C4 Geometrical Optics

- Geometrical optics, also known as Ray optics, ignores the wave nature of light and uses geometrical methods to study the propagation of light in a homogeneous medium and their applications.
- It applies when the size of the object is much larger than the wavelength of light, e.g., imaging, illumination. $\lambda/D \to 0$

Geometrical optics ⇔ Wave optics

⇕ ⇕

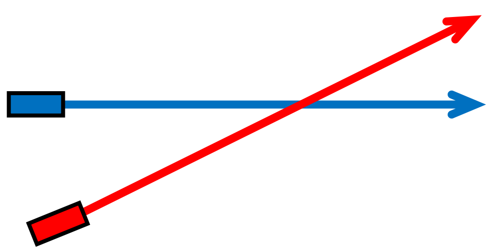
Far-field optics ⇔ Near-field optics

§ 4.1 Basic laws of ray optics

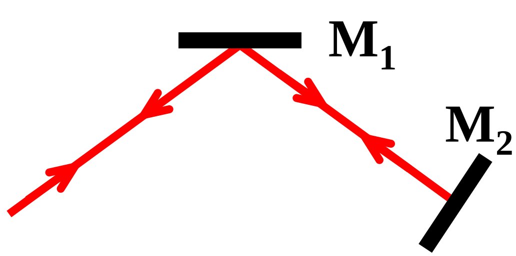
① **Rectilinear propagation**: In a homogeneous medium, light rays travel in straight lines.

② **Independent propagation.** When light rays meet in the medium, each one keeps its original propagation direction.

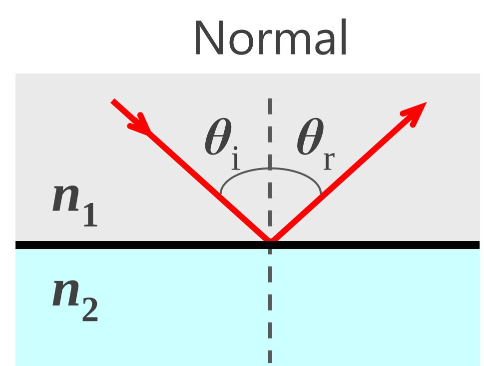
③ **Law of reflection**: The reflected ray lies in the **plane of incidence**; the angle of reflection equals the angle of incidence.



Independent



Reversible

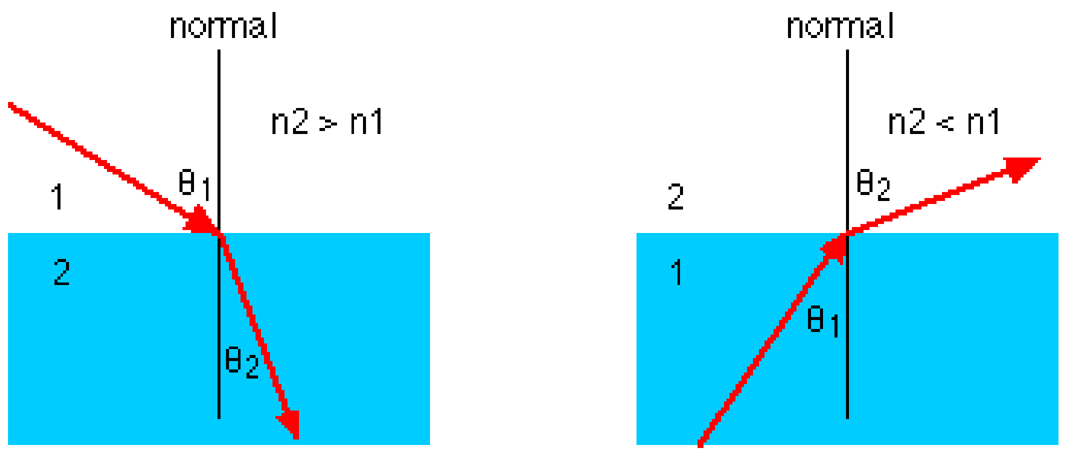


Reflection

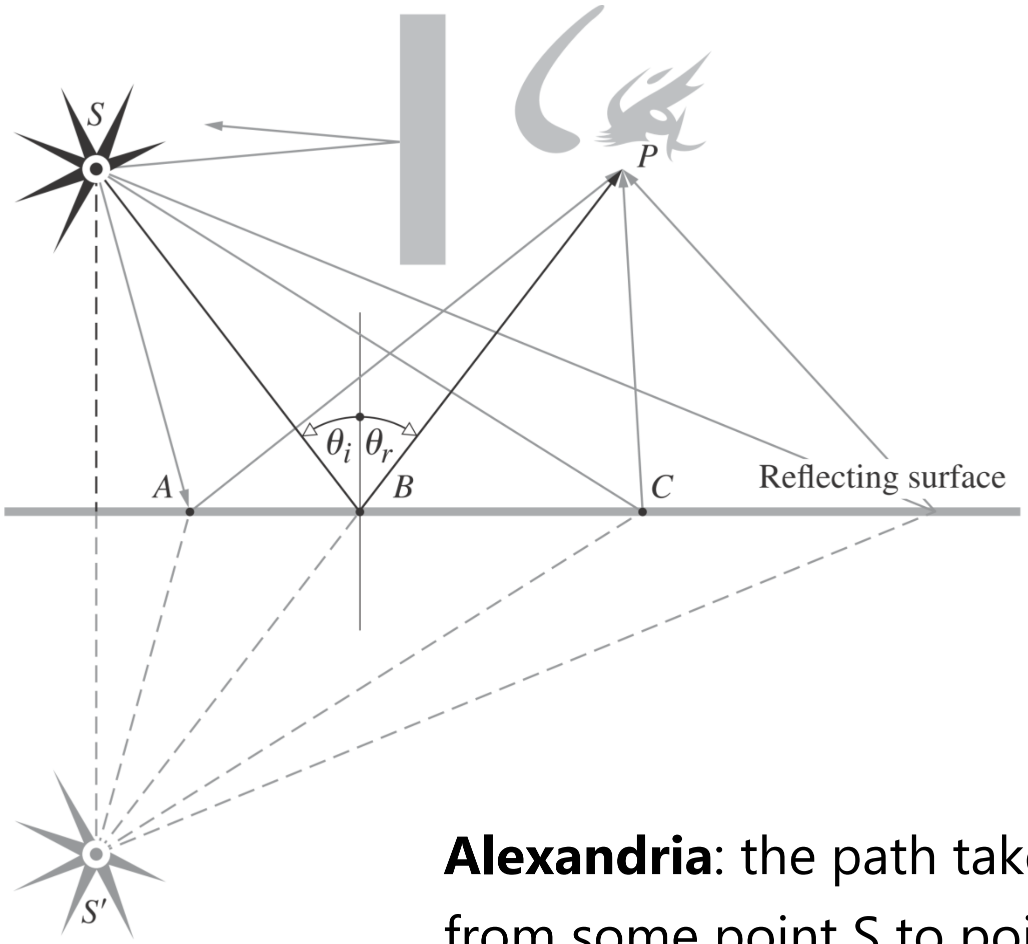
Snell's Law

④ **Law of refraction**: The refracted ray lies in the plane of incidence; the angle of refraction θ_2 is related to the angle of incidence θ_1 by :

$$\sin\theta_1/\sin\theta_2 = n_2/n_1$$ known as **Snell's law**



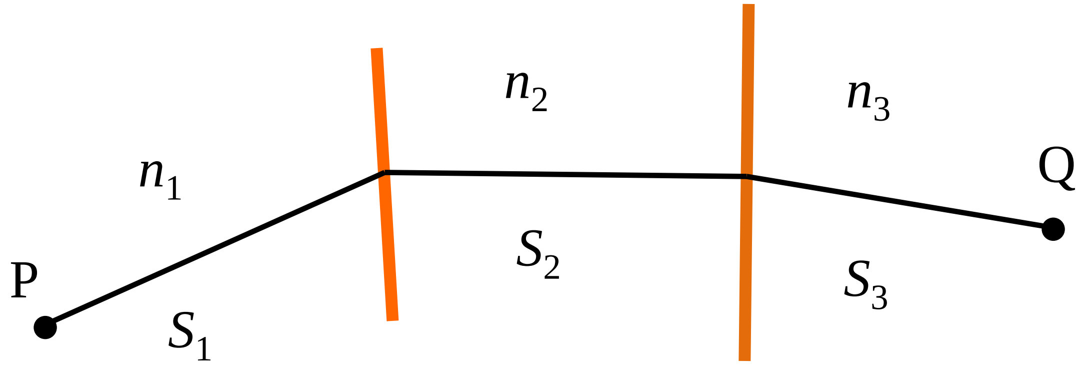
Least time?



Alexandria: the path taken by light in going from some point S to point P via a reflecting surface was the **shortest possible** one.

Optical path length

1657, **Fermat** first introduced the concept of optical path length, which unified the basic laws in geometric optics .



The travelling time for optical rays from P to Q

$$t = S_1/v_1 + S_2/v_2 + S_3/v_3 = \left(n_1 S_1 + n_2 S_2 + n_3 S_3\right)/c \qquad v_i = c/n_i$$

$$\left[l\right] = n_1 S_1 + n_2 S_2 + n_3 S_3$$

[l] is known as **optical path length (*OPL*)** from P to Q.

Optical path length

So the equation can be described as: $t = [l]/c$

The meaning of the t is: whatever the medium is, light spends the same amount of time for travelling the same $[l]$.

- For homogeneous medium: $[l] = nS$
- For piecewise homogenous medium: $[l] = \sum_{i=1}^{N} n_i S_i$
- For medium with continuously varying refractive index：

$$[l] = \int_P^Q n dS$$

$$\mathrm{d}[l] = \mathrm{d}n \cdot S + n \cdot \mathrm{d}S = (\mathrm{d}n + n)\mathrm{d}S \qquad \frac{\mathrm{d}n}{n} \to 0 \qquad \mathrm{d}[l] = n \cdot \mathrm{d}S$$

Fermat's Principle

- Fermat summarized the experimental laws of light propagation:

  The actual path between two points taken by a beam of light is the one that is traversed in the least time. >>**Principle of Least Time**.

- Modern version: Optical rays traveling between two points, A and B, follow a path such that the transit time (or the optical path length) is stationary with respect to the variation of that path. That is to say, in the actual path of light, the variation of the optical path is zero,

$$\delta[l] = \delta \int_P^Q n dS = 0$$

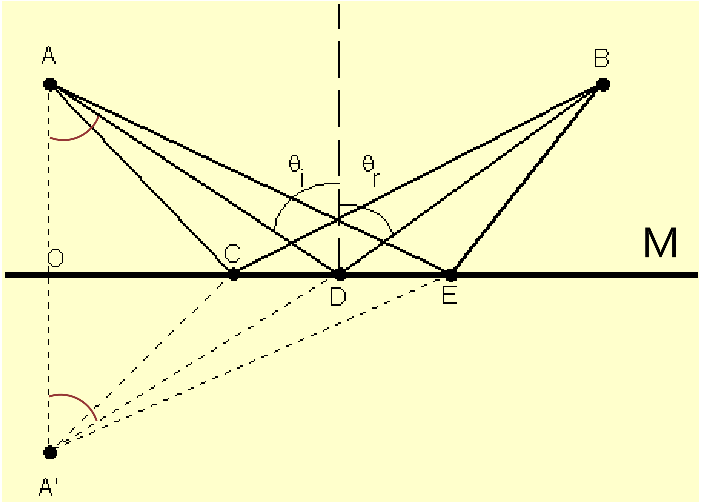
Fermat, 1601~1665, France

Fermat's Principle

① The optical path length is a minimum

Law of reflection deduced by Fermat's principle

What is the minimal length from A to B considering reflection?



Supposed C and E is on the mirror M, A′ is the image of the A about the M.

