PH 112 (2023)
Quantum Physics and Applications

Instructors:

- Prof. Kantimay Dasgupta (D1)
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D3 Instructor information

- Room 114, Physics Bldg.
- Email: shanki@iitb.ac.in
- Consultation hours: will inform after meeting CRs.

Why learn Quantum mechanics?

- Quantum mechanics is considered the most important discovery of the 20th century.
- Quantum theory made it possible to understand atoms. Atoms make molecules and there by understand Chemistry --- the chemical bond. Chemistry is the basis of Biology.
- Quantum mechanics permits us to understand solid bodies and there by conduction of electricity in solids.
- Quantum theory is the basis of semi-conductors. Semiconductor devices made possible miniaturized electronics, including the laptop/tab/mobile phone you use on a daily basis!
- Many technological inventions (referred to as first quantum revolution) of the last 60 years are based on principles of quantum mechanics.

Quantum theory in the real world

Practical Applications

- LASERs
- Semiconductors
- Transistors
- LED
- Night Vision Goggles
- CCD
- MRI / PET

Explanation of Phenomena

- Tunnelling
- Radioactive decay
- Periodic table

  Pauli Exclusion Principle explanation to Mendeleev's chart
- Anti-matter

Quantum theory in the future

- Dot LASERs
- Quantum Dot Screens
- Logic gates
- Computing
- Cryptography / Encryption
- Cloning
- Teleportation

PH-112: Learning objectives

- Discuss some insights that paved way to our understanding of microscopic systems.
  - evidence of the wave nature of electrons and describe how their wavelength depends on speed
  - explain how quantum theory differs from classical physics
- solve simple physical problems to understand
  - Quantization of energy
  - Tunneling of particles and applications

PH-112: Syllabus

Introduction Compton Scattering, de-Broglie hypothesis, Electron interference (double slit experiment) and Electron Diffraction (Davison - Germer experiment)
Concept of Wave packets Phase velocity, group velocity
Mathematical interlude Introduction to Fourier Transforms; Few examples (Step potentials, Gaussian wave packet), leading to concept of Uncertainty relation.
Quantum Physics Heuristic derivation of Schrodinger Equation. Concept of free particle, particle in a box problem. Finite Square well. Bound vs. unbound states. Superposition of eigenstates Scattering problem. Reflection and Transmission coefficients. A few examples. Concept of quantum tunnelling. Few realistic examples of tunnelling, e.g. alpha decay, Scanning Tunnelling Microscope. Concept of degenerate states

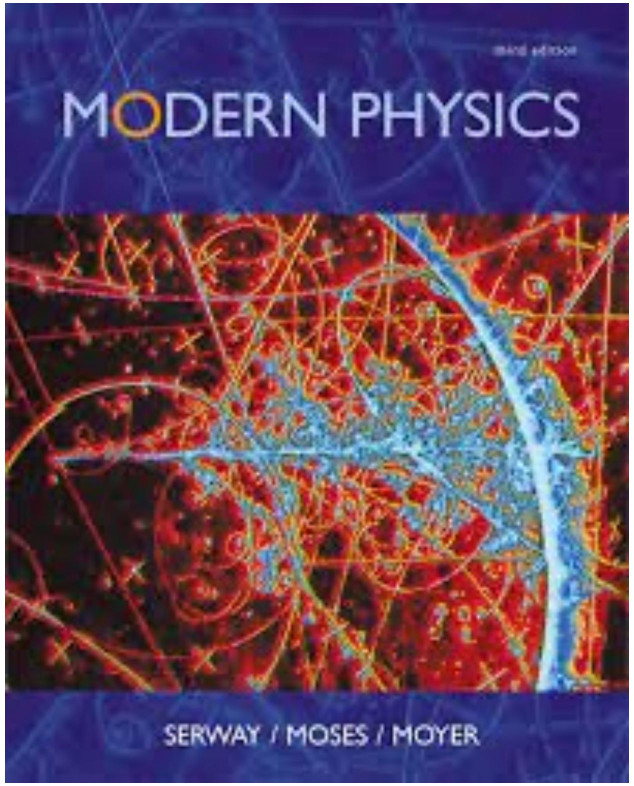
PH-112: Reference Book

Modern Physics (3rd Edition): R. A. Serway, C. J. Moses, C. A. Moyer, Thomson Learning Inc. 2005

Ideally you will read the relevant chapter/section after the lecture. You will gain a much better understanding of the topics by reading the material outside of class.

