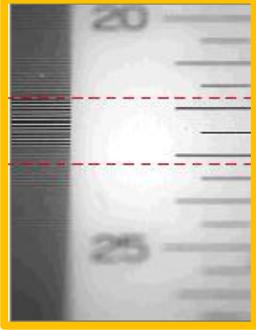
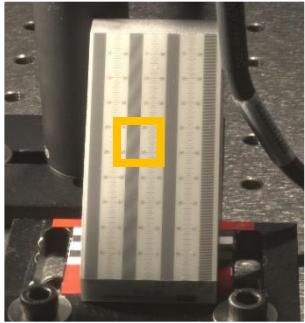


# Other Lens Designations

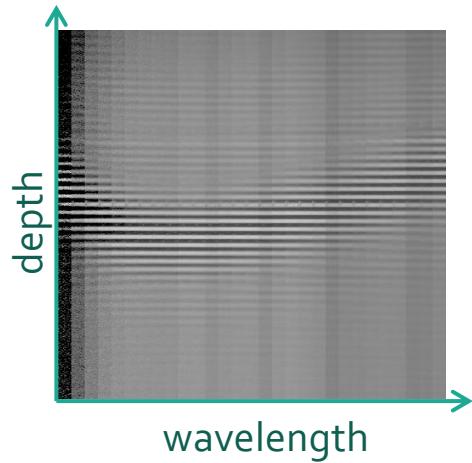
hyperspectral  
camera



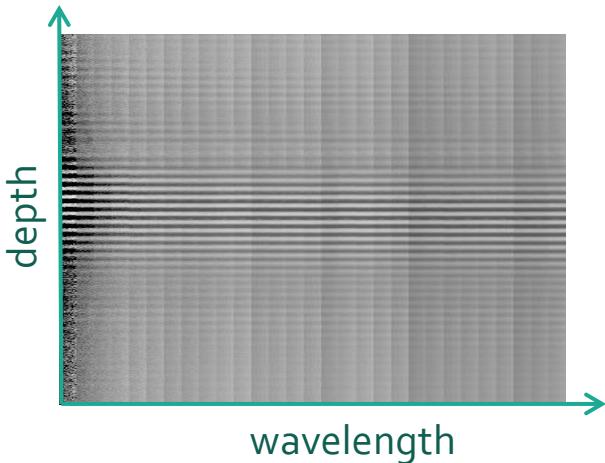
depth-of-field  
target



standard lens (\$500)



apoachromatic lens (\$5000)



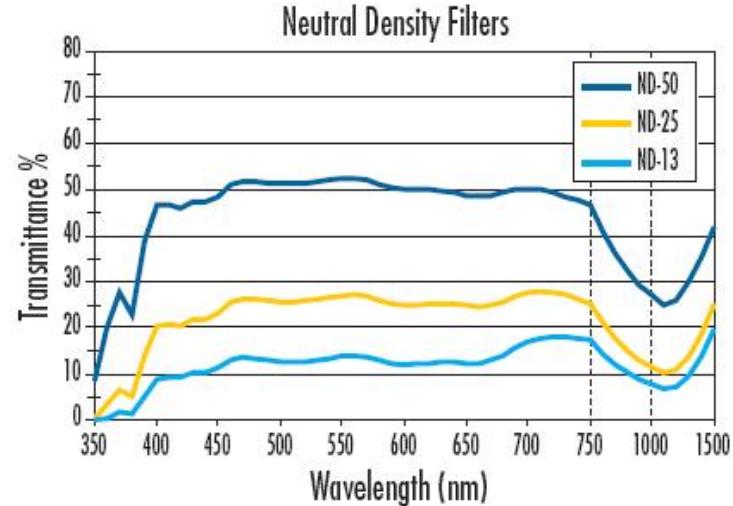
# Filters



# Neutral Density (ND) Filters

Alternative way to control exposure:

