# Thin Lenses

- A lens is an optical device consisting of two refracting surfaces
- The simplest lens has two spherical surfaces close enough together that we can neglect the distance between the surfaces (i.e., thin)
- Consider two spherical surfaces (with radii of curvature $R_1$ and $R_2$), separating three materials of index of refraction $n_1$, $n_2$, and $n_3$
- For the first surface, we can use the refracting surface equation to relate the object distance $p_1$, image distance $q_1$, and radius of curvature $R_1$, ignoring the second surface.

- From diagram (on board), we get

$$\frac{n_1}{p_1} + \frac{n_2}{q_1} = \frac{n_2 - n_1}{R_1}$$

- Now let the image formed by surface 1, $I_1$, be the object for surface 2, $O_2$
- $I_1$ is a virtual image. Therefore

$$p_2 = -q_1$$

- Here, we neglect the thickness of the lens
- Again apply the refracting surface equation, but for surface 2, neglecting surface 1
- The image, $I_2$, is real

$$\frac{n_2}{p_2} + \frac{n_3}{q_2} = \frac{n_3 - n_2}{R_2}$$

- Let $n_1=n_3=1$ (air or vacuum) and $n_2=n$

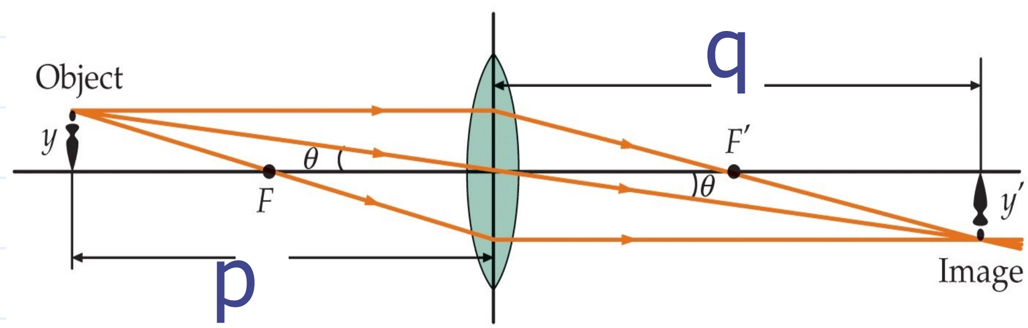
$$\frac{1}{p_1}+\frac{n}{q_1}=\frac{n-1}{R_1} \qquad \frac{n}{-q_1}+\frac{1}{q_2}=\frac{1-n}{R_2}$$

- Adding with $p_1=p$ and $q_2=q$, gives

$$\frac{1}{p}+\frac{1}{q}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

- Letting $p\rightarrow\infty$ and $q\rightarrow f$ gives

$$\boxed{\frac{1}{f}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)}$$




- This is the lens maker's equation

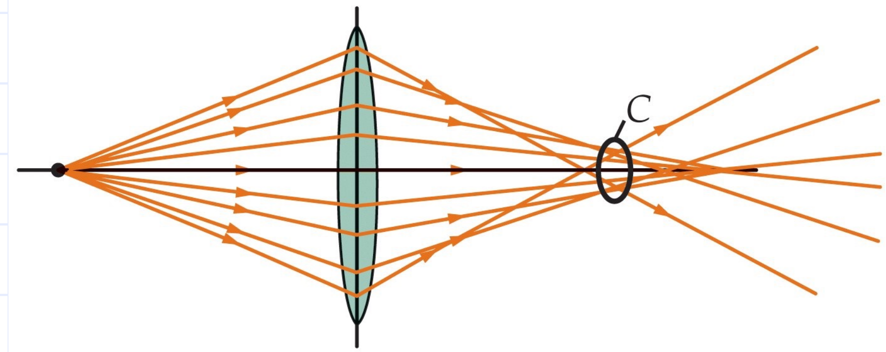
# Example Problem

- If a swimming pool full of water is 2.00 m deep. How far below the top of the water surface does the bottom appear when viewed from above?

