PHYC/ECE 463 Advanced Optics I

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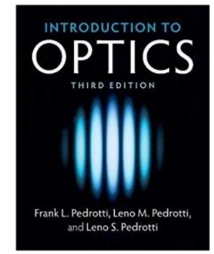
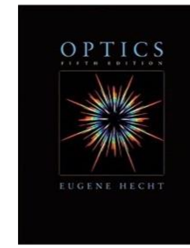
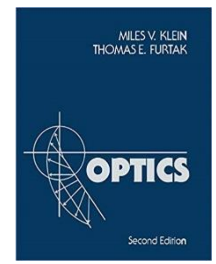
Lectures: Monday and Wednesday, 9:30-10:45 pm
PAIS 1160.

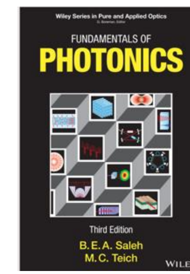
Textbook: Many good ones (See webpage)
Lectures: many based on Introduction to Optics (3rd Edition):
Frank L. Pedrotti Leno M. Pedrotti Leno S. Pedrotti. (Ch 1-28)

More good books in website
Additional resources
Optics, 4th Edition: E. Hecht.
Fundamentals of Photonics, 2nd Edition: B. E. A. Saleh, Malvin Carl Teich.
Optics, 2nd Edition, M. Klein and T. Furtak









Homework: Problem sets including problems from book(s) and additional ones about one set per week.
They are posted ~ one week before they are due. HW must be turned in the TA's mailbox before 5:00 pm on the due date.

Office hours: Monday 11am - 1pm. You may also arrange a meeting for another time via email.

TA: **Zadid Shifat.** Contact the TA (grader) via email to discuss any homework grading questions (by email, videocall, etc.).
You may also contact the TA for questions in the homework via email.

Grading
- Homework 20%
- 2 Midterm Exams: 2 x 25% = 50%
- Final: 30%

Tentative Exam Dates (subject to change): Midterms, September 22 and October 27. Final Wednesday, Dec. 10/12 7:30-9:30am(TBD).

Syllabus Topics

Below is a tentative list of topics that will be covered. You can find the calendar for the course in the Tentative Schedule

1. **Introduction to optics**- Overview and fundamentals of light; Fermat principle; reflection and refraction; ray and eikonal equations.
2. **Geometrical optics**- Image formation and ray tracing; Paraxial optics and basic optical elements (lens, mirrors, etc.); Matrix methods in paraxial optics; Stops and apertures; Aberration theory
3. **Physical optics**- Maxwell Equations, E&M waves and Gaussian beams; Dispersion and group and phase velocity; Fresnel equations of reflection and refraction though dielectric interface
4. **Interference**- Superposition of fields; Interference of multiple fields; Interference in multi-layer thin films (matrix formalism); Interferometers
5. **Diffraction theory**- Fraunhofer (far field) diffraction; Diffraction grating; Fresnel (near-field) diffraction; Fresnel plates
6. **Polarization**- polarization of light; Jones matrix formalism; Polarizers and waveplates; Stokes vectors
7. **Modern and quantum optics**- If time allows, we will discuss some special topics such as Fundamentals; Field quantization and Dirac notation; Quantum properties of light**,** laser cooling,

UNM | Department of Physics & Astronomy

Optical Science & Engineering

PHYC/ECE 463 Advanced Optics I

Class Website: https://www.unm.edu/~fbecerra/Phys463Fa25/

Tentative Schedule

Additional resources

Class overview: Lecture 1

Lasers: Anthony E. Siegman.
Laser Physics: P. W. Milonni, J. H. Eberly.
Optics, Light and Lasers: (2nd Edition) Dieter Meschede.
Fundamentals of Photonics, 2nd Edition: E. A. Saleh, Malvin Carl Teich.
Optics, 4th Edition: E. Hecht.
Laser Electronics (3rd Edition) by Joseph T. Verdeyen. (**JV**)

Tentative Schedule

Topic	Date	Subject	Reading	Homework	HW Due	Solutions
Introduction to Optics	08/19 (M)	Overview, Fermat's principle; Reflection and refraction				
Geometrical Optics	08/21 (W)	Paraxial optics, mirrors and lenses	Chapter 2	HW1	(W) Aug 28	HW1sol
	08/26 (M)	Matrix methods in paraxial optics				
	08/28 (W)	Paraxial ray equation; GRIN systems	Chapter 18; **JV** CH2	HW2	(W) Sep 4	HW2sol
	09/02 (M)	*Labor Day*				
	09/04 (W)	Optical resonators	Chapter 3; **JV** CH2	HW3	(W) Sep 11	HW3sol
	09/09 (M)	Apertures	Chapter 3			
	09/11 (W)	Prisms and optical systems	"	HW4	(W) Sep 18	HW4sol
	09/16 (M)	Prisms and optical systems	"			
Physical Optics	09/18 (W)	Wave optics	Chapter 4	HW5	(W) Sep 25	HW5sol
	09/23 (M)	Field propagation in a dielectric medium	Chapter 25			
	09/25 (W)	Fresnel Equations	Chapter 23, 25	HW6	(W) Oct 02	HW6sol

Required Background

Background in E&M, Differential Equations and Calculus, Optics, Matrix and linear algebra, etc.