You are free to explore other textbooks like

1. Tipler, Modern Physics
2. Thornton and Rex, Modern Physics



PH-112: D3 Schedule of lectures

Monday	9:30 – 10:25 AM
Tuesday	10:35 – 11:30 AM
Thursday	11:35 – 12:30 PM
Wednesday (Tutorials)	2:00 – 5:00 PM

PH-112: Evaluation Scheme

- You are expected to attend all lectures and tutorials. Attendance is compulsory for Lectures and tutorials.

- Like PH111, your final grade will be determined using the following weights :

Category	Number of Times	Weightage	Best of	Percentage
Moodle Quizzes	6	1	5	20 %
Tutorials	5	1	--	20 %
Quiz (3^{rd} week of May)	1	---	---	20 %
End-Semester	1	----	---	40 %

PH 112: Quantum Physics and Applications

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Week 0, Lecture 01 Motivation for Quantum Physics

D4, Spring 2023

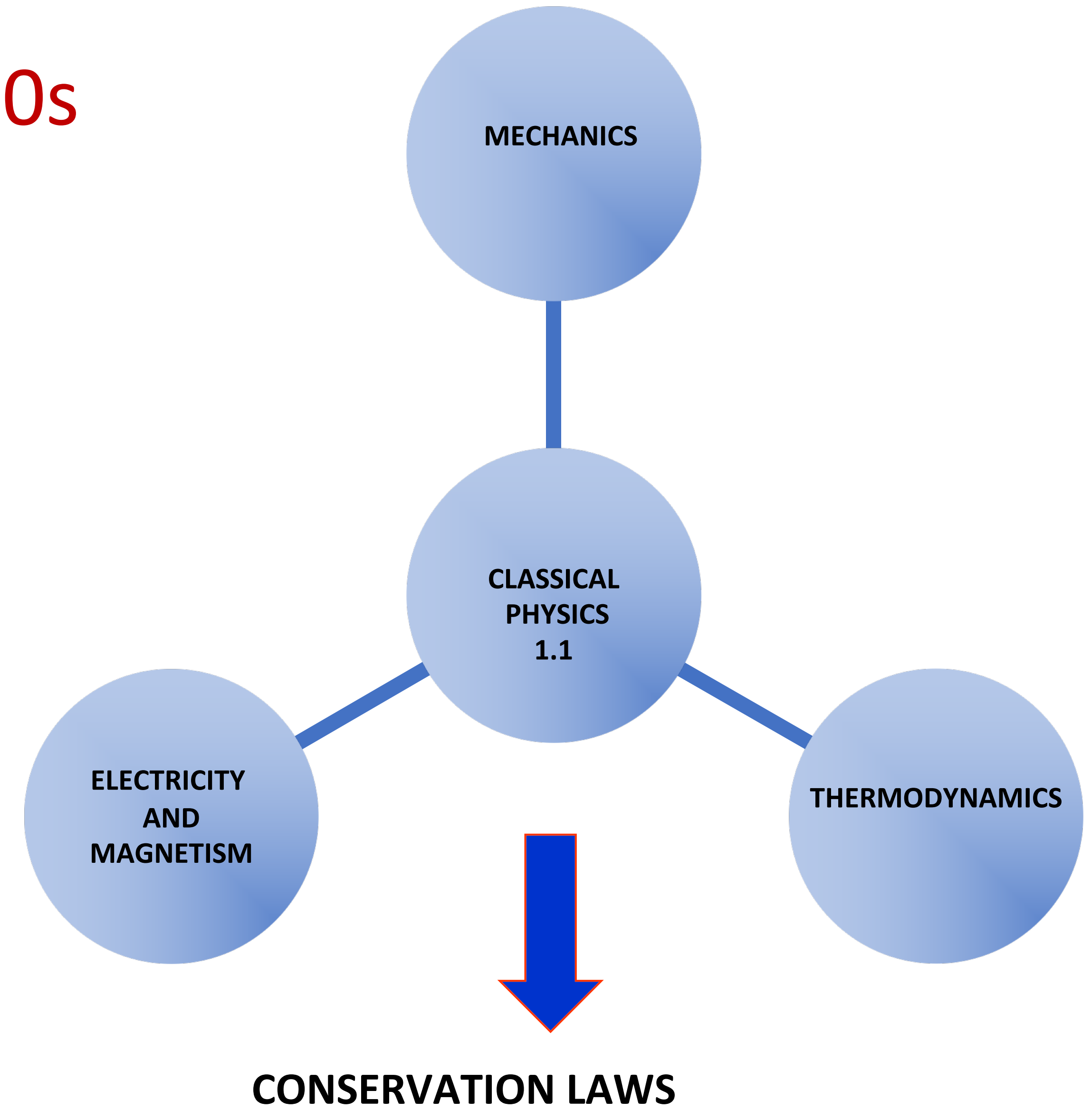
How predictions can go wrong?