# Example Problem

- The projection lens in a certain slide projector is a single thin lens. A slide 24.0 mm high is to be projected so that its image fills a screen 1.80 m high. The slide-to-screen distance is 3.00 m (a) Determine the focal length of the projection lens. (b) How far from the slide should the lens of the projector be placed in order to form the image on the screen?

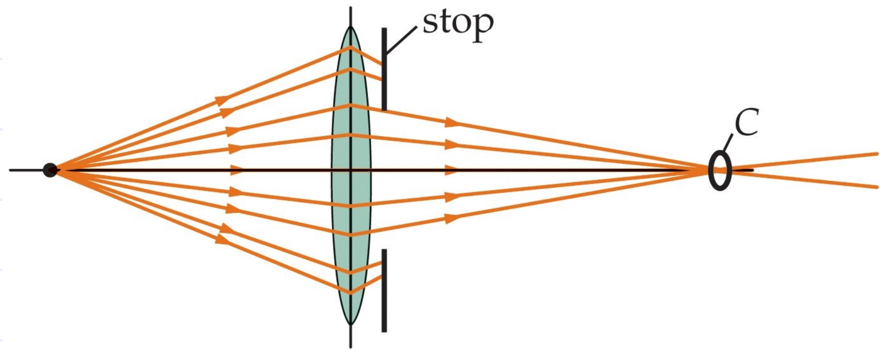
# Aberrations

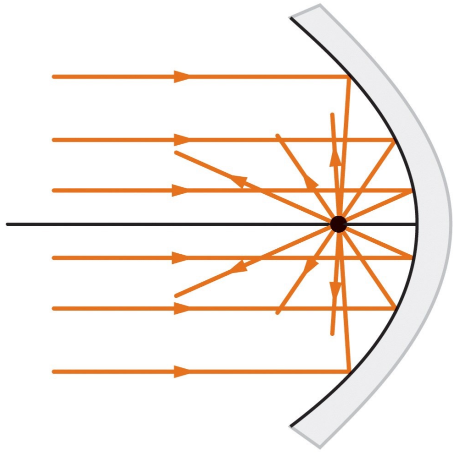



- In our development of the mirror and lens equations, we assumed paraxial rays, i.e. rays with small angles with respect to the principal axis
- We also assumed for lenses that they are thin
- These are approximations (but reasonable)
- For more precise determinations of images, we must use the laws of refraction and reflection to trace the paths of rays
- We find that two types of aberrations result from the use of spherical surfaces

# Spherical Aberrations

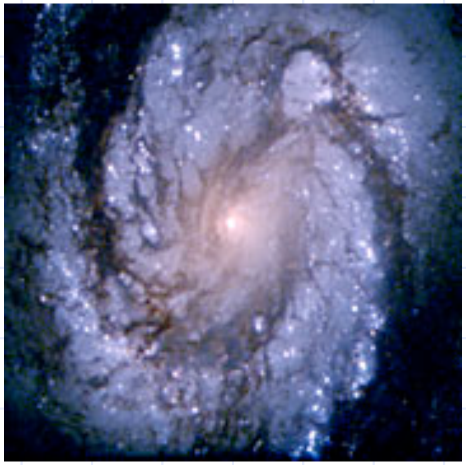
- A geometrical issue for rays of the same $\lambda$
- Rays further from the principal axis are focused closer to the lens for a converging lens
- Spherical aberration can be eliminated by the use of, for example, parabolic mirrors – all rays focus to a common point – but expensive
- Or apertures can be used to remove the non-paraxial rays