E&M

1. Maxwell Equations.
2. Wave equation (Solutions), Electromagnetic Waves, and Superposition
3. Boundary Condition Problems
4. Poynting Vector, Energy transfer across boundaries; and Propagation of light in materials

Math

1. Calculus and Partial Differential Equations
2. Linear Algebra and Matrix Methods
4. Trigonometry
5. Complex numbers (algebra)

Optics (background of an introductory Optics course, such as PHYC302)

Geometrical Optics

1. Laws of reflection and refraction
2. Imaging: Ray tracing and Matrix Methods
3. Optical elements, and optical systems.

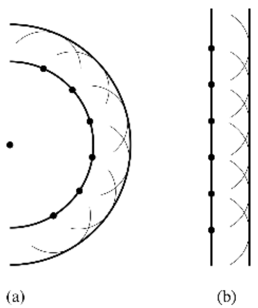
Physical Optics

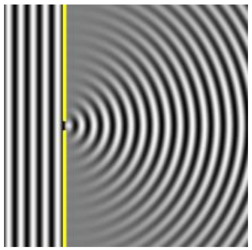
1. Wave equation, EM waves, and Superposition
2. Light-Matter interaction: Absorption and Dispersion
3. Interference, and Diffraction
4. Polarization

What is light?

- **Wave?** *Light can behave as a particle* ***and*** *as a wave*
- Particle?

Huygens principle



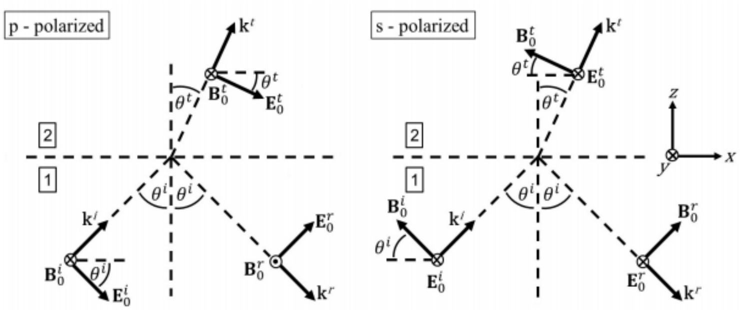


(wiki)

(1678)

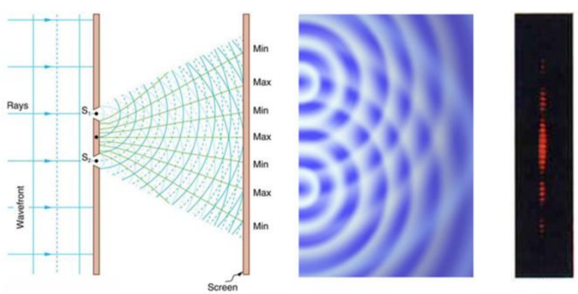
Fresnel Equations

(Polarization and Amplitude)



(1821)

Young double slit



(1801)

Maxwell Equations

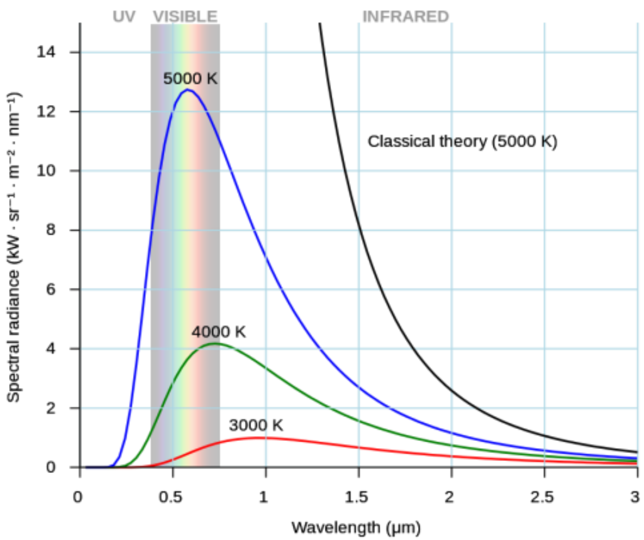
$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

(1861)

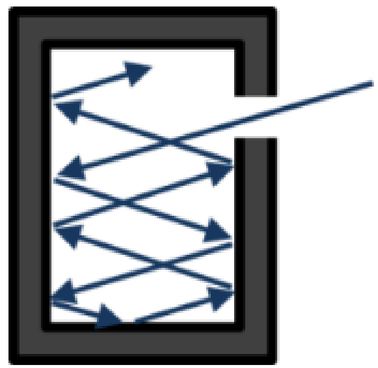
Historical notes of light

➢ **Quantum** mechanics is born: Planck (1900), Bohr (1913)