∴ ACB = A′CB (or AEB = A′EB)

So the AD+DB is the smallest *OPL*.

$$\theta_r = \angle DA'A = \angle DAA' = \theta_i$$

Fermat's Principle

Law of refraction deduced by Fermat's principle

Supposed A$(0, y_2)$, C$(x, 0)$, B(x_1, y_1), so the OPL from A to B

$$[l] = n_i \cdot \mathrm{AC} + n_t \cdot \mathrm{CB}$$

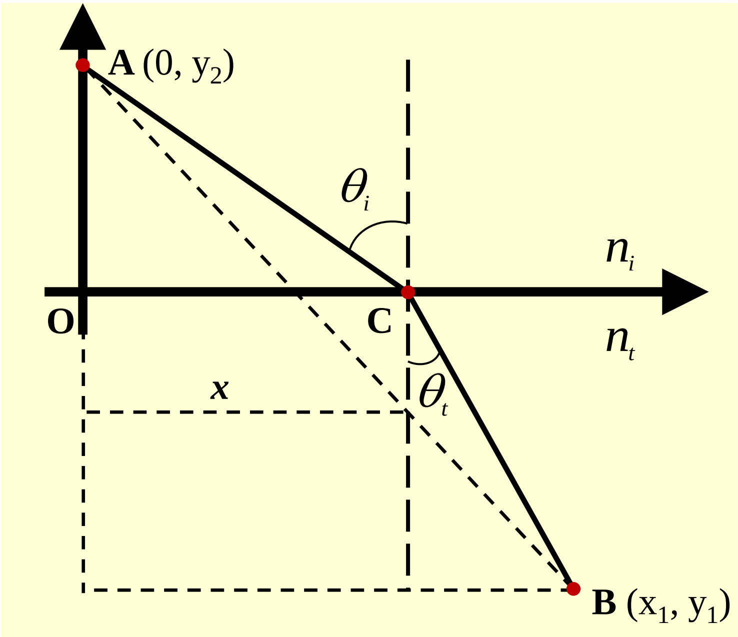
$$= n_i \sqrt{x^2 + y_2^2} + n_t \sqrt{(x - x_1)^2 + y_1^2}$$

$$\frac{d[l]}{dx} = n_i \frac{x}{\sqrt{x^2 + y_2^2}} + n_t \frac{(x - x_1)}{\sqrt{(x - x_1)^2 + y_1^2}} = 0$$

$$n_i \frac{x}{\sqrt{x^2 + y_2^2}} = n_t \frac{(x_1 - x)}{\sqrt{(x - x_1)^2 + y_1^2}}$$

$$\Rightarrow \quad n_i \sin\theta_i = n_t \sin\theta_t$$

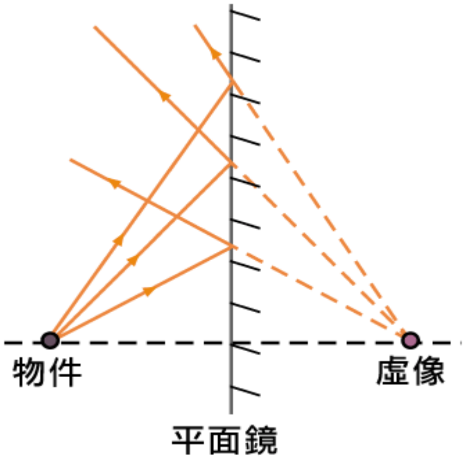
Snell's law



Fermat's Principle

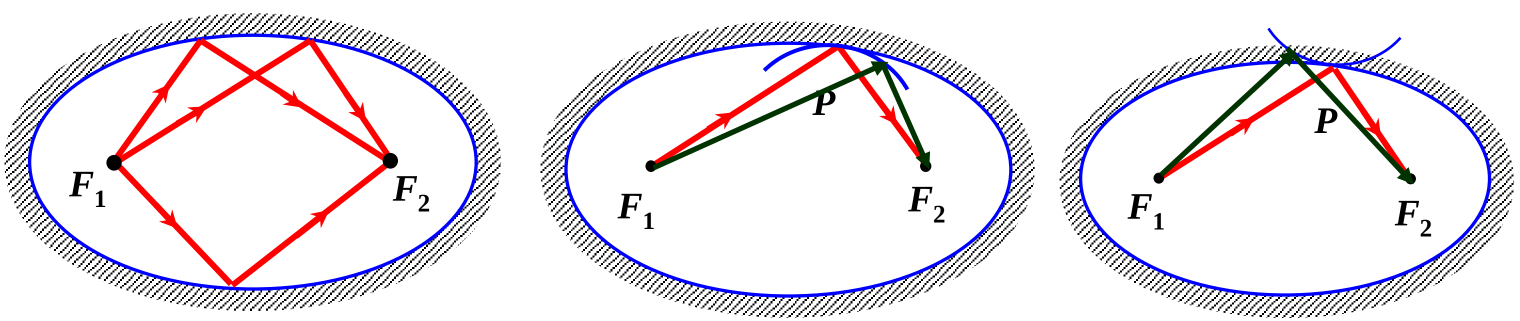
② **The *OPL* is a constant**

- Example: imaging of a plane mirror



③ **The *OPL* is a maximum**

- Example: A concave（凹）mirror internally tangent to an ellipse.



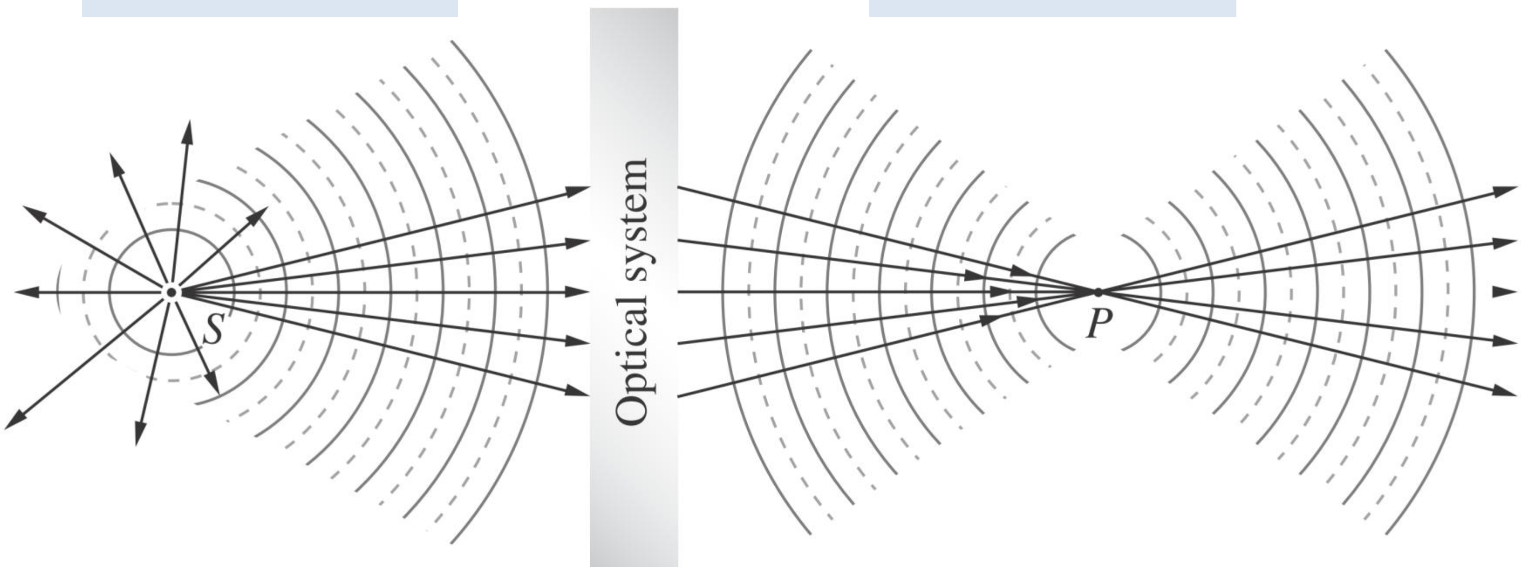
(a) Constant **(b) Max（red line）** **(c) Min（red line）**

§ 1.2 Imaging

In geometric optics, **imaging** is a major issue for an optical system.

Object space

Image space



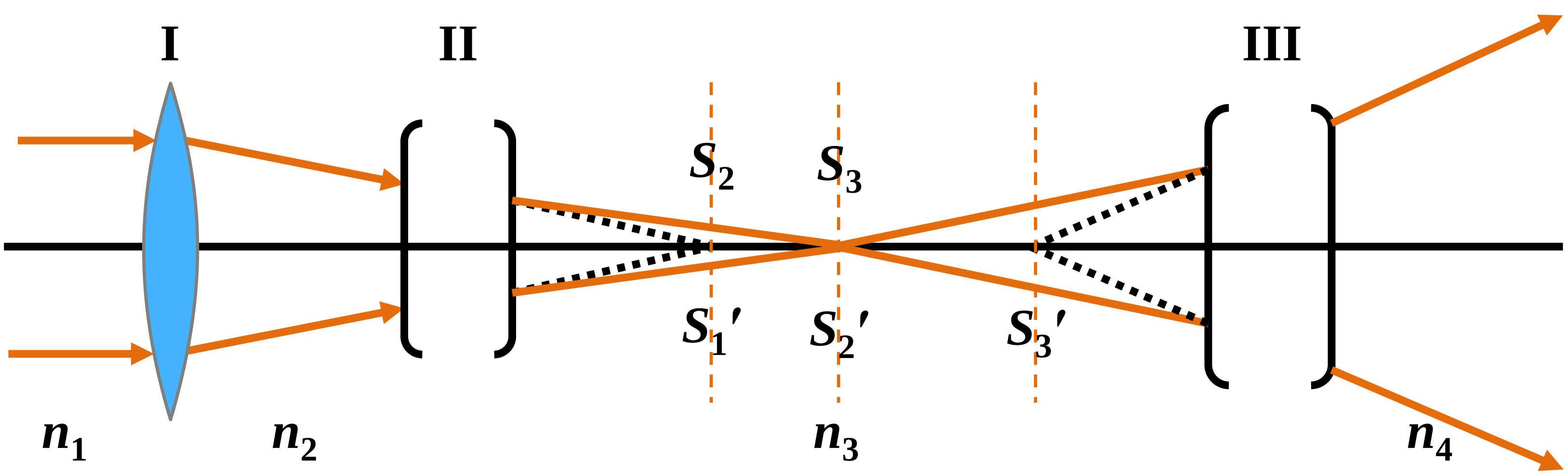
- According to the Principle of Reversibility, a point source at P would be imaged by the same optical system at S.
- S and P are **conjugate points**.

Optical system

Optical system: a system consisting of single or multiple optical elements.

Object space: The region where the incident light is

Image space: The region where the emerging light is

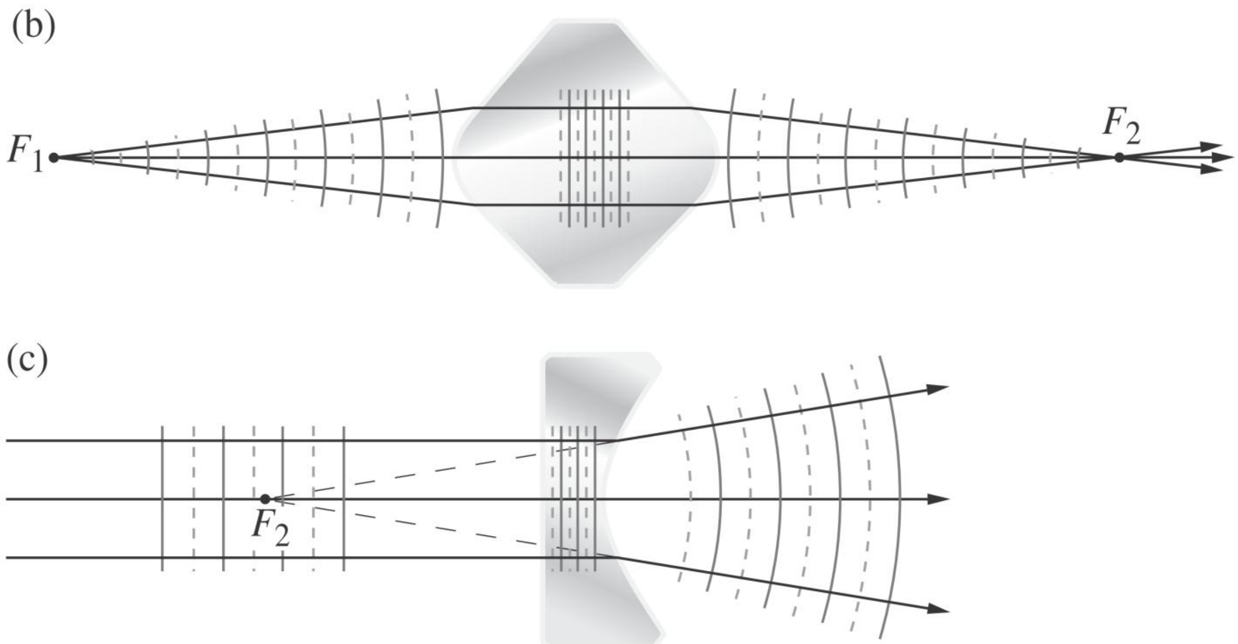


Optical system

- Generally, the image of a point source after an optical system is no longer a point (aberration & diffraction), but instead a blur spot.
- If it is perfectly imaged, >> **ideal optical system**. A plane mirror is an ideal optical system.
- Object point and image point are **conjugate points.**
- For an ideal optical system, the OPL of each light between object point S and image point P is equal. It is an example of a constant OPL in Fermat's principle.