- (Approximately) spectrally flat from 400-700 nm.
- Homogeneous glass that blocks by absorption or by reflection



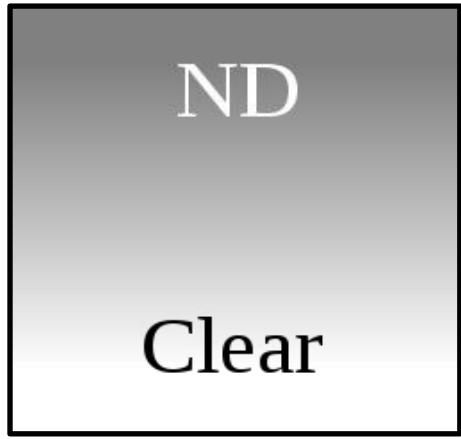
Often characterized by *optical density* (OD):

- Transmittance =  $10^{-\text{optical density}} * 100$ .
- Optical density is additive as you stack together ND filters.

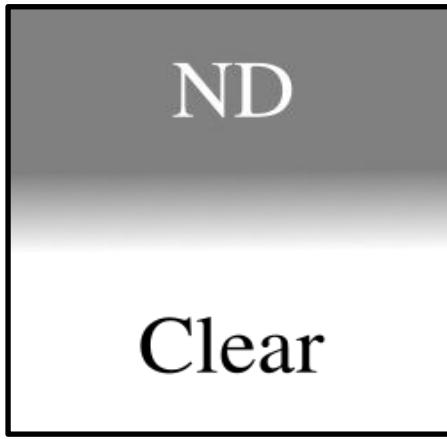


# Graduated Neutral-Density Filters

Variable optical density, from too high to too low/zero.



soft edge



hard edge



What are these filters useful for?



# Graduated Neutral-Density Filters

Useful in scenes with parts of very different brightness.

- Common scenario: Sky – horizon – ground.





# Polarizing Filters (or Polarizers)

Most commonly circular polarizers.

- Same principle as polarizing sunglasses.



What are these filters useful for?



# Polarizing Filters (or Polarizers)

Reduce sky light



Reduce haze





# Polarizing Filters (or Polarizers)

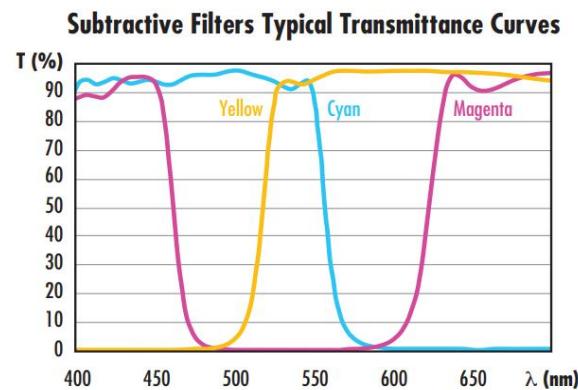
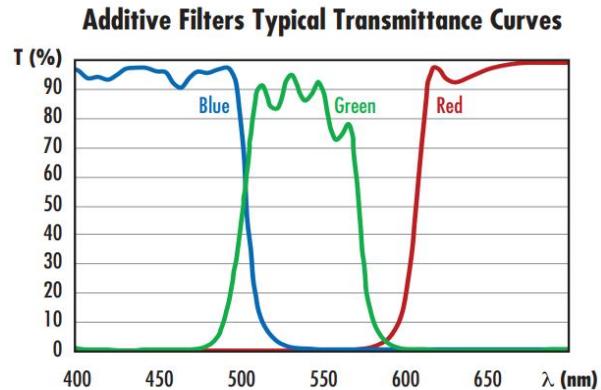
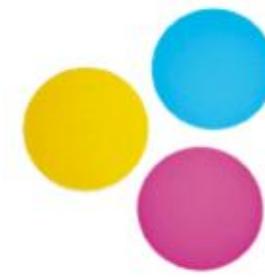
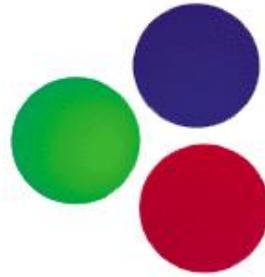
Reduce direct reflections





# Spectral (color) Filters

Mostly used for scientific applications or under very special lighting settings.