➢ Wave? *Light can behave as a particle **and** as a wave* ➢ **Particle?**

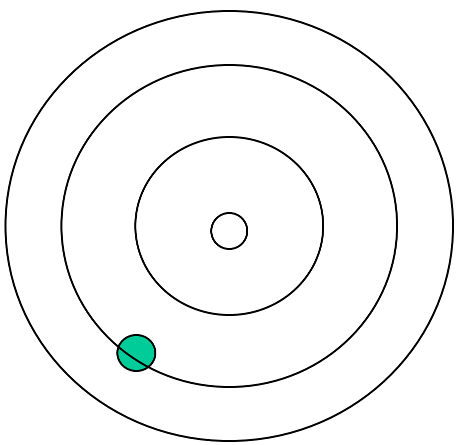


(1900)



Planck

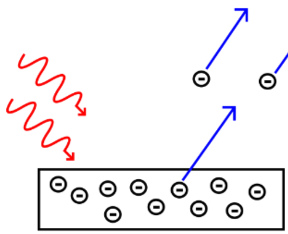
(1913)



Bohr

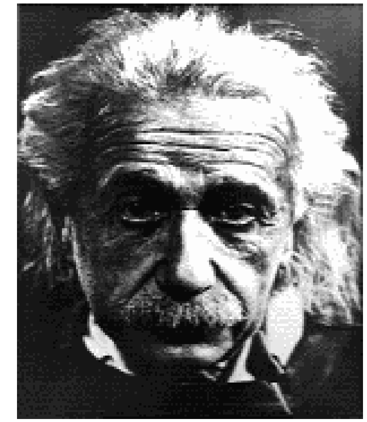
A Brief History of Laser

- Einstein postulated the principle of the "stimulated emission" (1917)

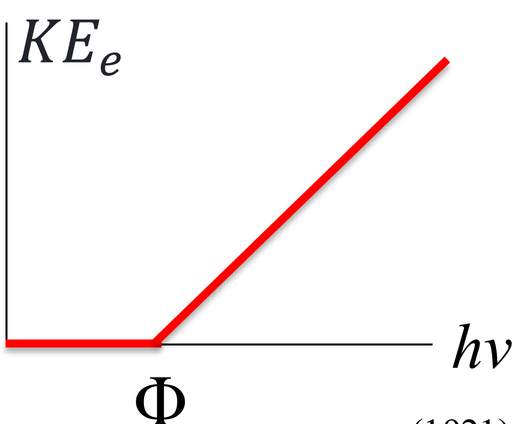


(1906)

$$KE_e = h\nu - \Phi$$

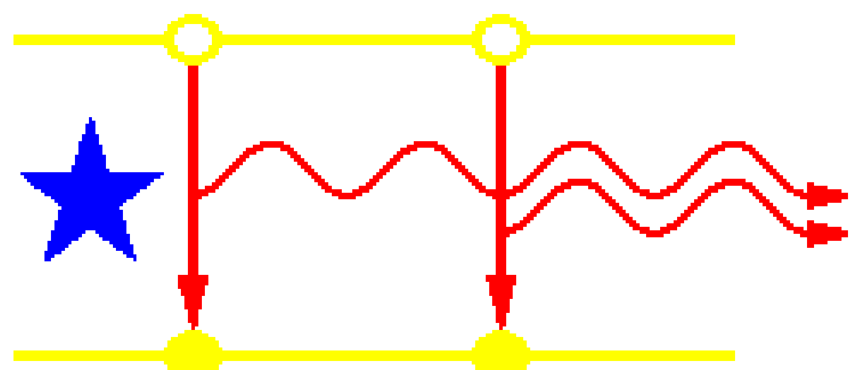


Einstein



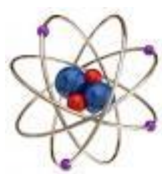
(1921)

(1917)



Optics: properties of light: Special Relativity

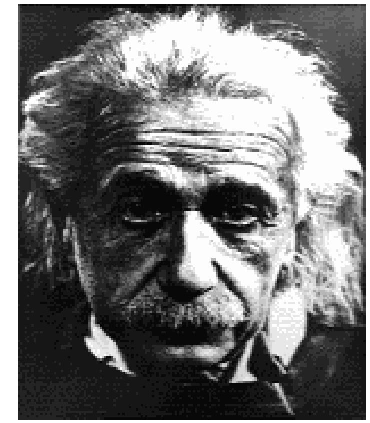
- Photons: quanta of light
- Relativistic particle



$$p = \frac{\sqrt{E^2 - m^2c^4}}{c}$$

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E^2 - m^2c^4}}$$

$$v = \frac{pc^2}{E} = c\sqrt{1 - \frac{m^2c^4}{E^2}}$$



m: rest mass
p: momentum
E: total energy
v: velocity
h: Planck constant

Photon: $m = 0$

$$p = \frac{E}{c}$$

$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

$$v = \frac{pc^2}{E} = c$$

$V_{light} = c$

Relativistic mass

$$\frac{m}{\sqrt{1 - v^2/c^2}}$$

Wave Particle Duality

Any particle has a wave-like behavior (de Broglie 1924)