Optical system

- The image can be **real** or **virtual**.



- Both virtual and real images can be seen by the human eyes, but only real images can be received by a screen. Why?
- The object can also be **real** or **virtual** (related to the system)

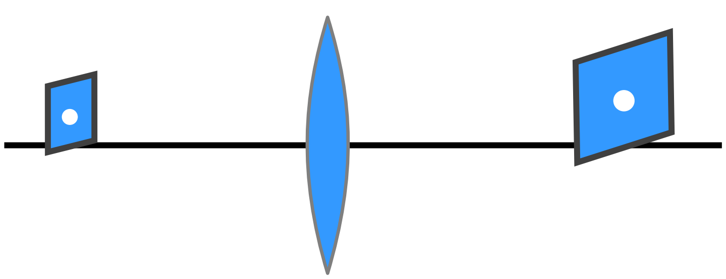
Ideal optical system

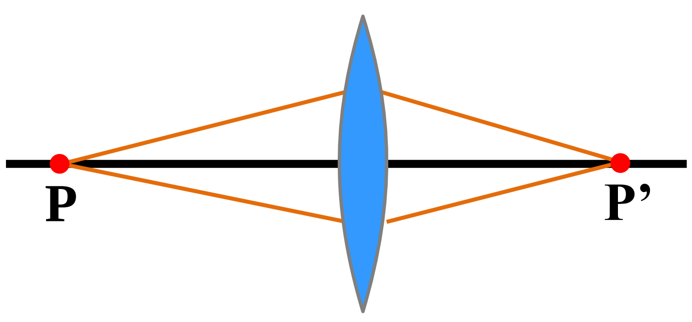
Ideal optical system: the homocentric beam pass through the optical system and is exactly imaged at one point.

① Conjugacy

- Each point/line/plane on the object corresponds to a point/line/plane on the image.

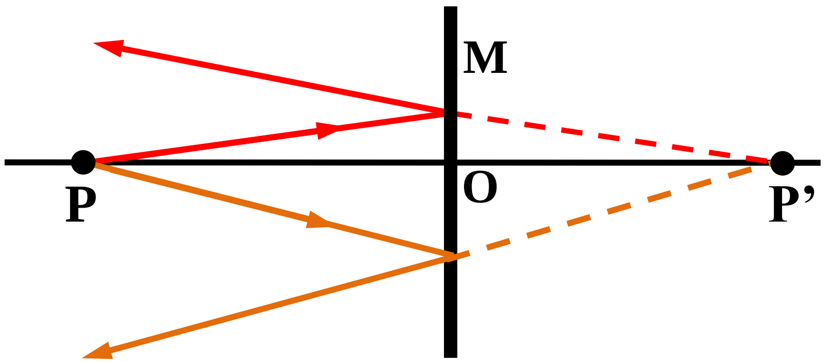
② Equal optical path length





Ideal optical system

Question 1: Is a plane mirror an ideal optical system?



PM = MP′

Yes!

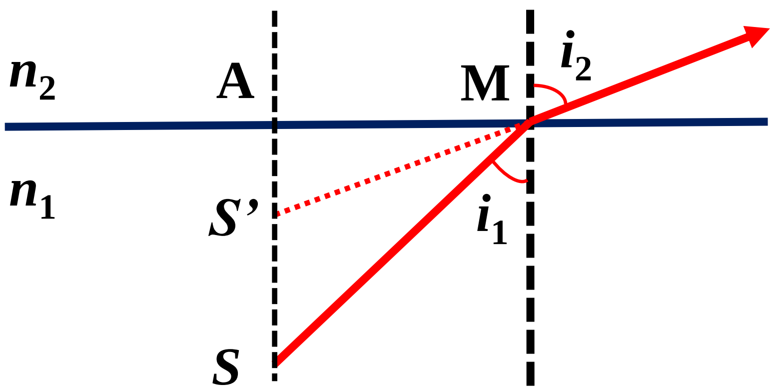
The image is same as the object and they are symmetric about the mirror!

The homocentric rays is still homocentric after being reflected by the plane mirror.

Ideal optical system

Question 2: Is a planar refraction system an ideal optical system?

No!



$$\overline{AM} = \overline{AS} \cdot \tan i_1 = \overline{AS'} \cdot \tan i_2$$

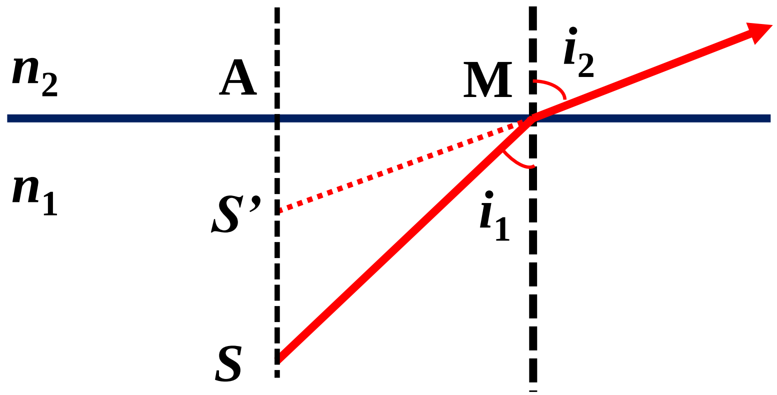
$$\overline{AS'} = \overline{AS} \cdot \frac{\sin i_1 \cos i_2}{\sin i_2 \cos i_1}$$

$$= \overline{AS} \cdot \frac{n_2 \cos i_2}{n_1 \cos i_1}$$

$\because$ the position of S' is changing with the angel i_1.

Ideal optical system

When the i_1 and i_2 is very small

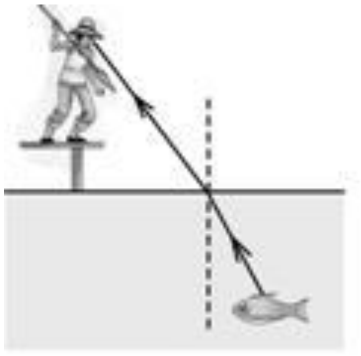


$$\cos i_2 \approx \cos i_1 \approx 1$$

$$\overline{AS'} = \overline{AS} \cdot \frac{n_2 \cos i_2}{n_1 \cos i_1} = \overline{AS} \cdot \frac{n_2}{n_1}$$

When the incident angle is small, the plane refraction system is approximately an ideal optical system.

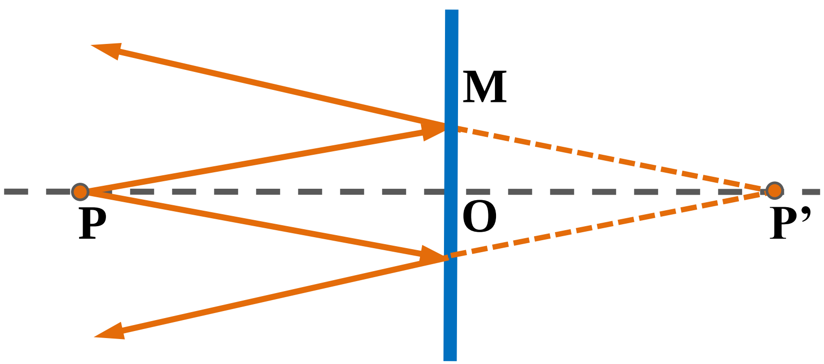
Fishing?



Aplanatic Surface

Aplanatic Surface: A surface that allows all light rays to travel an equal OPL between two points.

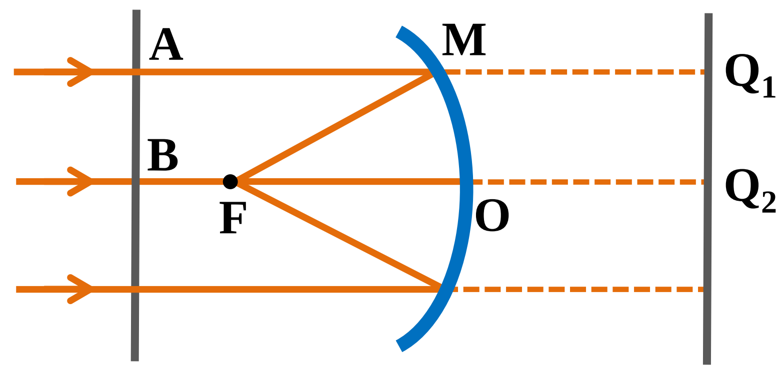
Aplanatic surface using reflection



$$PM - MP' = 0$$

(P and P’)

Aplanatic Surface is a plane



$$AM + MQ_1 = BO + OQ_2$$

(infinity and F)

Aplanatic Surface is a paraboloid

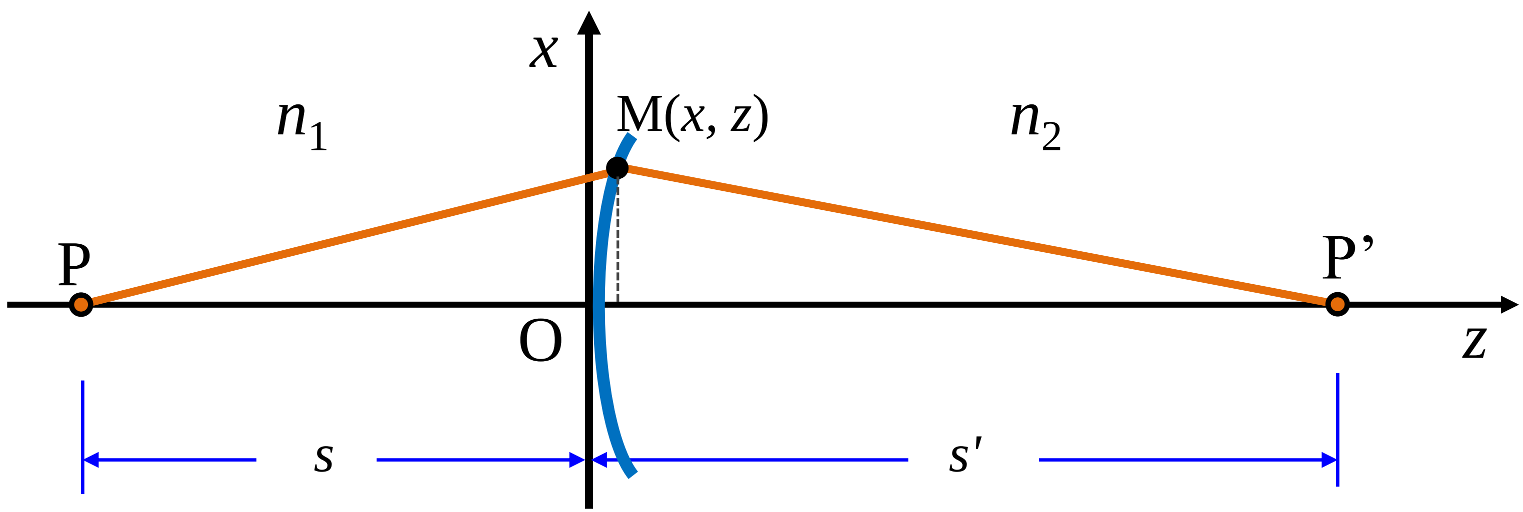
Aplanatic Surface

$$n_1\mathrm{PM} + n_2\mathrm{MP}' = n_1 s + n_2 s'$$

Aplanatic surface using refraction

$$n_1\sqrt{(s+z)^2 + x^2} + n_2\sqrt{(s'-z)^2 + x^2} = n_1 s + n_2 s'$$

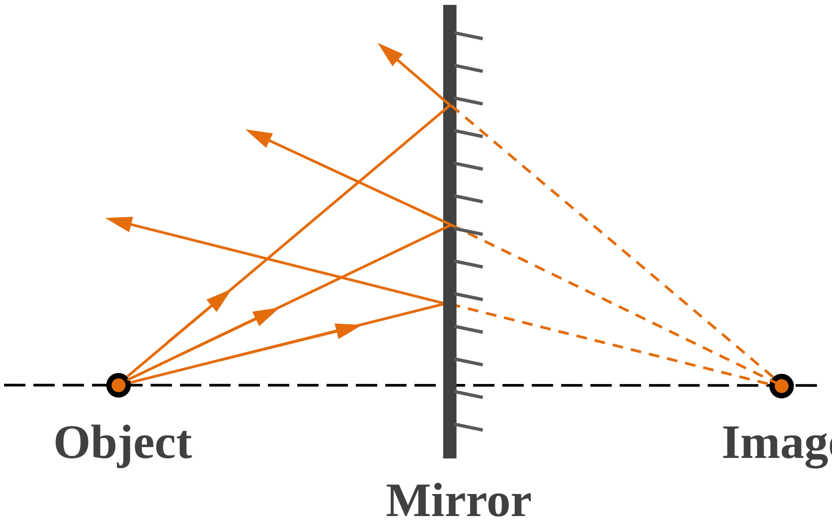
The equation describes an oval line. The curve rotates around the optical axis to form the Cartesian oval surface, which is the aplanatic surface of points P and P′.