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…Our future discoveries must be looked for in the sixth place of decimals.

- Albert A. Michelson, 1894 (known for measuring speed of light)

Classical Physics of the 1890s

- Mechanics
- Electromagnetism
- Thermodynamics



Conservation Laws: Triumph of classical physics

1. **Conservation of energy**: The total sum of energy (in all its forms) is conserved in all interactions.

2. **Conservation of linear momentum**: In the absence of external forces, linear momentum is conserved in all interactions.

3. **Conservation of angular momentum**: In the absence of external torque, angular momentum is conserved in all interactions.

4. **Conservation of charge**: Electric charge is conserved in all interactions.

Classical Mechanics

Mechanics: Two eras

Galileo to Newton

1. Principle of inertia

2. Establishment of experiments and observations as a way to understand nature.

Newton's Laws of Motion:

I law (*law of inertia*): An object in motion with a constant velocity will continue in motion unless acted upon by some net external force.

II law: Introduces force (F) as responsible for the the change in linear momentum (p):

$$\vec{F} = m\vec{a} \quad \text{or} \quad \vec{F} = \frac{d\vec{p}}{dt}$$

III law (*action and reaction*): **F**orce exerted by body 1 on body 2 is equal in magnitude and opposite in direction to the force that body 2 exerts on body 1.

$$\vec{F}_{21} = -\vec{F}_{12}$$

Electrodynamics

Electromagnetism: Culminates in Maxwell's Equations

- Gauss's law (Φ_E):
  (definition of electric field)
  $$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0}$$
- Gauss's law (Φ_B):
  (definition of magnetic field)
  $$\oint \vec{B} \cdot d\vec{A} = 0$$
- Faraday's law:
  (relates Electric current and magnetic field)
  $$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$
- Ampère's law:
  (relates magnetic field with electric current)
  $$\oint \vec{B} \cdot d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I$$

Thermodynamics

The four laws of Thermodynamics

- **First law (Energy conservation)**: The change in the internal energy (ΔU) of a system is equal to the heat (Q) added to a system plus the work (W) done by the system

$$\Delta U = Q + W$$

- **Second law**: It is not possible to convert heat completely into work without some other change taking place.

- **The "zeroth" law**: Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.

- **Third law**: It is not possible to achieve an absolute zero temperature.

Thermodynamics: Key results

Introduced following concepts:

1. Thermal equilibrium
2. Internal energy *(U)*
3. Perpetual motion: Such processes can not take place due to limitations of energy.