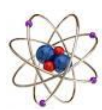
$$\lambda = \frac{h}{p}$$

← Planck constant $6.6x10^{-34}$ J.s

← Momentum

Baseball ball $\lambda_{ball} = 1x10^{-25}\ m$

(~.2kg at 30 m/s)



An electron in an atom $\lambda_{electron} \approx 0.1x10^{-9} m$

What is important about λ?

- If $\lambda \ll 1$, The wavelike properties of the body are not evident in the interaction with atoms/matter.

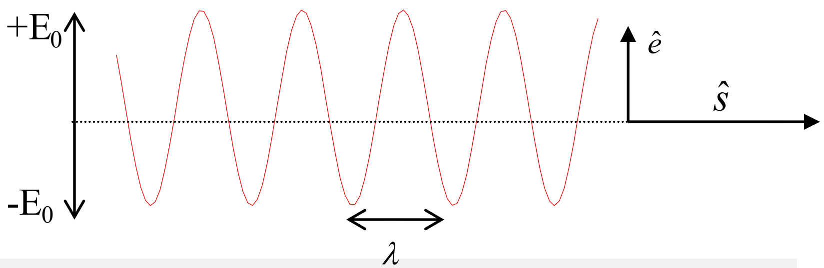
- if $\lambda \sim d_{atom} = 1$ Å, wave properties are important in the interaction.

Electron microscope: electron as wave: (electron diffraction λ ~ 0.1nm)

What is light?

❖Electromagnetic radiation:

$$E = \hat{e}E_0 \cos(\omega t - kz + \varphi)$$



❖Propagation is governed by Maxwell's equations

E = instantanous electric field

E_0 = amplitude

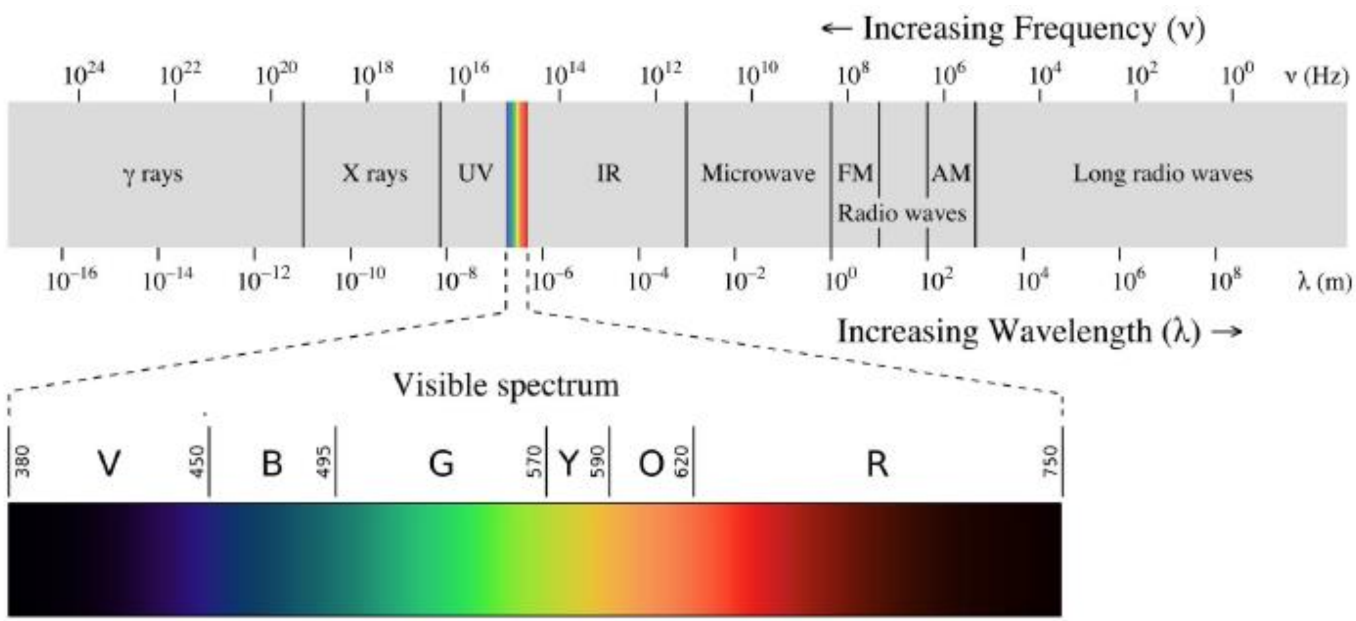
$\hat{e}$ = polarization vector

$\omega = 2\pi\nu = 2\pi c/\lambda$ = frequency

$\vec{k} = \frac{2\pi}{\lambda}\hat{s} = \frac{\omega}{c}\hat{s}$ = wavevector

λ = wavelength

φ = phase



Maxwell Equations

ME: No charge or current sources

$$\nabla \cdot \mathbf{D} = 0,$$

$$\nabla \cdot \mathbf{B} = 0,$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}.$$

