Light, the Eye, Sensors and Cameras

form of energy, electromagnetic radiation
dual nature:
- photons: travel in straight line at constant speed, which
depends on the medium (vacuum: $3 \times 10^8$ m/s), they might
have different energy
- wave: wavelength

\[ E = h\nu = c \cdot h / \lambda \]  

\( h \) is the Planck's constant
\( c \) speed of the wave
\( \nu \) frequency
\( \lambda \) wavelength

# of photons
amplitude
Image formation

Why there is no image on a white paper
Pinhole
Each point in the scene projects to a single (or very small) point in the image
• The focal length $f$ is the distance between the pinhole and the sensor
• If we double $f$ we double the size of the projected object
Problems:
- limited light
- the size of the pinhole limits sharpness
Converging lenses

Lenses focus the light from different directions/rays (refraction)

Photograph made with small pinhole

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, equivalent in size to an aperture of f/50. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.

Photograph made with lens

This time, using a simple convex lens with an f/16 aperture, the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter: only 1/100 sec.

The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.
How to draw the rays

• Three rules
  1. incident rays parallel to the principal axis converge to the focal point
  2. incident rays passing through the center of the lens do not modify their direction
  3. incident rays through the focal point on the right side of the lens get reflected and travel parallel to the principal axis

Thin lens approx:
d small compared to R1 and R2
Example
Example
Example
Example
Example
Example

clear image
Example

- Clear image
- Blurred image, out of focus
Thin lens formula
Thin lens formula

\[
\frac{y'}{d'} = \frac{y}{d} \Rightarrow \frac{y'}{y} = \frac{d'}{d}
\]
Thin lens formula

\[
\frac{y'}{d'} = \frac{y}{d} \Rightarrow \frac{y'}{y} = \frac{d'}{d}
\]

\[
\frac{y'}{d' - f} = \frac{y}{f} \Rightarrow \frac{y'}{y} = \frac{d' - f}{f}
\]
Thin lens formula

\[
\begin{aligned}
\frac{y'}{y} &= \frac{d'}{d} \\
\frac{y'}{y} &= \frac{d' - f}{f} \\
\frac{d'}{d} &= \frac{d' - f}{f} \\
\end{aligned}
\]

\[
\Rightarrow \frac{d}{d'} = \frac{d - f}{f} \Rightarrow \frac{d'}{d} = \frac{d'}{f} - 1 \Rightarrow \frac{1}{d} = \frac{1}{f} - \frac{1}{d'}
\]

\[
\frac{1}{d'} + \frac{1}{d} = \frac{1}{f}
\]
Objects at infinity focus at $f$

if $d \to \infty$

$d' \to f$

When the object gets closer, the focal plane moves away from $f$. At the limit:

if $d \to f$

$d' \to \infty$

an object at distance $f$ requires the focal plane to be at infinity
Objects at infinity focus at $f$

if $d \to \infty$

$d' \to f$
Effect of focal length on image size

\[ M = \frac{y'}{y} = \frac{d'}{d} \]

\[ \frac{1}{f} = \frac{1}{d} + \frac{1}{d'} \Rightarrow M = \frac{f}{d - f}, \quad d > f \]

Effect of focal length on field of view
Depth of field (dof)
Depth of field (dof)

some tolerance (circle of confusion)
Depth of field (dof)

some tolerance (circle of confusion)
Depth of field (dof)

some tolerance (circle of confusion)

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Depth of field (dof)

Some tolerance (circle of confusion)

Depth of field
Getting the right exposure

- Shutter speed: how long the sensor is exposed to light, expressed in fractions of a second
  1/30 1/60 1/125 1/500 1/1000 ...
- Aperture: diaphragm controls how much light we allow through the lens (it is expressed as a fraction of focal length):
  (f/2.0, f/2.8, f/4, f/5.6, f/8 .. f/22)
Getting the right exposure

- Shutter speed: how long the sensor is exposed to light, expressed in fractions of a second
  1/30 1/60 1/125 1/500 1/1000 ...
- Aperture: diaphragm controls how much light we allow through the lens (it is expressed as a fraction of focal length):
  (f/2.0, f/2.8, f/4, f/5.6, f/8 .. f/22)
Effect of aperture: depth of field

LESS DEPTH OF FIELD

Wider aperture \( f/2 \)

MORE DEPTH OF FIELD

Smaller aperture \( f/16 \)
Effect of shutter speed: motion blur

Slow shutter speed

Fast shutter speed