Aplanatic Surface

Some comments

- Object and image is relevance only to one optical system.
- The equal OPL between a object and its image applies to both real/virtual object, and real/virtual image.



The OPL between the object and its virtual image is constant 0.

- For virtual object/image, a virtual OPL (negative value) can be introduced.
- An point object can be imaged perfectly by an aplanatic surface, but it not for objects of finite size.

Homework	Problem 7.36
Homework*	Read about the **Principle of Least time** (Feynman Lectures on Physics). Generalized Reflection and Refraction.

Next week

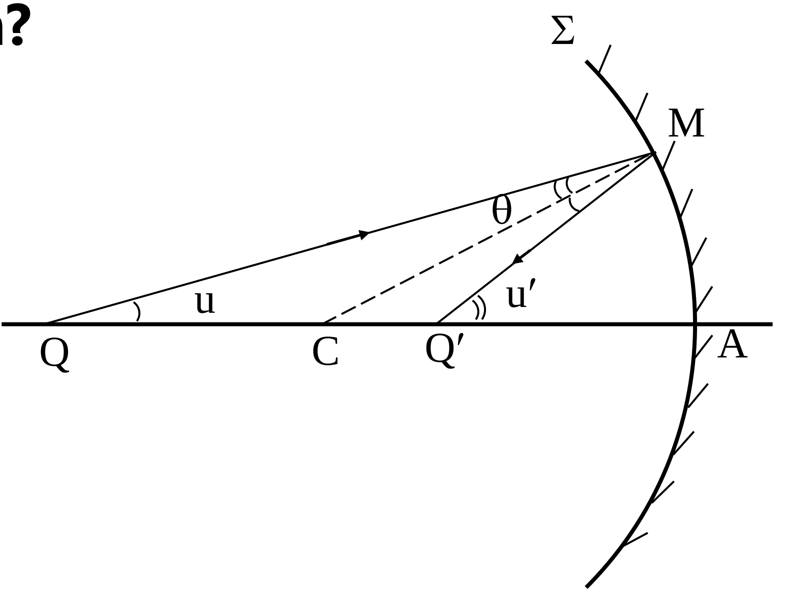
Lens, Mirrors:

Sections 5.2, 5.4

§ 1.3 Spherical surface imaging

① What is paraxial condition?

- Spherical surface mirror Σ, whose center is C. A is the vertex. CA defines the **optical axis** (main axis).



$$u \leq 5°$$

- The ray with a small angle with the optical axis is called the **paraxial rays**. >>**paraxial condition**

$$\cos i = 1 - \frac{i^2}{2!} + \frac{i^4}{4!} \cdots \approx 1 \qquad \sin i = i - \frac{i^3}{3!} + \frac{i^5}{5!} \cdots \approx i \qquad \tan i \approx \sin i \approx i$$

Sign convention

为了导出物像的一般关系，须对有关参量规定一套符号规则。注意符号规则的定义不是唯一的。

- 基准点：球面顶点(单球面系统)、焦点
- 基准线：光轴、各折射点的法线
- 长度量：由指定原点量起顺光线传播方向为正，反之为负。
- 高度量：垂直向上为正，反之为负。
- 角度量规定：以锐角衡量，以主光轴顺时针转到光线为正。
- 规定：图上只标绝对值。

Sign Convention II

TABLE 5.1 Sign Convention for Spherical Refracting Surfaces and Thin Lenses* (Light Entering from the Left)

s_o, f_o	$+$ left of V
x_o	$+$ left of F_o
s_i, f_i	$+$ right of V
x_i	$+$ right of F_i
R	$+$ if C is right of V
y_o, y_i	$+$ above optical axis

*This table anticipates the imminent introduction of a few quantities not yet spoken of.

Sign Convention II

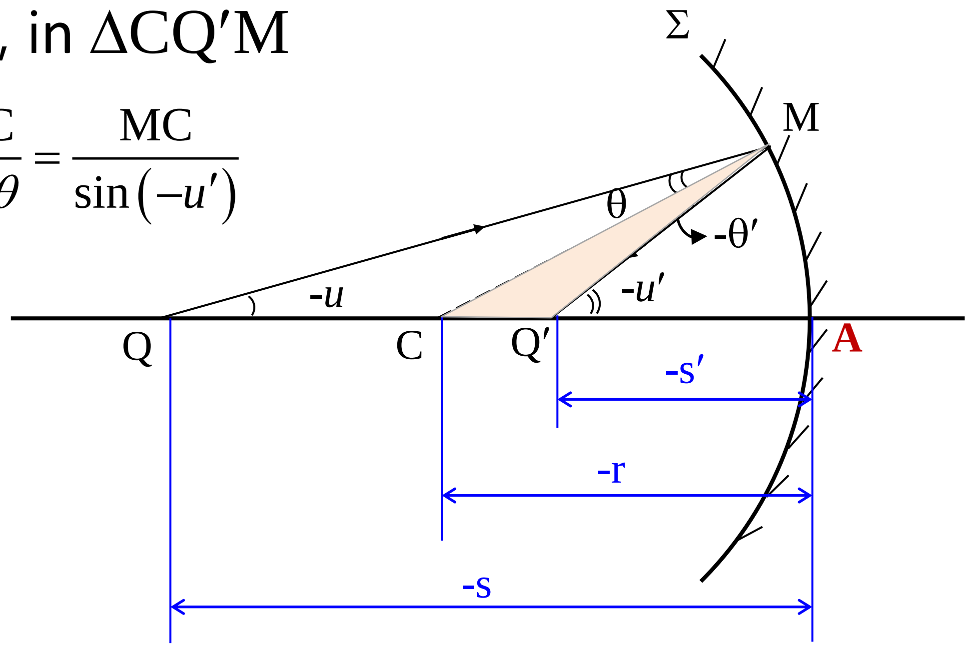
TABLE 5.2 Meanings Associated with the Signs of Various Thin Lens and Spherical Interface Parameters

Quantity	Sign +	Sign −
s_o	Real object	Virtual object
s_i	Real image	Virtual image
f	Converging lens	Diverging lens
y_o	Erect object	Inverted object
y_i	Erect image	Inverted image
M_T	Erect image	Inverted image

Reflection at spherical surfaces

According to Law of Sines, in $\Delta CQ'M$

$$\frac{Q'C}{\sin(-\theta')} = \frac{MC}{\sin(\pi-(-u'))} \Rightarrow \frac{Q'C}{\sin\theta} = \frac{MC}{\sin(-u')}$$



In ΔCQM $\quad \dfrac{QC}{\sin\theta} = \dfrac{MC}{\sin(-u)}$

$$\Rightarrow \frac{QC}{Q'C} = \frac{\sin(-u')}{\sin(-u)}$$

$$QC = -s-(-r) = r-s$$

$$Q'C = -r-(-s') = s'-r$$

QA: optical axis. A: vertex of Σ.

Using **paraxial condition**:

$$\sin(-u) \approx \tan(-u) = MA/QA$$

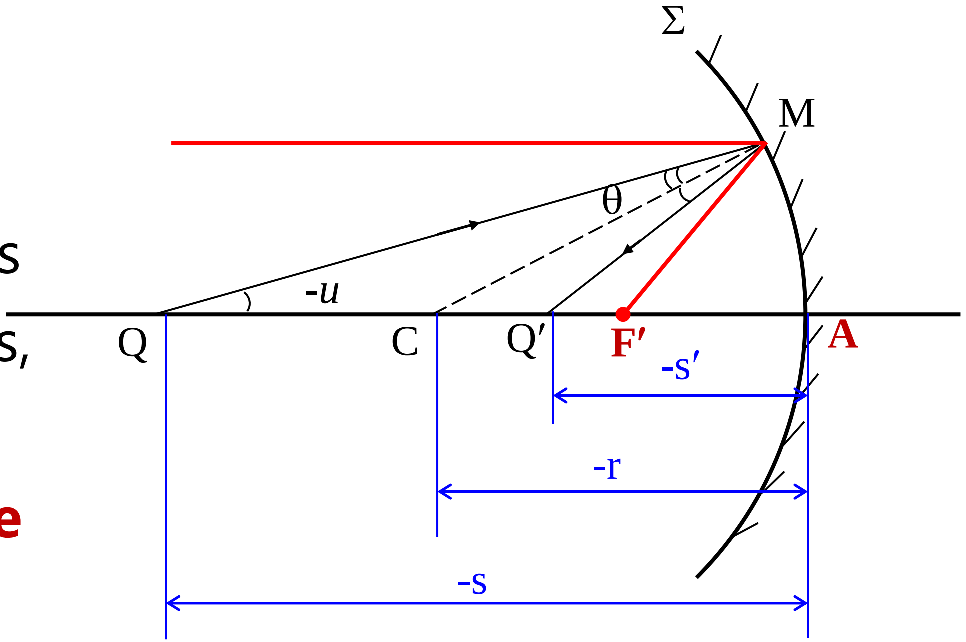
$$\sin(-u') \approx \tan(-u') = MA/Q'A$$

$$\Rightarrow \frac{QC}{Q'C} = \frac{QA}{Q'A} \quad \begin{cases} \dfrac{r-s}{s'-r} = \dfrac{-s}{-s'} \\ \boxed{\dfrac{1}{-s} + \dfrac{1}{-s'} = -\dfrac{2}{r}} \end{cases}$$

Reflection at spherical surfaces

$$\boxed{\frac{1}{-s}+\frac{1}{-s'}=-\frac{2}{r}}$$

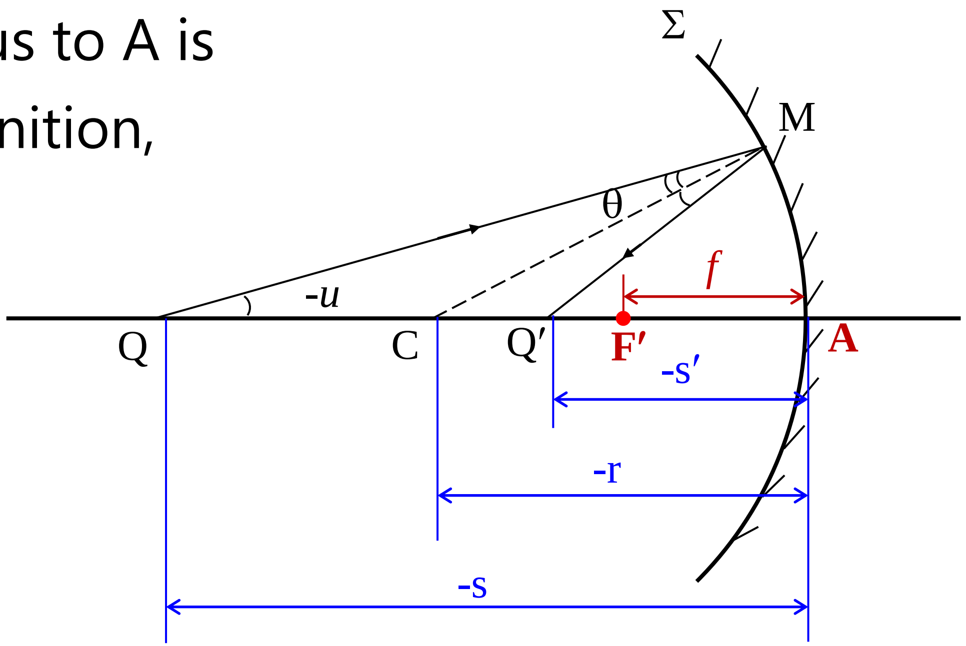
- When the incident light is parallel to the optical axis, $-s=\infty$, then $-s'=-r/2$. This point is called **image focus**, marked as F′.



- Otherwise, if $-s=-r/2$, then $-s'=\infty$.
  The point where $-s=-r/2$ is also called **object focus**, marked as F.