Wave Equation

$$\nabla^2 \mathbf{E} - \nabla(\nabla \cdot \mathbf{E}) - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\epsilon_0 c^2}\frac{\partial^2 \mathbf{P}}{\partial t^2}$$

Transverse fields

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial^2 t} = \frac{1}{\epsilon_0 c^2}\frac{\partial^2 \mathbf{P}}{\partial^2 t}$$

Propagation in a dielectric

Atomic Polarization $\mathbf{P}$

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

$$\mathbf{P} = \epsilon_0 \chi \mathbf{E}$$

Susceptibility

Physics

$$\mathrm{E}(\mathbf{r}, t) = \Re\mathrm{e}\{\mathcal{E}(\mathbf{r}, \omega) e^{-i\omega t}\}$$

Engineering

$$\mathrm{E}(\mathbf{r}, t) = \Re\mathrm{e}\{\mathcal{E}(\mathbf{r}, \omega) e^{j\omega t}\}$$

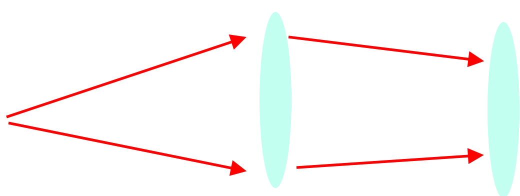
Models of light

$|\alpha\rangle$

$$\lim_{\lambda \to 0} \{\text{Physical Optics}\} = \{\text{Geometrical Optics}\}$$

Geometrical Optics

$\lambda <<$ dimensions of optical systems



Light as rays

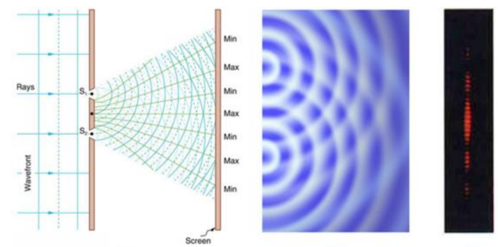
Ray tracing

Matrix methods

- Imaging
- Imaging systems
- lens design
- Some Optical Devices
- Other…

Physical (Wave) Optics

$\lambda \approx$ dimensions of optical systems



Light as waves

Wave optics

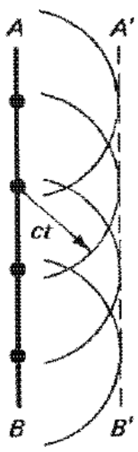
Gaussian optics

Matrix methods

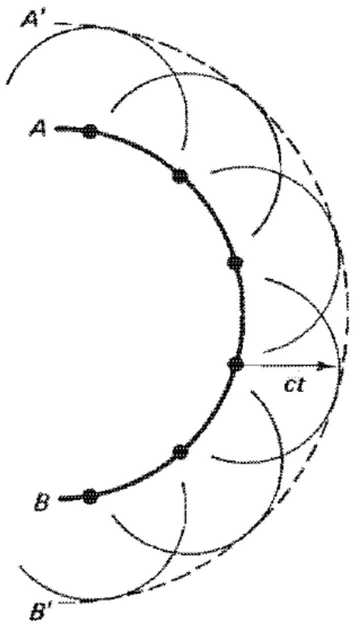
- Wave properties
- Interference
- Diffraction
- Coherence (Quant and Class)
- Etc…

Huygens Principle

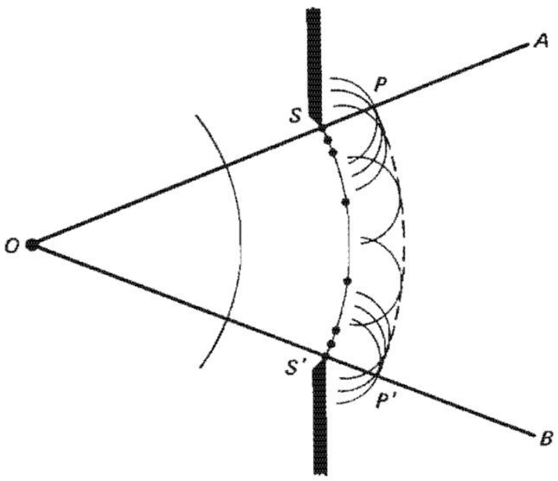
Each point on the surface of a wave disturbance (**wavefront**) may be a source of spherical waves, which themselves progress with the speed of light in the medium ($\boldsymbol{v} = {}^{c}/_{n}$) and whose envelope at a later time $\boldsymbol{t}$ constitutes the new wavefront.
(*Each point on the surface of the wavefront may act as a source of spherical waves (wavelets), which themselves propagating with* $\boldsymbol{v}$ *in the medium, and whose envelope at later times* $\boldsymbol{t}$ *constitutes the new wavefront*.)