Establishes the following:

1. Temperature *(T)* as a measure of internal energy *(U)*
2. Heat as energy *(Q)*
3. Atomic theory of matter

Kinetic Theory

Kinetic Theory of Gases: Key results

1. Relates Internal energy (*U*) to the average molecular kinetic energy.

2. Relates average molecular kinetic energy to absolute temperature *(T).*

3. *Equipartition theorem:* Internal energy (*U*) is equally distributed among the number of degrees of freedom (*f*) of the system

$$U = nN_A \langle K \rangle = \frac{f}{2} nRT$$

(N_A = Avogadro's Number)

Ideal gas equation of state

$$PV = nRT$$

n is moles of a simple gas,

R is the ideal gas constant, 8.31 J/mol · K

Molar **heat capacity** (c_V) is

$$c_v = \frac{du}{dt} = \frac{f}{2} R$$

Kinetic Theory of Gases: Other key results

4. Derivation of molecular speed distribution *f* (*v*) by Maxwell:

$$f(v) = 4\pi N \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-mv^2/2kT}$$

5. Determination of the *root-mean-square* of the molecular speed by Boltzmann:

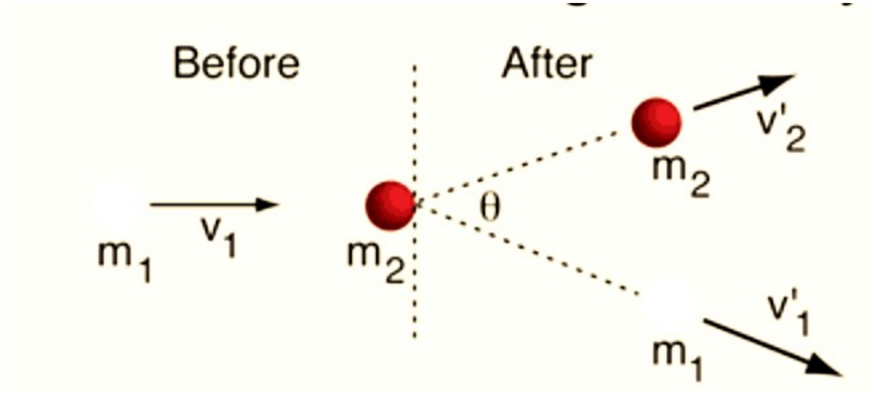
$$v_{rms} = \sqrt{\langle v^2 \rangle} = \sqrt{\frac{3kT}{m}}$$

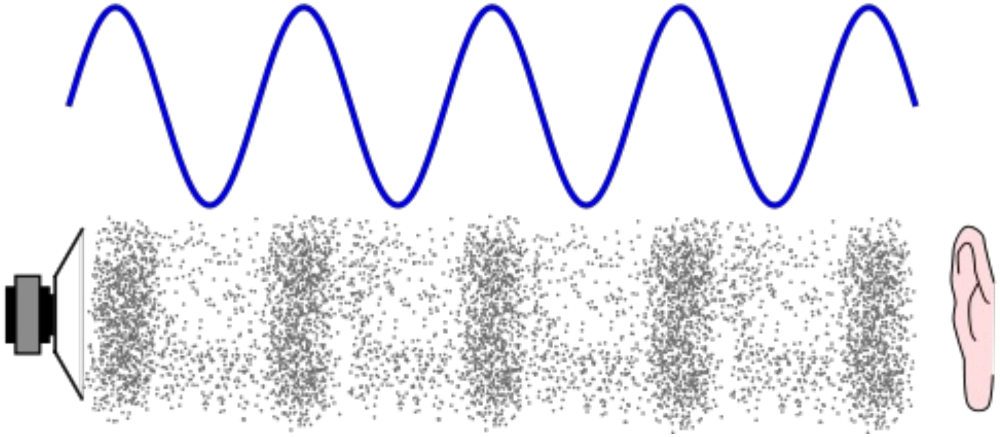
Thus relating energy to the temperature for an ideal gas

Transfer of Energy

Transfer of energy

Energy transfer can take place in two ways:





Point mass interaction:

Transfer of momentum and kinetic energy: *particles*

Extended region interaction:

Energy transfers via vibrations and rotations: *waves*

Particles vs. Waves

Two distinct phenomena that describe physical interactions are: Particles and Waves

1. Both required the concept of mass.

   Particles in the form of point masses and waves in the form of perturbation in a mass distribution --- a material medium.