Reflection at spherical surfaces

The distance from the focus to A is called focal length. By definition,



Object focal length f and **image focal length** f' are:

$$f = \lim_{s' \to \infty} s$$

$$f' = \lim_{s \to \infty} s'$$

$$\frac{1}{-s} + \frac{1}{-s'} = -\frac{2}{r}$$

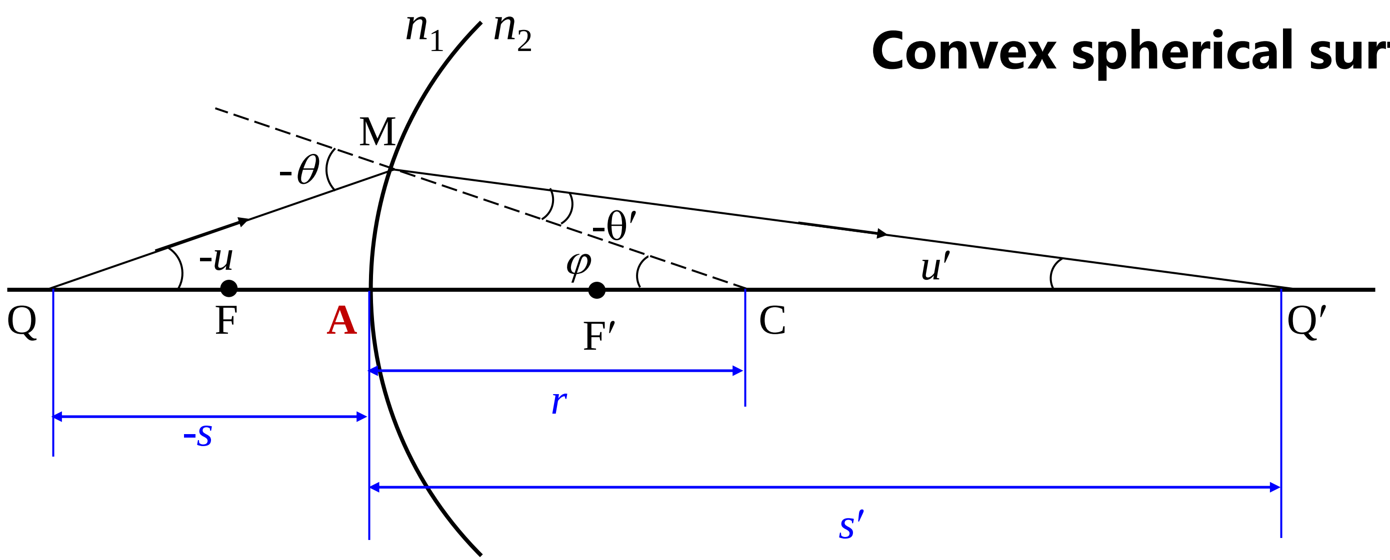
So, $f = f' = r/2$

$$\boxed{\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}}$$

If $r \to \infty$, $s = s'$. This is the case of plane mirror imaging.

Refraction at spherical surfaces

Convex spherical surface



From the figure, $-\theta = -u + \varphi$, $-\theta' = \varphi - u'$

According to paraxial condition:

$$-u = -\tan u = MA/-s$$

$$u' = \tan u' = MA/s'$$

$$\varphi = MA/r$$

Snell's Law: $n_1 \sin(-\theta) = n_2 \sin(-\theta')$

$$n_1(-\theta) = n_2(-\theta')$$

$$\Rightarrow \left\{ \begin{aligned} & n_1(-u+\varphi) = n_2(\varphi - u') \\ & n_1\left(\frac{MA}{-s} + \frac{MA}{r}\right) = n_2\left(\frac{MA}{r} - \frac{MA}{s'}\right) \\ & \boxed{\frac{n_1}{-s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{r}} \end{aligned} \right.$$

Refraction at spherical surfaces

$$\boxed{\frac{n_1}{-s}+\frac{n_2}{s'}=\frac{n_2-n_1}{r}} \equiv \Phi \qquad 光焦度$$

Since:

$$f=\lim_{s'\to\infty} s=-\frac{n_1 r}{n_2-n_1}=-\frac{n_1}{\Phi}$$

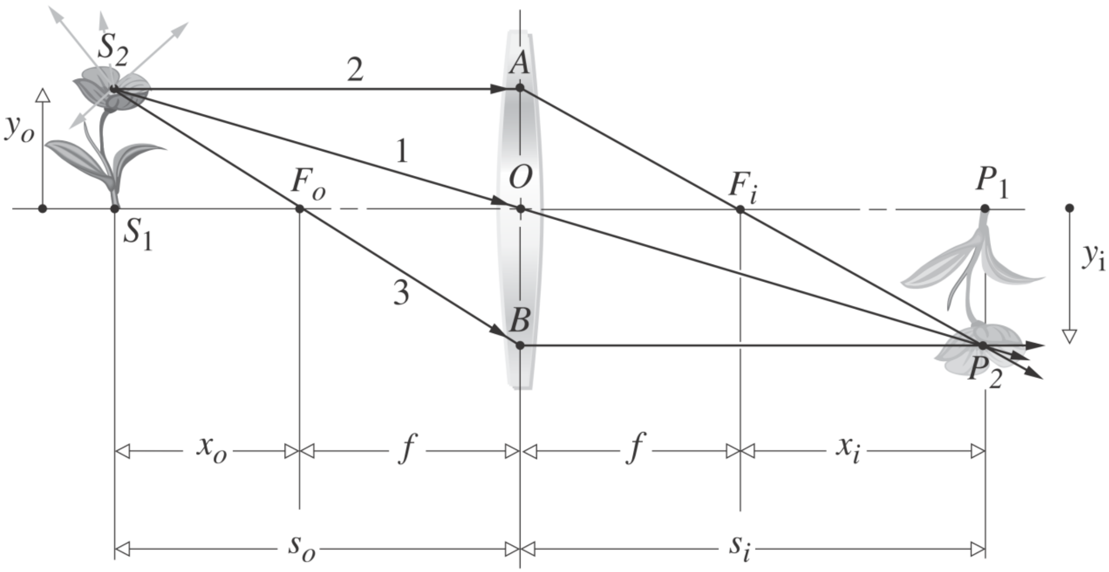
$$f'=\lim_{s\to\infty} s'=\frac{n_2 r}{n_2-n_1}$$

Then:

$$\boxed{\frac{f}{s}+\frac{f'}{s'}=1}$$

- This formula is called **Gaussian Lens Formula**.
- Reflection at spherical surface is a special case ($f=f'$)

Newton form of Lens Formula

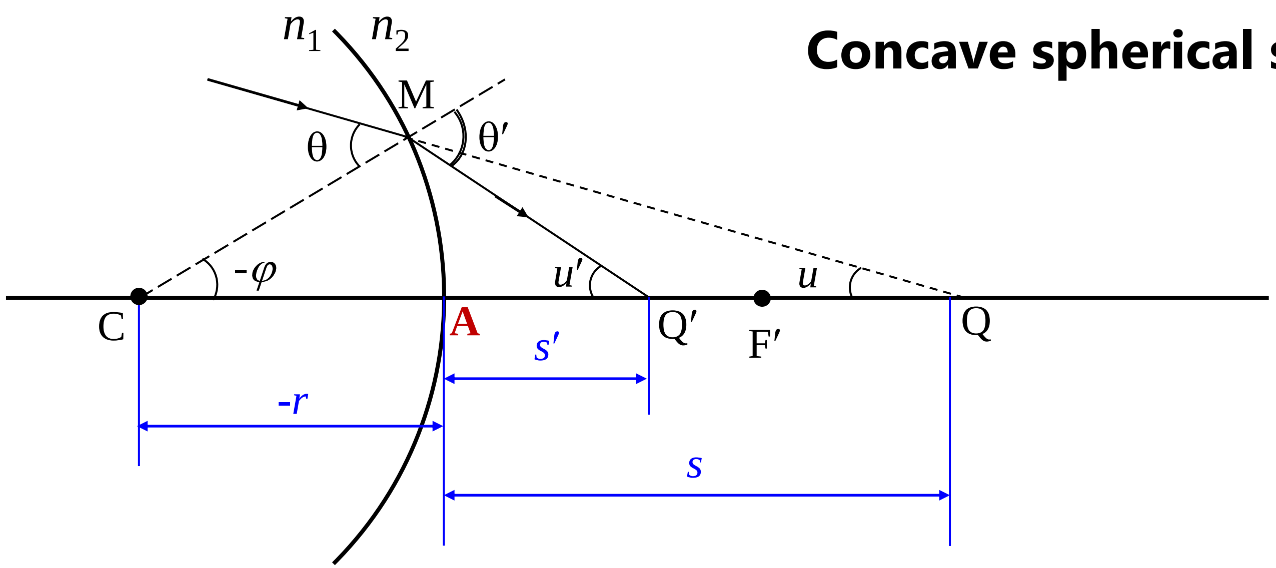


- If the object distance and image distance are defined from F and F', represented by x_o and x_i, and the sign convention is the same as before, then the lens formula is:

$$\boxed{x_o x_i = ff'}$$

Refraction at spherical surfaces

Concave spherical surface



From the figure, $\theta = u - \varphi,\ \theta' = -\varphi + u'$

Using paraxial condition:

$u = \tan u = \mathrm{MA/s}$

$u' = \tan u' = \mathrm{MA/s'}$

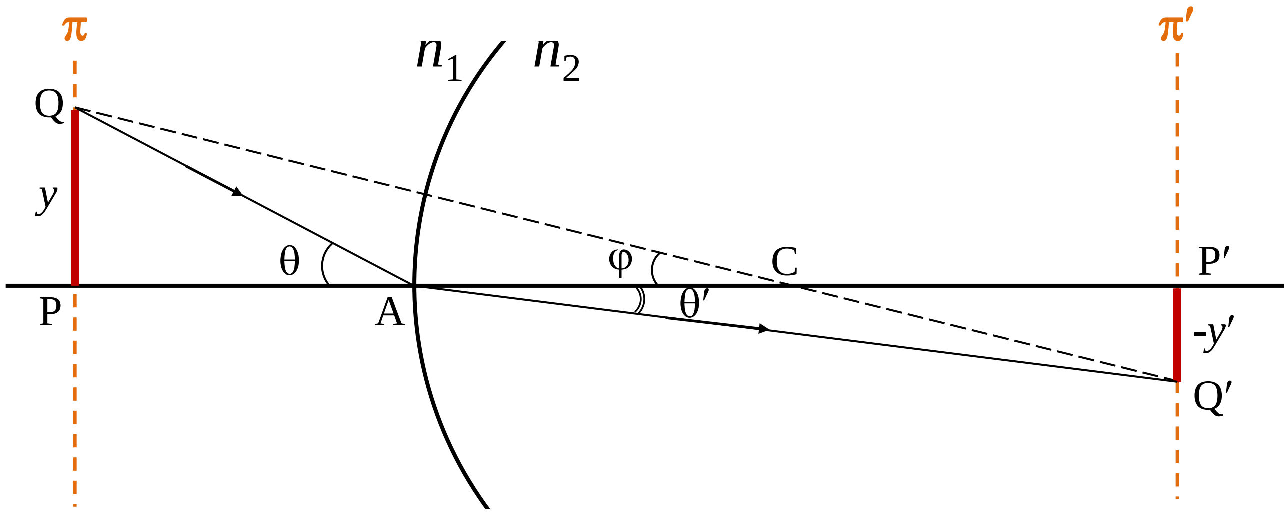
$-\varphi = \mathrm{MA}/(-r)$

Snell's Law: $n_1 \sin\theta = n_2 \sin\theta'$

$n_1\theta = n_2\theta'$

$$\Rightarrow \begin{cases} n_1(u-\varphi) = n_2(-\varphi + u') \\ n_1\left(\frac{\mathrm{MA}}{s} + \frac{\mathrm{MA}}{-r}\right) = n_2\left(\frac{\mathrm{MA}}{-r} + \frac{\mathrm{MA}}{s'}\right) \\ \boxed{\frac{n_1}{-s} + \frac{n_2}{s'} = \frac{n_2 - n_1}{r}} \end{cases}$$

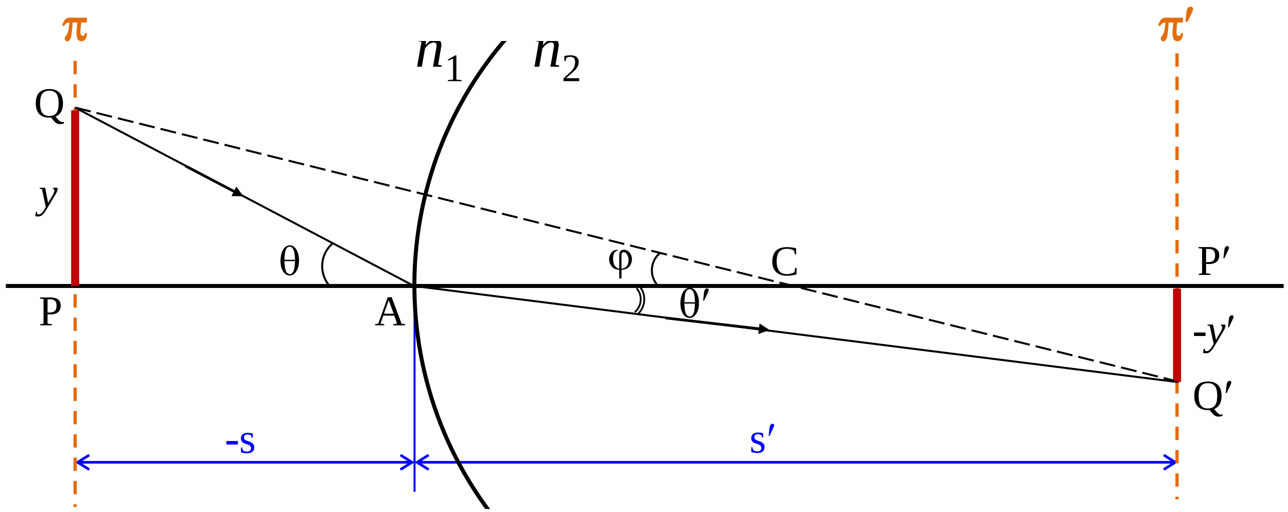
Imaging for off-axis points



From the imaging of an on-axis point P, rotate the PP′ around C by φ, P→Q, P′→Q′. Then, Q and Q′ are conjugate points.