Plane Wave



Spherical Wave



Wavefront after Aperture

Fermat Principle

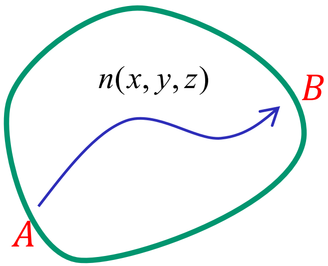
Light travels between two points along the path that requires the least time, as compared to other nearby paths.

- *This corresponds to a straight line in a homogeneous medium*
- *Also, this principle applies to inhomogeneous media*

Modern version:
A light ray, in going between two points, must traverse a trajectory with *optical path length* which is stationary with respect to variations of the path.

The optical path length of a ray from a point A to a point B:

$$S = \int_A^B n ds = \int_A^B n(x, y, z) ds$$



An extremum in the light travel time between A and B is an extremum of the optical path length between those points. The optical length of the path followed by light between A and B, is an extremum.

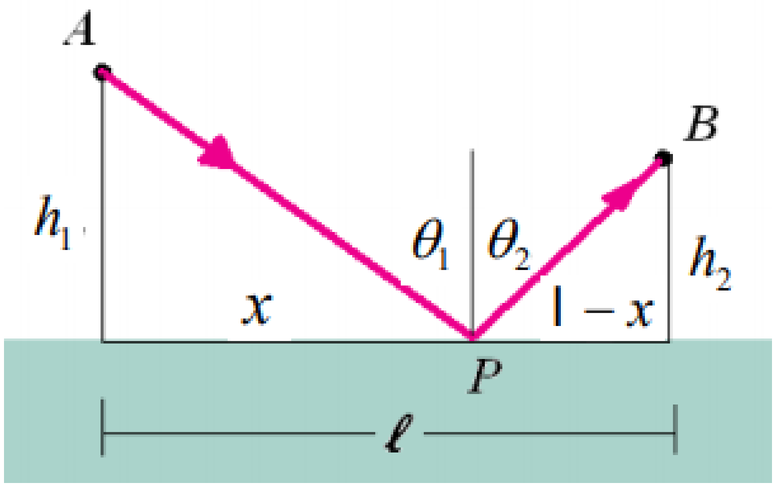
$$\delta S = \delta \int_A^B n ds = 0 \longrightarrow \delta \int_A^B F(y, y', x) dx = 0$$

$$s = s(x, y)$$

Euler–Lagrange equation

$$\frac{\partial F}{\partial y} - \frac{d}{dx}\frac{\partial F}{\partial y'} = 0$$

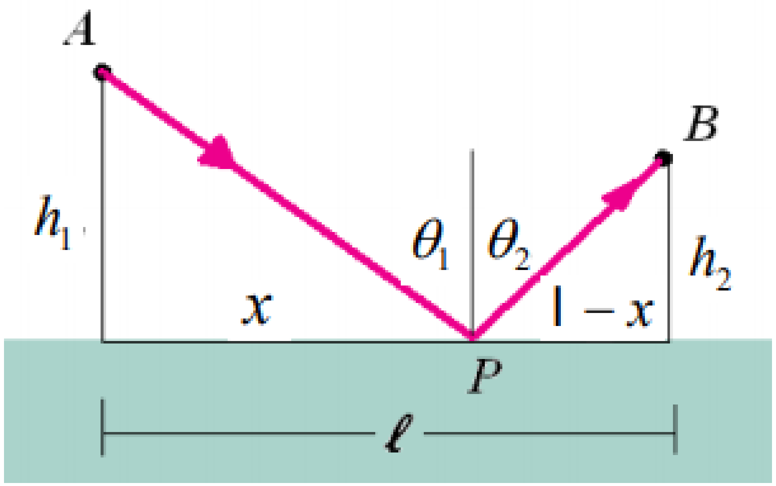
Fermat Principle
Law of Reflection



Fermat Principle
Law of Reflection

Calculate time ***t*** that takes light to travel from point **A** to point **B**