2. The distinctions are observationally quite clear; however, not so for the visible light.

3. By 17th century, major disagreement concerning the nature of light!

What is the nature of Light?

Two views on the nature of Light

Corpuscular (Particle) nature of Light

1. Particles of light travel in straight lines or rays
2. Can explain sharp shadows.
3. Can explain Reflection and Refraction.

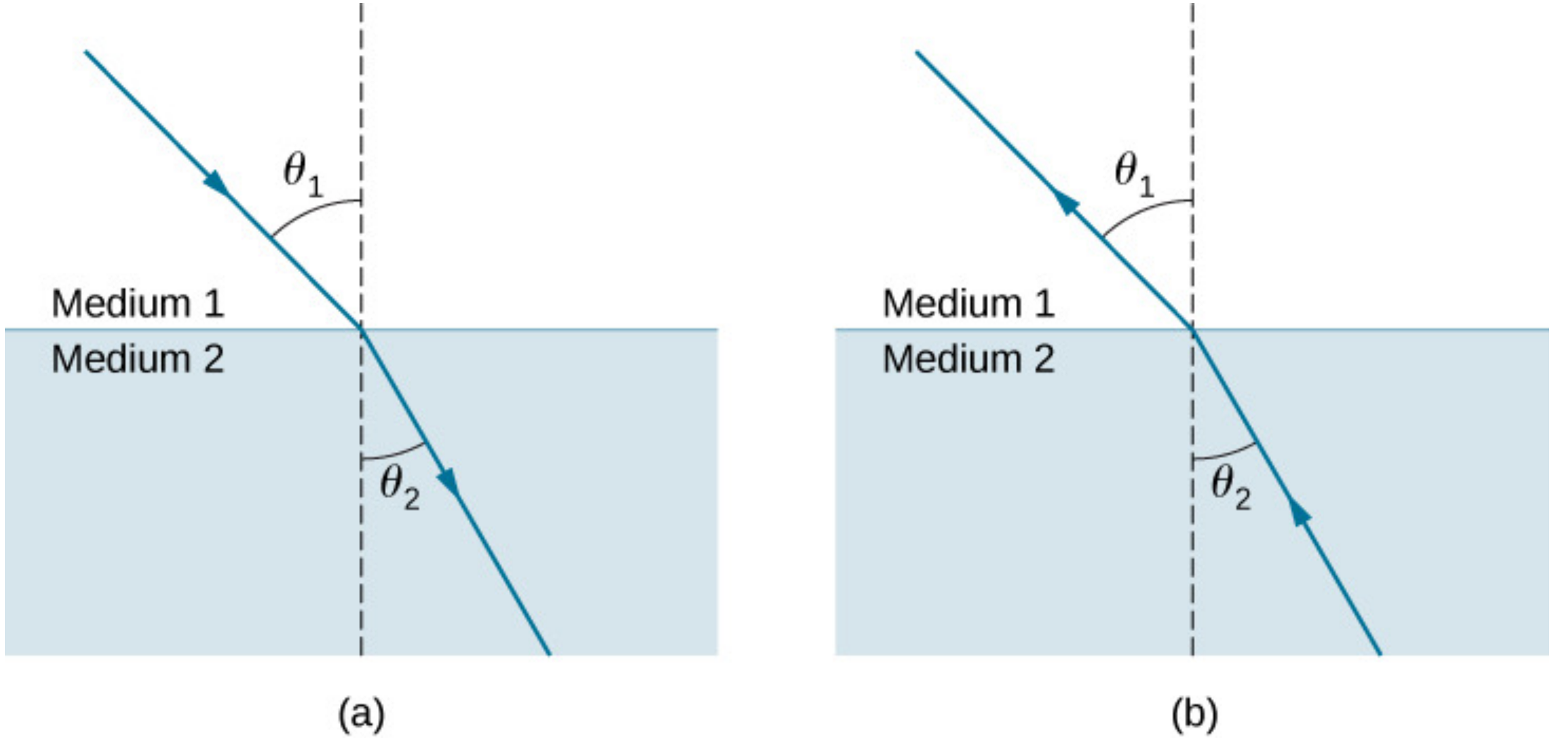
Promoted by Newton

Wave nature of Light

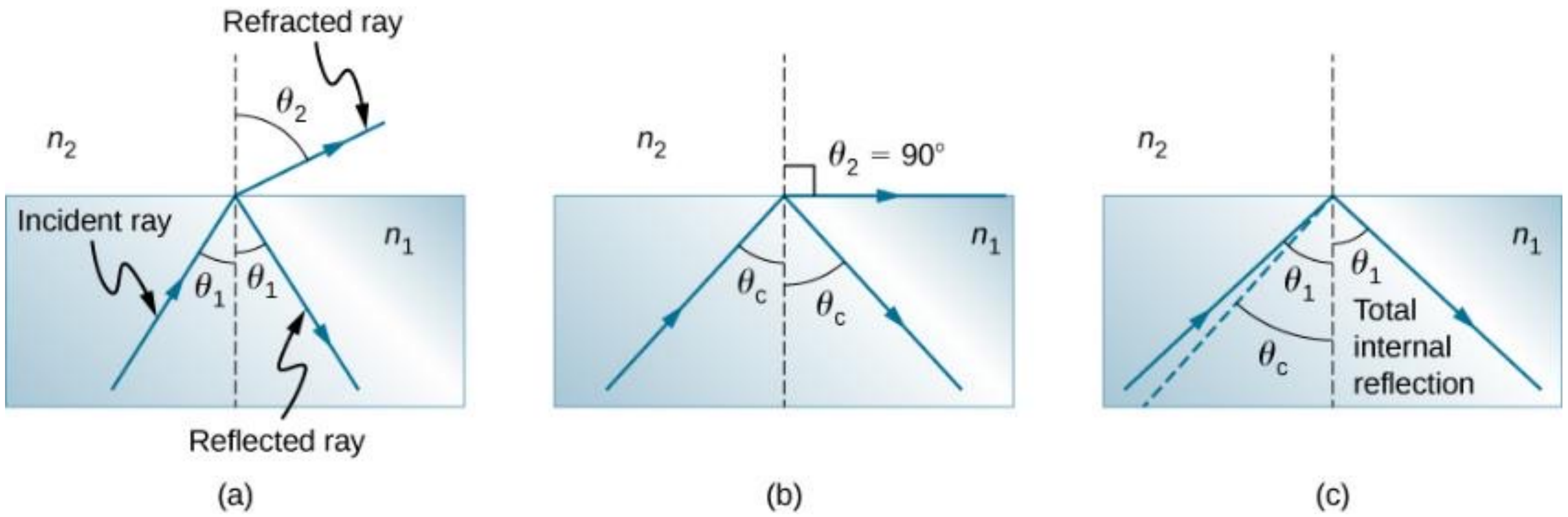
1. Light propagates as a wave of concentric circles from the origin.
2. Can explain Interference and Diffraction.
3. Can not explain sharp shadows.