Since φ is small, PQ can be seen as a line segment perpendicular to the main axis. The plane is called the **object plane** and represented by π. Similarly, there is a plane π′ where P′Q′ lies, called the **image plane**. π and π′ are conjugate planes.

Imaging for off-axis points



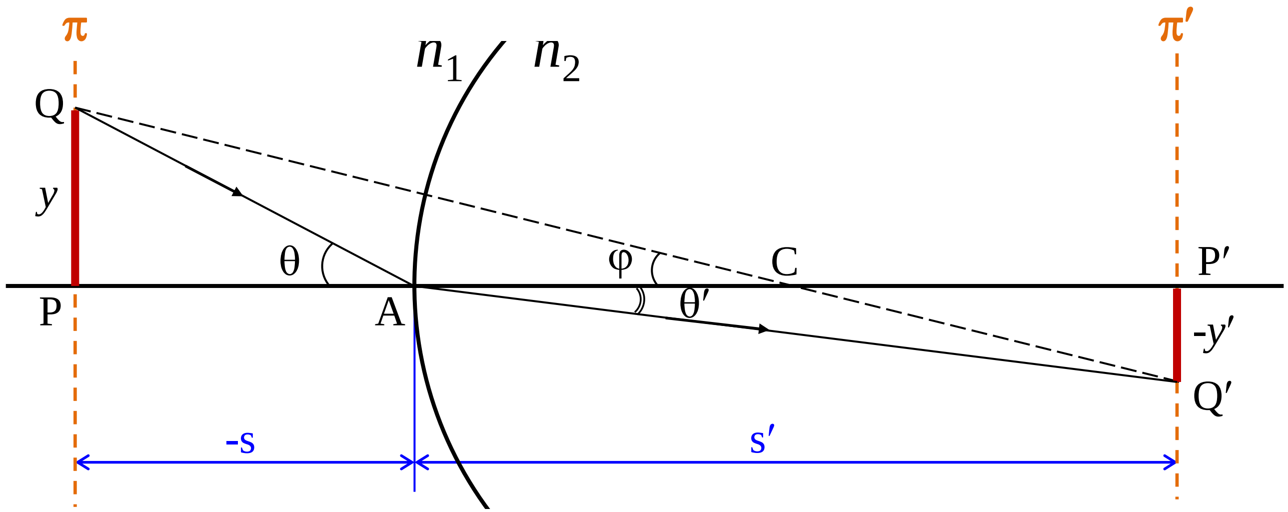
If the length of PQ is y, P′Q′ is $-y'$.

Transverse magnification β: the ratio of the height of image and object: $$\beta = y'/y$$

$\beta > 0$, Upright; $\beta < 0$, Inverted.

$|\beta| > 1$, Magnified; $|\beta| < 1$, Minified.

Imaging for off-axis points



$\because$ $\theta = \text{PQ/PA} = y/(-s)$

$\theta' = \text{P}'\text{Q}'/\text{Q}'\text{A} = -y'/s'$

$\because$ Snell's law: $n_1\theta = n_2\theta'$

$\therefore$ $-n_1 y/s = -n_2 y'/s'$

$\Rightarrow$

$$\begin{cases} \beta = \dfrac{y'}{y} = \dfrac{n_1 s'}{n_2 s} \\ \beta < 0 \quad \text{Inverted} \\ n_1 < n_2 \quad |\beta| < 1 \quad \text{Minified} \end{cases}$$

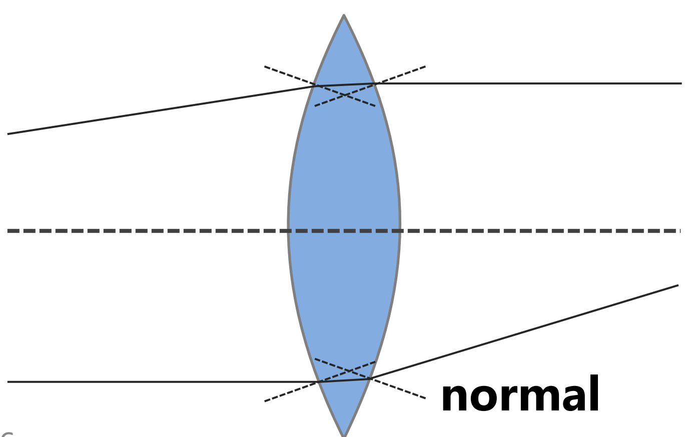
For spherical mirrors, $\beta = -s'/s$

§ 1.4 Imaging by thin lens

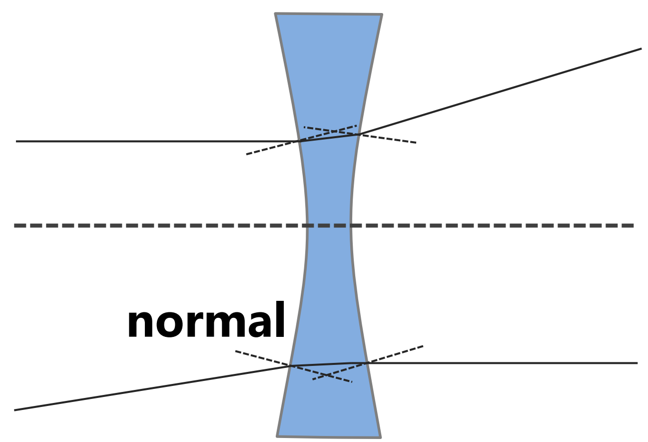
- **Thin lens**: the lens whose central thickness is negligible compared with the radius of curvature.
- **Optic axis**: the axis that connects two curvature centers.
- **Optic center**: In a thin lens, the vertices of two refraction spheres can be approximated as coincident, and the point is called optical center.

The thin lens is composed of two coaxial refraction spheres:

convex lens



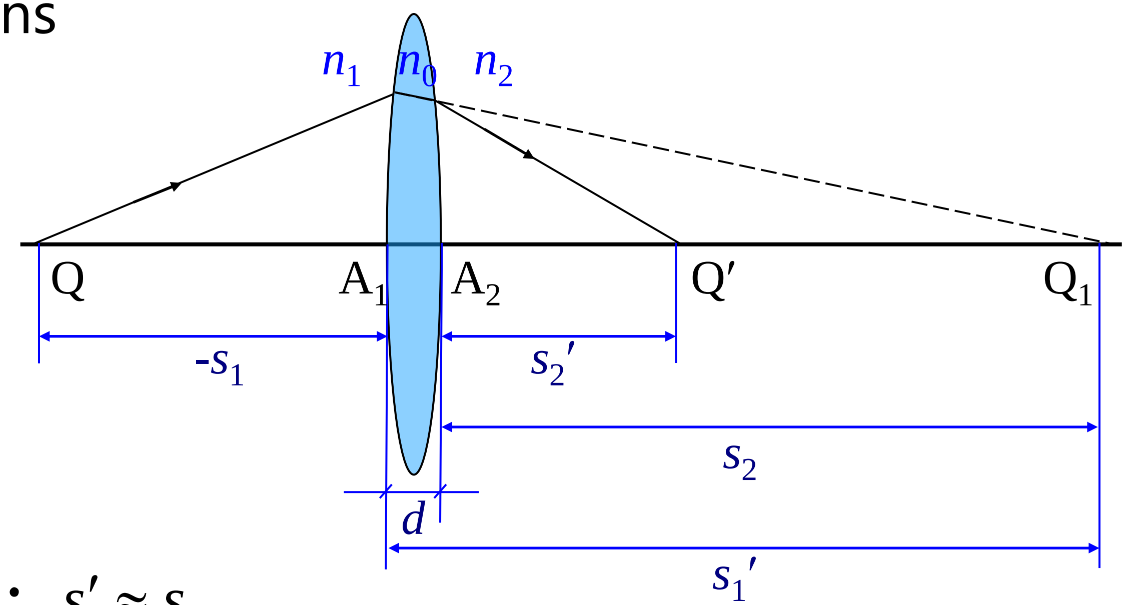
concave lens



Lens equation

According to the Lens equation:

$$\begin{cases} \dfrac{n_1}{-s_1} + \dfrac{n_0}{s_1'} = \dfrac{n_0 - n_1}{r_1} \\ -\dfrac{n_0}{s_2} + \dfrac{n_2}{s_2'} = \dfrac{n_2 - n_0}{r_2} \end{cases}$$



For thin lens, $d \approx 0$, $\therefore\ s_1' \approx s_2$

$$\frac{n_1}{-s_1} + \frac{n_2}{s_2'} = \frac{n_0 - n_1}{r_1} + \frac{n_2 - n_0}{r_2} \equiv \Phi$$

- Similar to single spherical mirror, Φ is the focal power. It is the sum optical power of two refraction surface.

Lens equation

Definition of the thin lens: f、f'

$$\frac{n_1}{-s_1}+\frac{n_2}{s_2'}=\frac{n_0-n_1}{r_1}+\frac{n_2-n_0}{r_2}\equiv\Phi$$

$$f=\lim_{s'\to\infty}s=-\frac{n_1}{\dfrac{n_0-n_1}{r_1}+\dfrac{n_2-n_0}{r_2}}$$

$$f'=\lim_{s\to\infty}s'=\frac{n_2}{\dfrac{n_0-n_1}{r_1}+\dfrac{n_2-n_0}{r_2}}$$

$$\Rightarrow\quad\frac{f}{f'}=-\frac{n_1}{n_2}$$

∴ Thin lens equation：

$$\frac{n_1}{-s_1}+\frac{n_2}{s_2'}=\Phi\quad\Rightarrow\quad\boxed{\frac{f}{s_1}+\frac{f'}{s_2'}=1}\quad\xRightarrow{n_1=n_2}\quad\boxed{\begin{cases}f=-f'\\-\dfrac{1}{s}+\dfrac{1}{s'}=\dfrac{1}{f'}\end{cases}}$$

Gaussian Lens Formula

Lens equation

- Transverse magnification of single spherical lens：

$$\beta = \frac{y'}{y} = \frac{n_1 s'}{n_2 s}$$

- Transverse magnification of single spherical lens：

$$\beta = \beta_1 \cdot \beta_2 = \frac{n_1 s_1'}{n_0 s_1} \cdot \left(\frac{n_0 s_2'}{n_2 s_1'} \right) = \frac{n_1 s_2'}{n_2 s_1}$$

- When the thin lens is in air, then $n_1 = n_2 = 1$， so

$$\beta = \frac{s_2'}{s_1}$$

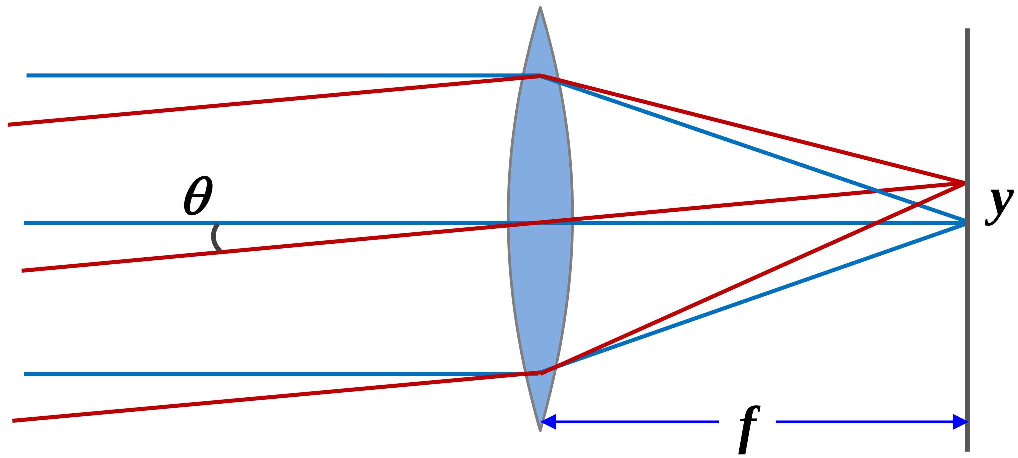
Focal plane

- **Focal plane**: a plane normal to the optical axis and passing though the image focus. First/**front focal plane** and Second/**back focal plane.**

- If the light emanate from point P on the front focal plane passes through the thin lens, the outgoing light must be **collimated**, and along the direction of OP.
- Parallel light incident at any angle will converge at **one point** on the back focal plane.