# Filter Size

The filter size you need to use is determined by the lens you are using.

- You can find the filter size marking in the front of the lens.
- You can avoid having to buy dozens of filters by using step-up and step-down rings.



filter size marking



# Prisms

# Prisms

Many different types of prisms that produce different types of reflections.

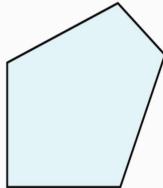
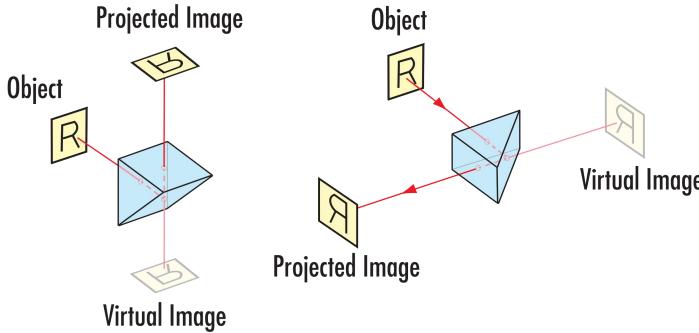
Right Angle Prism



Penta Prism



Any use of pentaprism in photography?





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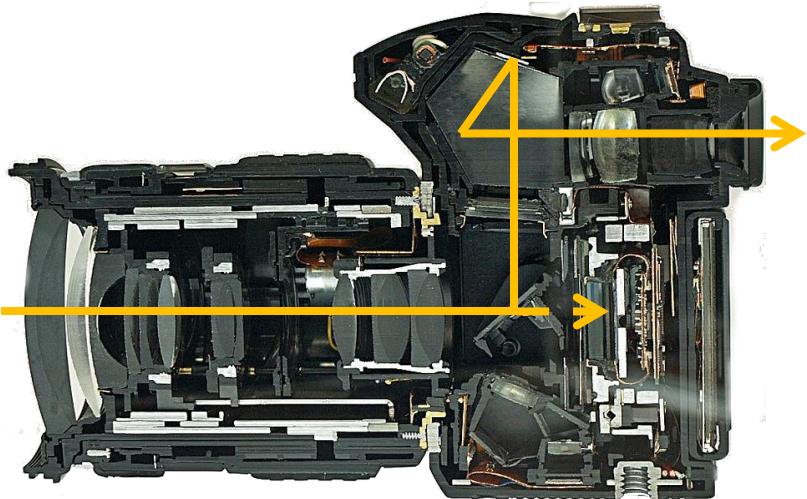
# DSLR and Mirrorless Camera



# Single Lens Reflex (SLR) Cameras

Mechanism to provide direct view through the lens (TTL).

- Any downsides?