Promoted by Christian Huygens

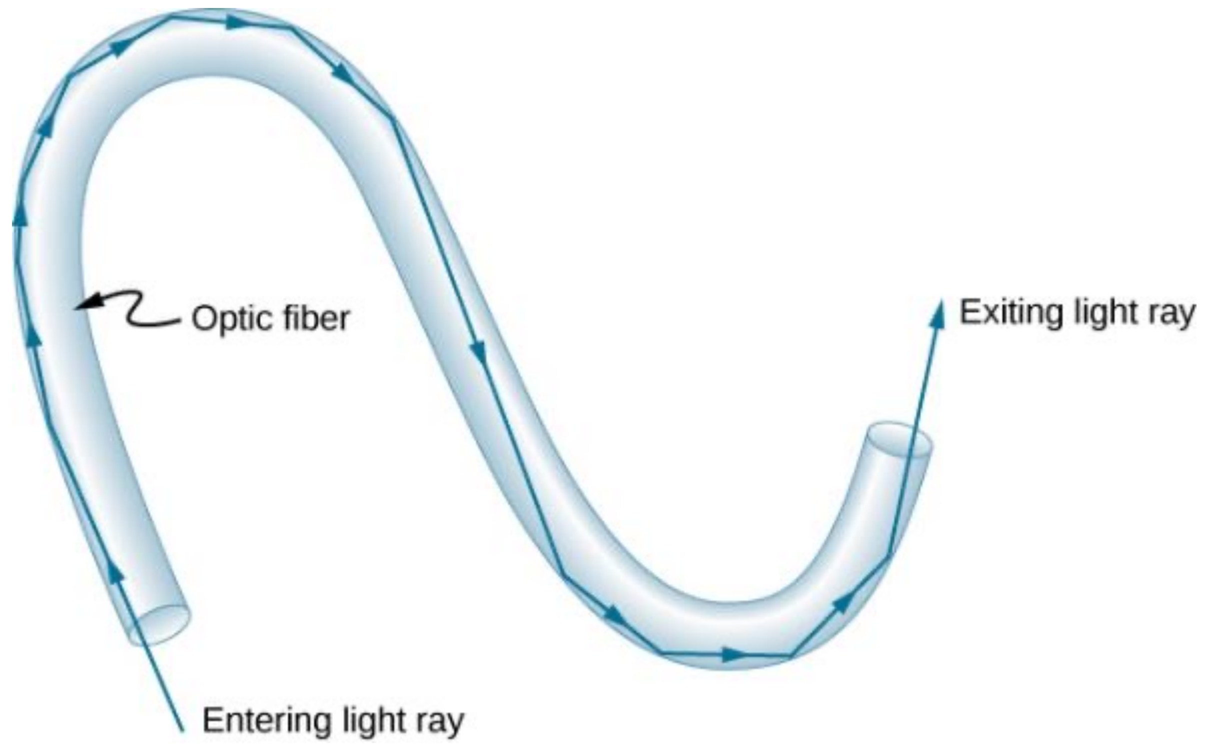
Particle nature of Light: Reflection and Refraction