Focal plane

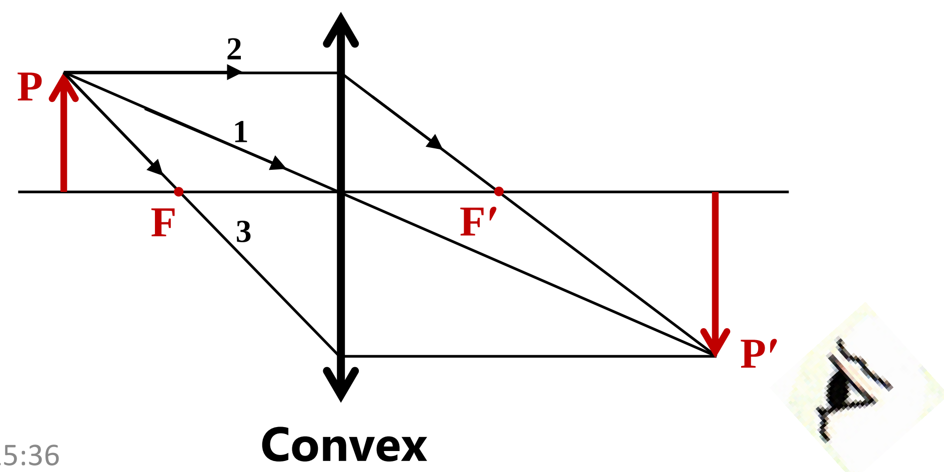
A lens makes a correlation between a direction and a location on a plane.



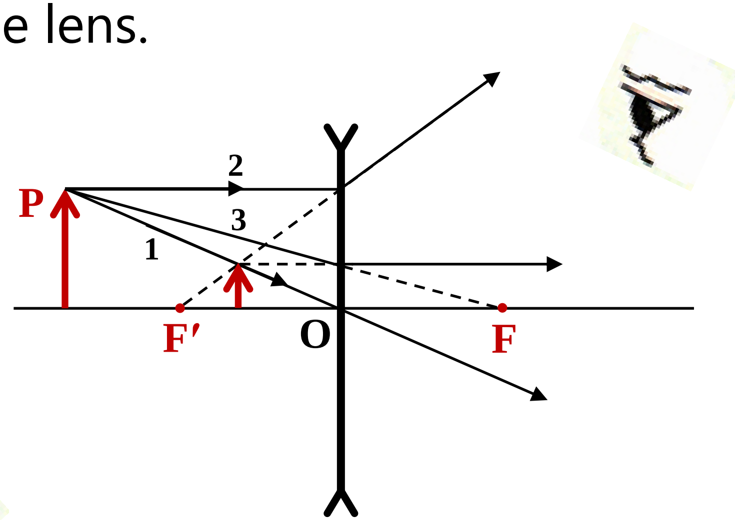
- Two parallel beams incidence with an angle of θ converse on the focal plane with a distance : $\boxed{y = f \cdot \tan\theta \approx f \cdot \theta}$
- Angle (i.e., propagation direction, momentum) v.s. position.
- Imaging by a lens is equivalent to perform twice the Fourier transform. >>Chapter 8

Ray diagram

- For **off-axis point P**, any two of the following three pairs.
  ① The incident light PO passing through the optical center is still in the original direction when it exits;
  ② The incident light parallel to the main axis passes through the image focus F′;
  ③ When the incident light passes though the focal point F, it is parallel to the main axis after the lens.



Convex



Concave

Ray diagram

- For **on-axis Point P**, two ways to get the image point P'.

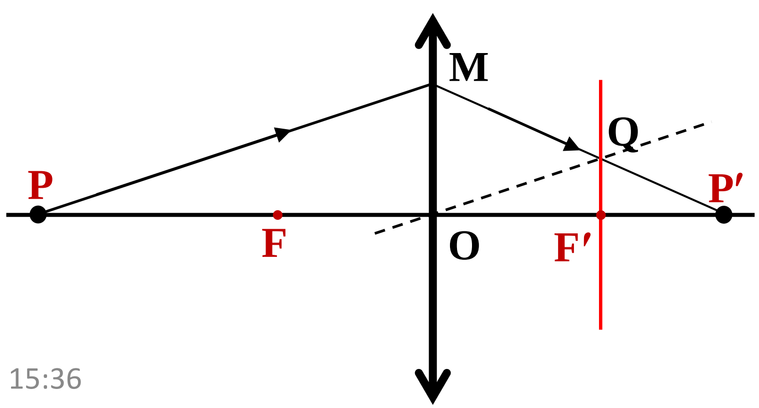
(a) Move the P away from the main axis (vertical), find the image point, move the image point back to the main axis, and get P'.

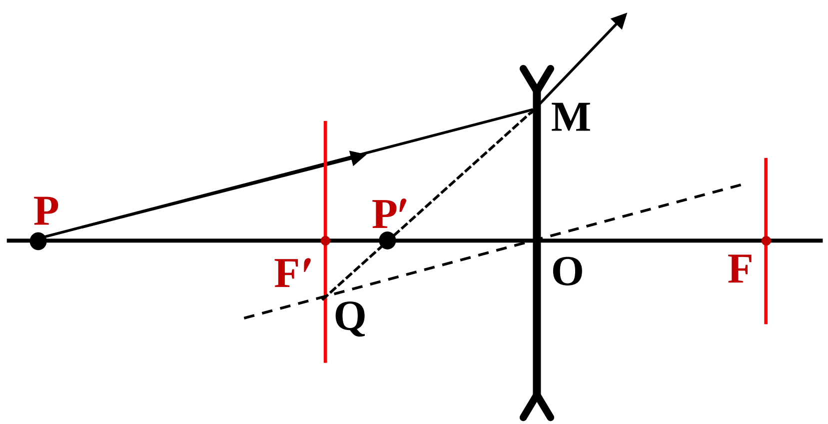
(b) Using focal plane:

① Plot an arbitrary line PM;

② Plot a parallel line that passes the optical center O with the OQ crossing the focal plane at Q;

③ Connected M and Q, the line MQ intersects the main axis at P'.

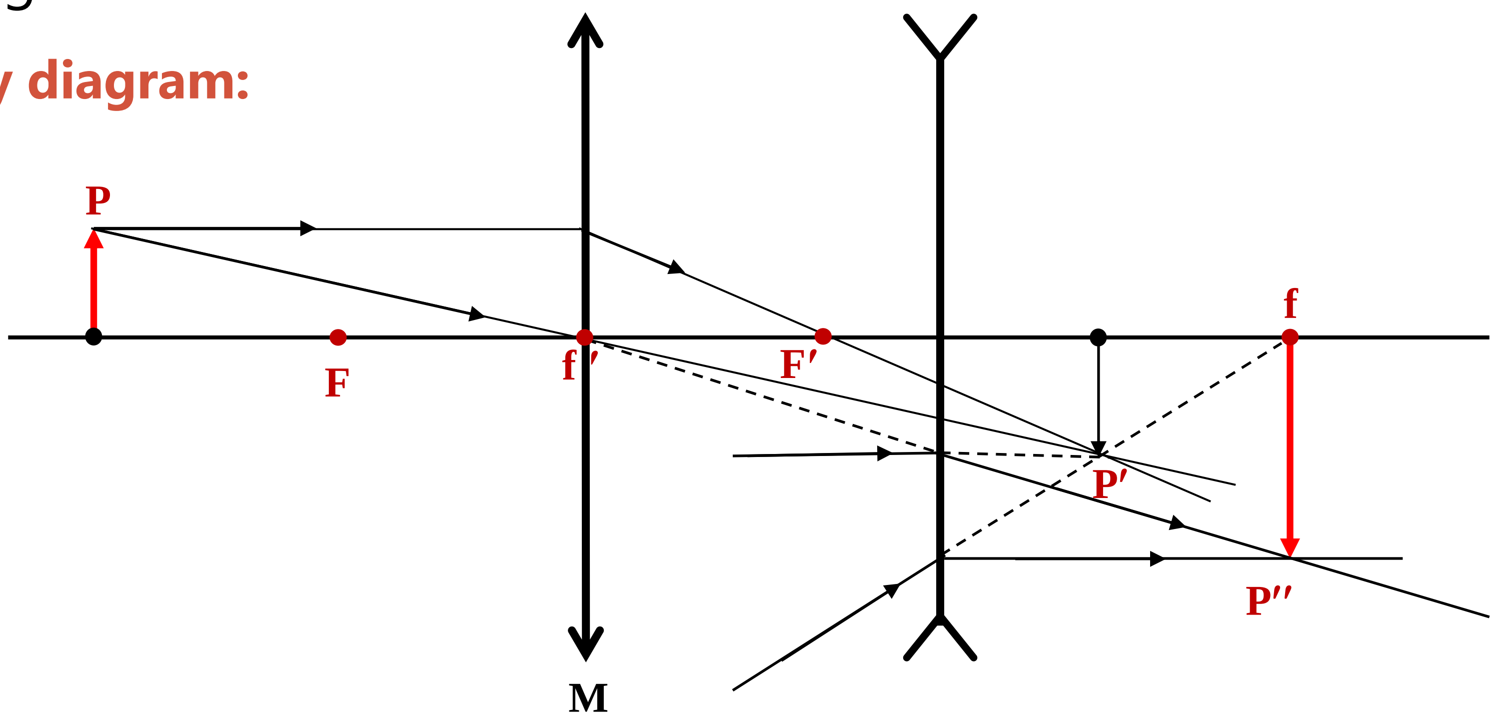




Thin-Lens combinations

Exercise: The distance from P to the lens M ($f_1 = 15$ cm) is 30 cm. Place a concave lens 20 cm away from the convex lens on the other side ($f_2 = 20$ cm), where is the P″ ? And compute the magnification.

Ray diagram:



Thin-Lens combinations

According to the lens equation, $-1/s + 1/s' = 1/f_1$

then： $1/s' = 1/f - 1/s = 1/30$

$\therefore s' = 30$ cm

Magnification: $\beta = -s'/s = -1$

For concave lens, object distance： $s_1 = 30 \text{ cm} - 20 \text{ cm} = 10$ cm

Similarly， $s'_1 = 20$ cm. $\beta_{total} = -2$

- This system changes the size of the image by slightly changing the position of the concave mirror.

§ 1.5 Stops in optical system

- **Stop**： Optical elements that limit the imaging beam. e.g., a lens, an aperture, the frame of windows.

- The functionality of an optical stop?

  ① Improve the image quality and reduce some aberrations

  ② Control light intensity through the system

  ③ Limit the scope of imaging (field size)

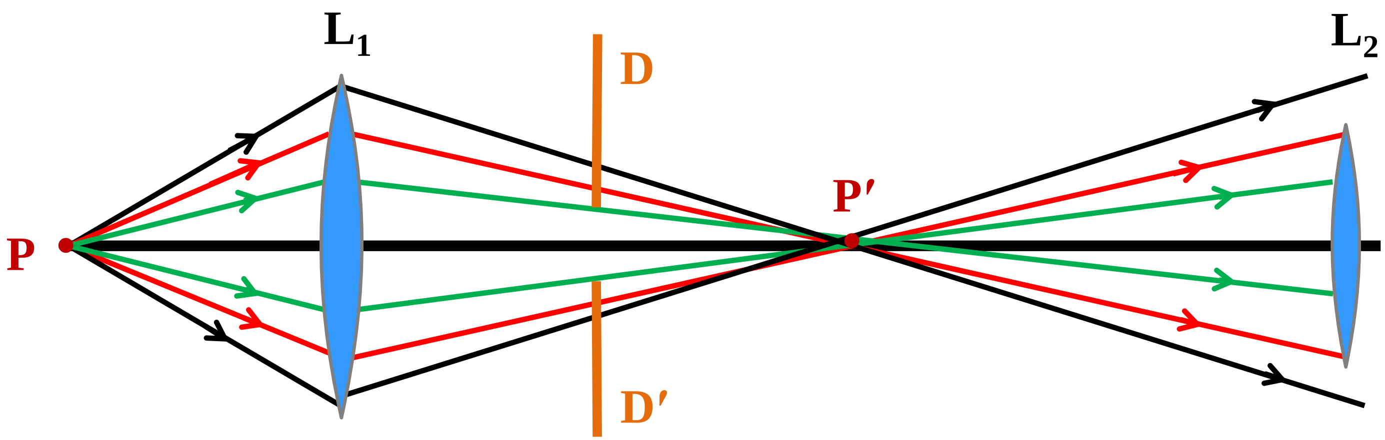
  ④ Block harmful light

- Aperture stop, Field stop, Glare stop (消杂散光光阑)

Aperture stop

- **Aperture stop**: The aperture that limits the breadth of the beam of light coming from an axial object point as it passes through the system.