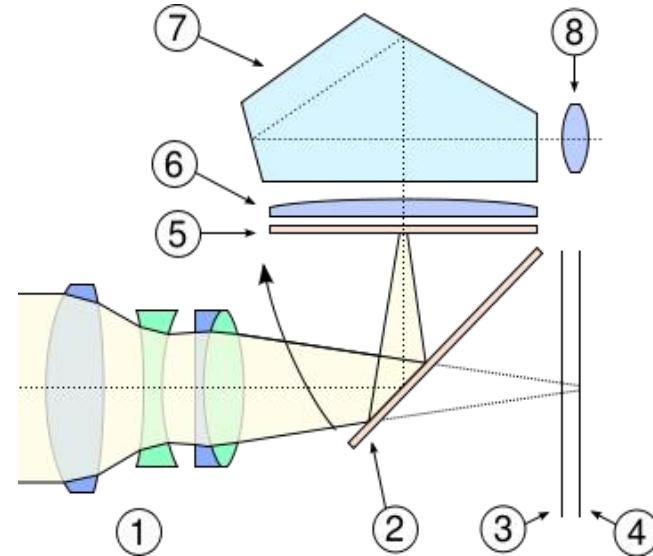


1 - Front-mount Lens

2 - Reflex Mirror at 45 degree angle

3 - Focal Plane Shutter

4 - Film or Sensor



5 - Focusing Screen

6 - Condenser Lens

7 - Optical Glass Pentaprism (or Pentamirror)

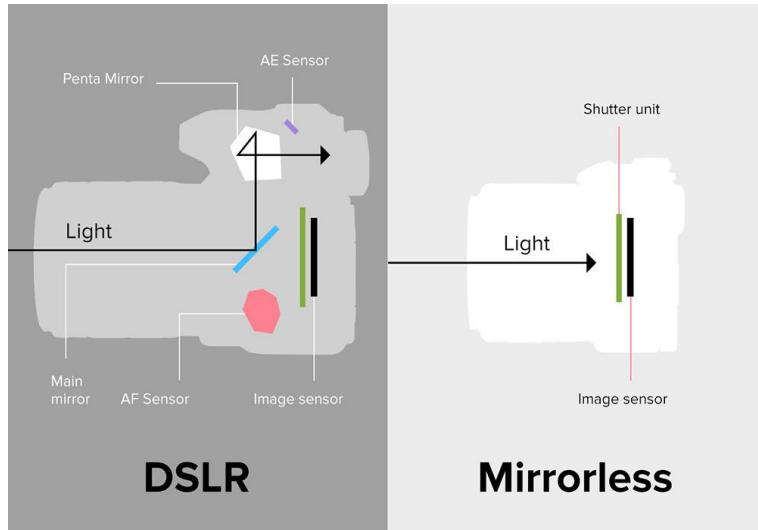
8 - Eyepiece (a.k.a. viewfinder)



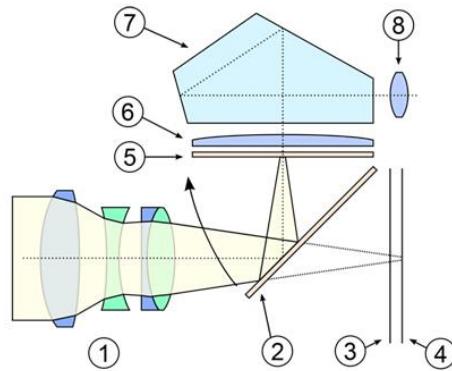
# SLR Versus Mirrorless

Mirrorless cameras used to be mostly point-and-shoot, but are quickly becoming the dominant choice for high-end photography.

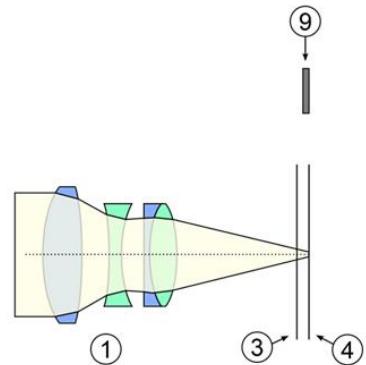
- What are some pros and cons of mirrorless compared to SLR?



DSLR Camera



Mirrorless Camera



- 1 - Front-mount Lens
- 2 - Reflex Mirror at 45 degrees
- 3 - Focal Plane Shutter
- 4 - Film or Sensor

- 5 - Focusing Screen
- 6 - Condenser Lens
- 7 - Optical Glass
- 8 - Eyepiece (a.k.a. viewfinder)



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# Thank You!

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