$$OpticalPath = \overline{AP} + \overline{PB}$$



$$t = \frac{\sqrt{x^2 + h_1^2}}{c} + \frac{\sqrt{(l - x)^2 + h_2^2}}{c}$$

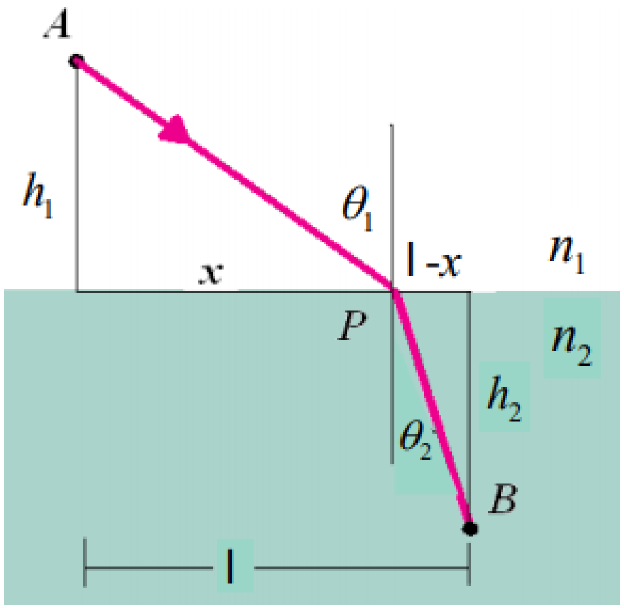
Find the extremum of the optical path length between those points
In this case, that corresponds to minimize the time of travel ***t***

$$0 = \frac{dt}{dx} = \frac{x}{c\sqrt{x^2 + h_1^2}} + \frac{-(l - x)}{c\sqrt{(l - x)^2 + h_2^2}} \rightarrow$$

$$\frac{x}{\sqrt{x^2 + h_1^2}} = \frac{(l - x)}{\sqrt{(l - x)^2 + h_2^2}} \rightarrow \sin\theta_1 = \sin\theta_2 \rightarrow \boxed{\theta_1 = \theta_2}$$

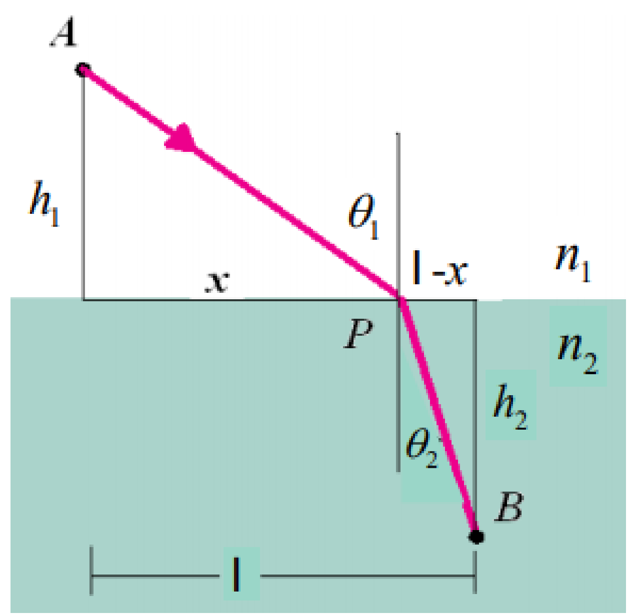
$$\sin\theta = opposite\, side \,/\, hypotenuse$$

Fermat Principle
Law of Refraction



Fermat Principle
Law of Refraction

Calculate time ***t*** that takes light to travel from point **A** to point **B**



$$\text{Optical Path} = \overline{AP}n_1 + \overline{PB}n_2$$

$$t = \frac{\sqrt{x^2 + h_1^2}}{c/n_1} + \frac{\sqrt{(l - x)^2 + h_2^2}}{c/n_2}$$

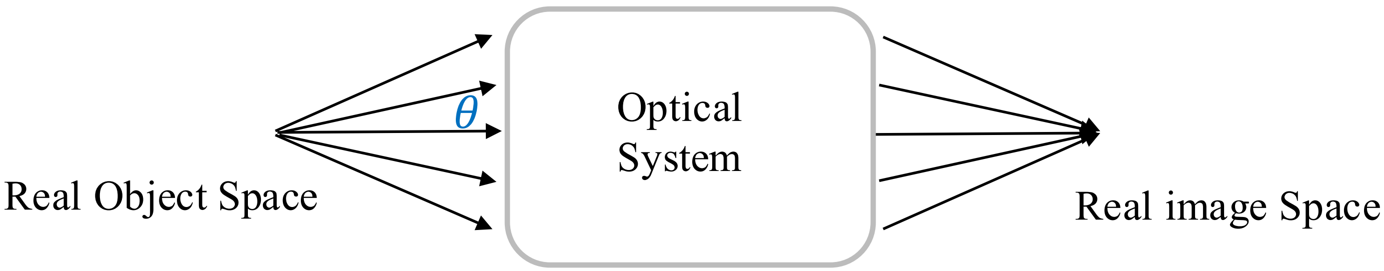
Find the extremum of the optical path length between those points
In this case, that corresponds to minimize the time of travel ***t***

$$0 = \frac{dt}{dx} = \frac{n_1 x}{c\sqrt{x^2 + h_1^2}} + \frac{-n_2(l - x)}{c\sqrt{(l - x)^2 + h_2^2}} \rightarrow \frac{n_1 x}{\sqrt{x^2 + h_1^2}} = \frac{n_2(l - x)}{\sqrt{(l - x)^2 + h_2^2}} \rightarrow \boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

$$\sin\theta = opposite\ side / hypotenuse$$

Imaging by an Optical System

Geometric optics can be used to design imaging systems to produce the image of an object in real space (image space)



All rays need to obey Fermat's principle and have a minimum transit time.