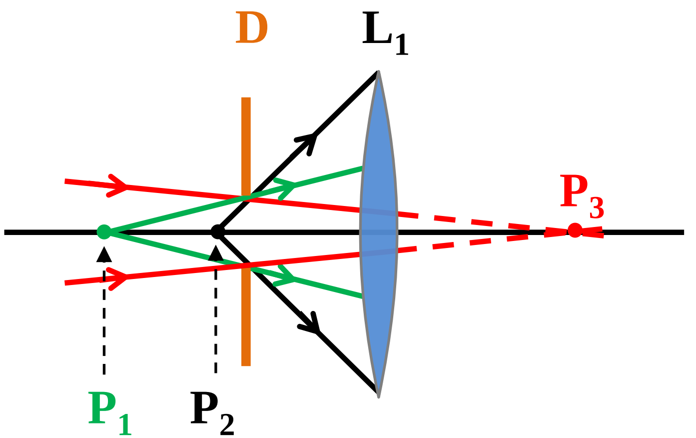
  It determines the **cross-section size** of the optical beam and **optical power** through the optical system.



L_1 -> L_2 -> DD′

Aperture stop

- For a fixed point, the aperture stop is determined by the relative position and size of the apertures in the system.



For P_1, D is aperture stop

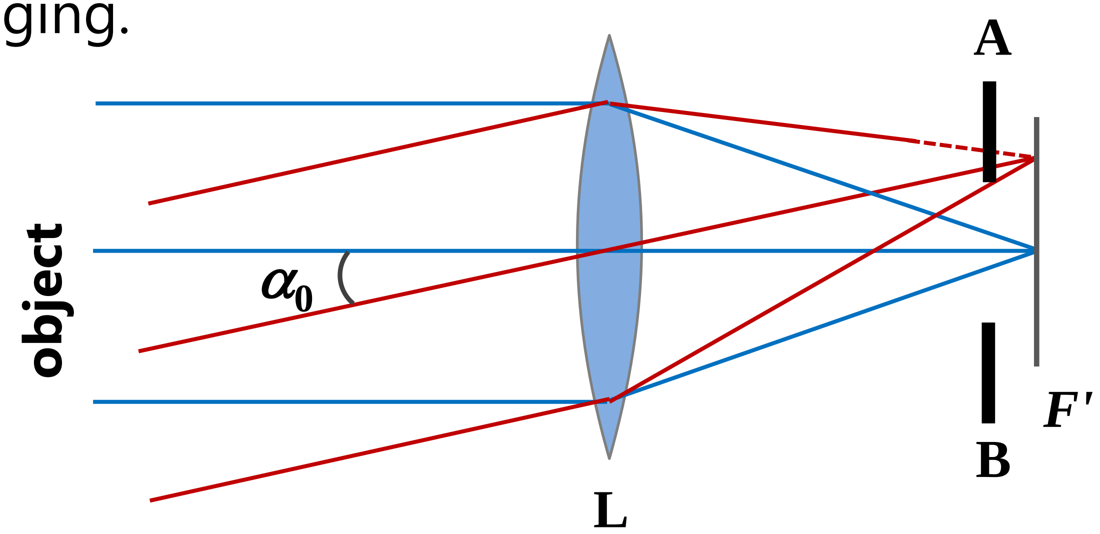
For P_2, L is aperture stop

For P_3, D is aperture stop

- Comments: The actual aperture stop is related to the position of the object point on the axis.

Field stop

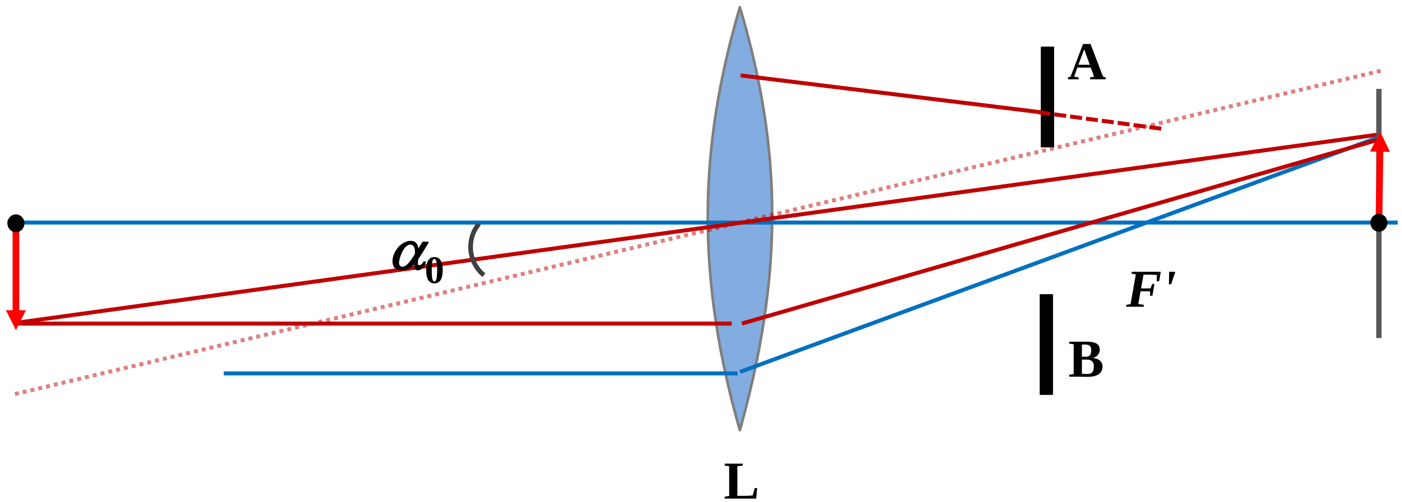
- **Field stop**: A stop that limits the size or angular breadth of imaging.



- L: aperture stop. AB, the field stop.
- For an object point on-axis, the presence of AB does not change the brightness of the F'.
- The light beam off the axis is blocked by AB.
- Vignetting: The center of the image is bright and the edges are dark.

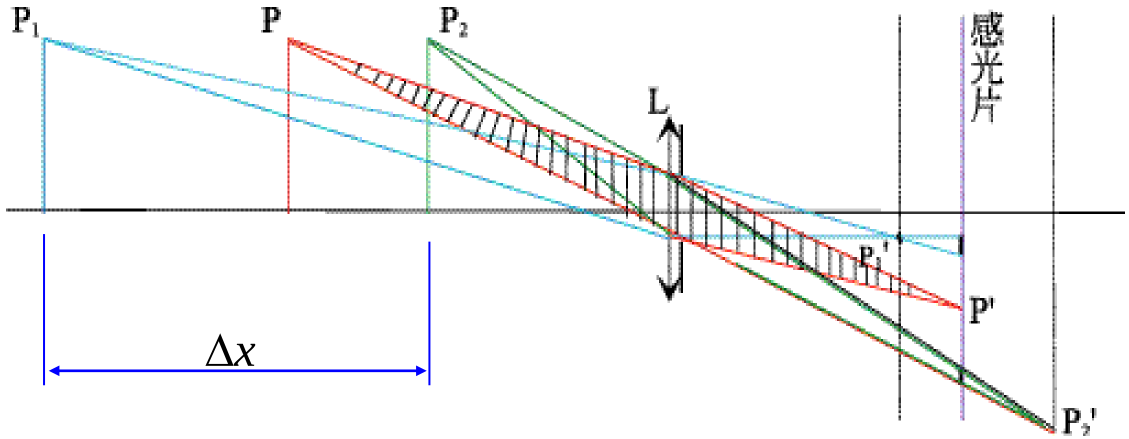
Aperture stop and field stop

- An aperture can be both an aperture stop (point on the axis) and a field stop (off-axis point)



- When the stop is in the object plane or image plane, it is only the field stop.
- When the stop is in the focal plane, it is only the aperture stop.

Depth of field/focus



- For a given aperture, if the position of P varies a distance Δx, the image of it on the photosensitive film can be seen as clear, then the distance within the object space Δx is called the **depth of field**. The corresponding distance in the image space is called the **depth of focus.**

Aperture、*f* number、

- **Relative aperture**： The ratio of the diameter of an aperture stop to the focal length of an objective lens ***D*/*f*** .
- The larger the D/f, the stronger the capability of the system to collect light.
- ***f* number**: reciprocal of D/f

E.g: an object lens $f = 160$ mm, diameter $D = 20$ mm. f number: $160/20 = 8$, marked as ***f* /8**. Indicating that the focal length of the system is 8 times that of the diameter.

- **Numerical Aperture**: $NA = n_0 \sin\alpha$

n_0: the refractive index of the surrounding medium

α: Incidence angle

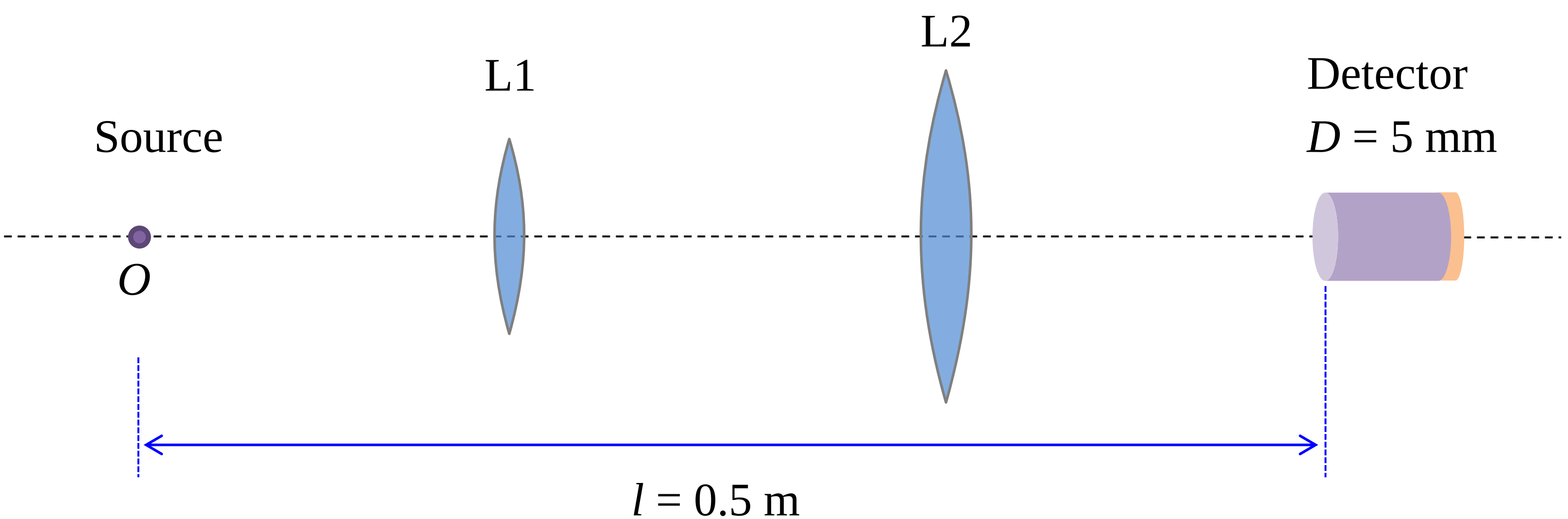
Homework	Problem 7.36 Problem 5.5, 5.26, 5.47 and the one in next slice
Homework*	Read about the **Principle of Least time** (Feynman Lectures on Physics). Generalized Reflection and Refraction.

Next week

Reflection and Refraction at interfaces,
Fresnel Equations,
Sections 4.2-4.4, 4.6

Homework

已知某光路中，一点光源（光源亮度与方向无关）固定在如图所示位置，两个无像差的薄透镜直径D_1 = 25 mm、D_2 = 38 mm，焦距为f_1= 0.1m、f_2= 0.2m，与光源相距l = 0.5m处固定一个开口直径5 mm，长度2 cm的探测器，试求如何放置两个透镜才能使收集效率最大？（假设空气折射率为1）



注：L1、L2的先后顺序可调、位置可动，也可只取一个或不用。但Source和Detector位置固定。