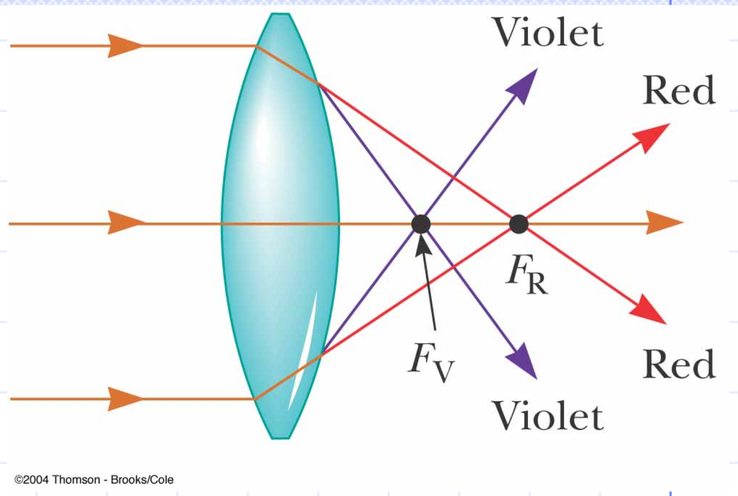
# Hubble's spherical aberration

Before



Fixed

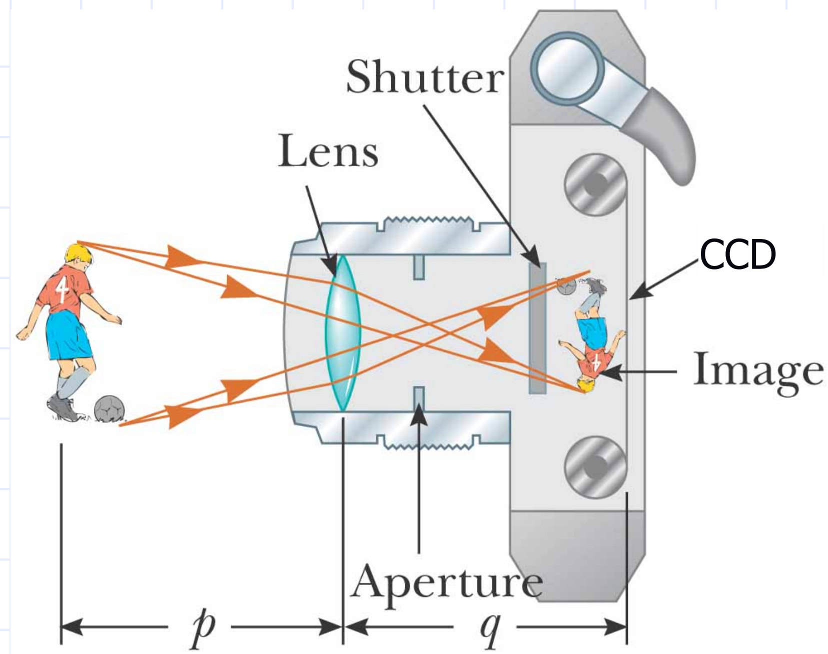
# Chromatic Aberration




- Since the index of refraction is a function of λ, rays with different λ will refract at different angles when passing through a lens (for the same paraxial ray)
- The rays focus at different locations for each λ
- Not a problem for monochromatic light beams
- For ordinary (polychromatic) light, chromatic aberration can be reduced by
  - materials with minimal λ dependence on n
  - use combinations of diverging and converging lenses

# Optical Devices: The Camera

- The camera system consists of a converging lens, aperture, shutter, and CCD
- q is adjusted to focus a real, inverted image on the CCD for large object distance (p>>q)
- The shutter is opened for a time duration $\Delta t$. Usually, between 1/30 to 1/250 s exposure time.
- This allows light to strike the CCD creating the image.



- The intensity of the light reaching the CCD is proportional to the area "viewed" by the camera and the effective area of the lens – controlled by the diameter D of the aperture)
- Light intensity I is the rate of light energy received by the CCD per unit area (energy/area/time)
- When p>>f and q ≈ f, the area of the image is ≈$f^2$. Therefore, I is proportional to $D^2/f^2$.
- In photography, the light-gathering capability of a lens is expressed in terms of f/D called the <u>f-number</u>. Therefore $I \propto (f-\text{number})^{-2}$
- Increasing D by √2 reduces f-number by 1/√2 and increases I by 2 at the CCD

- Typical f-numbers
  f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16
  large → small aperture (exposure)
- The following combinations give same exposure
  f/4 & 1/500s = f/5.6 & 1/250s = f/8 & 1/125 s

# Example Problem

- A camera is being used with a correct exposure at f/4 and a shutter speed of 1/16 s. In order to photograph a rapidly moving subject, the shutter speed is changed to 1/128 s. Find the new f-number needed to maintain satisfactory exposure.