This is achieved by equaling optical paths:

$$\mathrm{OP}_{\mathrm{ray}\ i} = \mathrm{OP}_{\mathrm{ray}\ j} \quad \forall i, j$$

Paraxial Optics: propagation close to optical axis:

$$\sin\theta \approx \theta$$

Roadmap of course

Geometrical Optics

λ<< dimensions of optical systems

Introduction to optics

Fundamentals

Fermat principle

Reflection and refraction

ray and eikonal equations

Geometrical optics

Image formation and ray tracing

Paraxial optics and basic optical elements (lens, mirrors, etc.)

Matrix methods

Stops and apertures

Aberration theory

Polarization

Polarization of light

Jones matrix formalism

Polarizers and waveplates

Stokes vectors

Physical (Wave) Optics

$\lambda \approx$ dimensions of optical systems

Physical optics

Maxwell Equations

E&M waves and Gaussian beams

dispersion and group/phase velocity

Fresnel equations

Interference

Superposition of fields

Interference of multiple fields and (matrix formalism)

Interferometers

Diffraction theory

Fraunhofer (far field) diffraction

Diffraction grating

Fresnel (near-field) diffraction

Modern and Quantum Optics

Field quantization

Sign convention in Ray Optics (for next class)

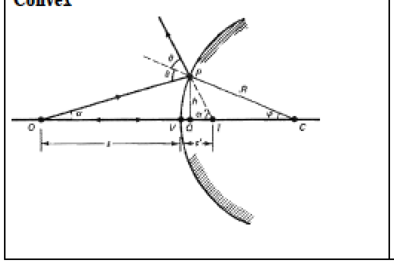
Sign Convention: Mirrors and Lenses

Object Distance (S)	
S>0 (Real)	"O" to the Left of "V"
S<0 (Virtual)	"O" to the Right of "V"
Image Distance (S')	
S'>0 (Real)	"O" to the Left of "V" (Mirror) "O" to the Right of "V" (Lens, Refractive Surface)
S'<0 (Virtual)	"O" to the Right of "V" (Mirror) "O" to the Left of "V" (Lens, Refractive Surface)
Radios of Curvature (R)	
R>0 (Convex)	"C" to the Right of "V"
R<0 (Concave)	"C" to the Left of "V"

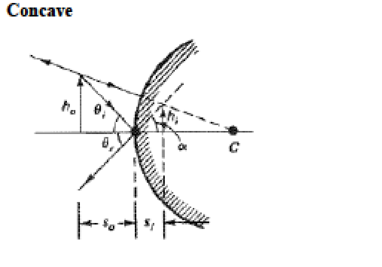
S.- Object Distance
S'.- Image Distance
R .- Radios of Curvature
O.- Object Point
V.- Vertex
C.- Center of Curvature
F.- Focal point
f.- Focal distance

Mirror

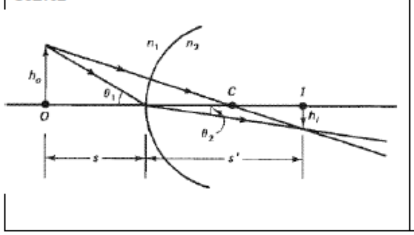
Convex



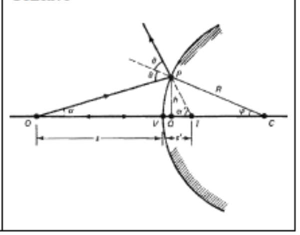
Concave



Convex



Concave



Imaging Equation: Mirror

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

Imaging Equation: Refractive Surface $n_1 \rightarrow n_2$

$$\frac{n_1}{s}+\frac{n_2}{s'}=-\frac{n_2-n_1}{R}=\frac{1}{f}$$

Magnification: $m=\frac{h_i}{h_o}=-\frac{n_1 s'}{n_2 s}$

Object height h_o
Image height h_o
Erected image $m>0$
Inverted image $m<0$

Ray Tracing: Mirrors
Ray leaving a point P at the tip of object

Ray 1. Ray Parallel to the Optic Axis (OA). After Reflection: - Concave: Passes through the Focal Point - Convex: propagates as if it cam from focal Point
Ray 2. Leaves P in a direction towards or from F - Concave: Passes trough F→ Reflects and propagates parallel to OA - Convex: Leaves P as it came from F→ Reflects and emerges parallel to OA
Ray 3. Leaves P and propagates along the line joining P and C (Center of curvature) Reflects along the same line.

Thin Lens: $n_1 \rightarrow n_2 \rightarrow n_1$