Particle nature of Light: Reflection and Refraction

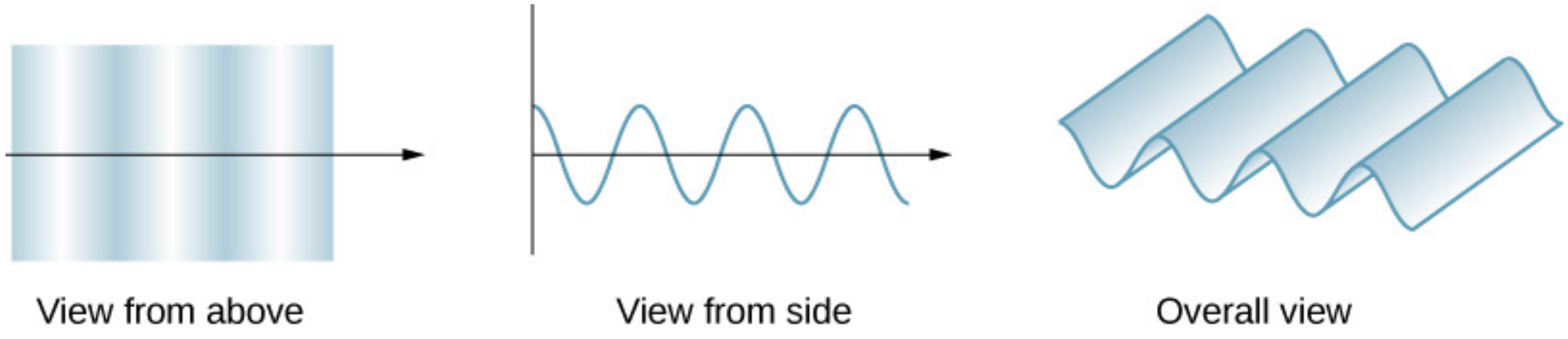


Particle nature of Light in action



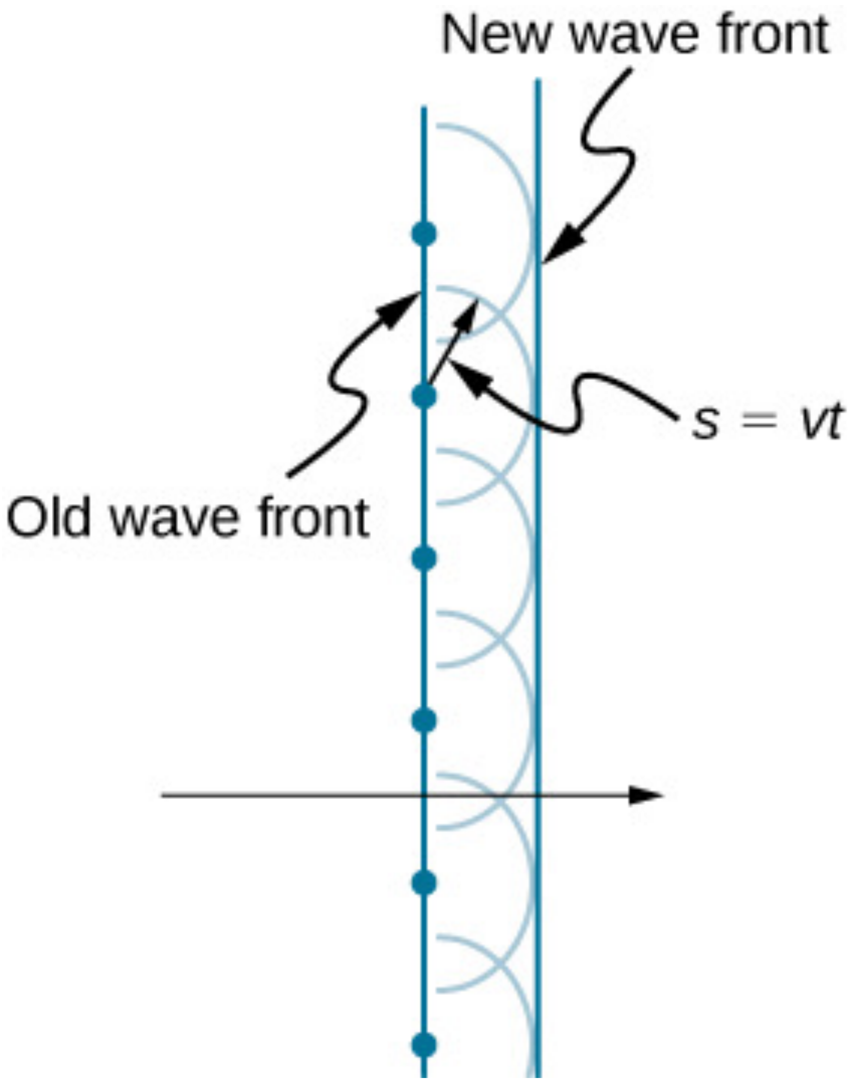
Light entering a thin optic fiber may strike the inside surface at large or grazing angles and is completely reflected if these angles exceed the critical angle. Such rays continue down the fiber, even following it around corners, since the angles of reflection and incidence remain large.

Wave nature of Light



A transverse wave, such as an electromagnetic light wave, as viewed from above and from the side. The direction of propagation is perpendicular to the wave fronts (or wave crests) and is represented by a ray.

Wave nature of Light

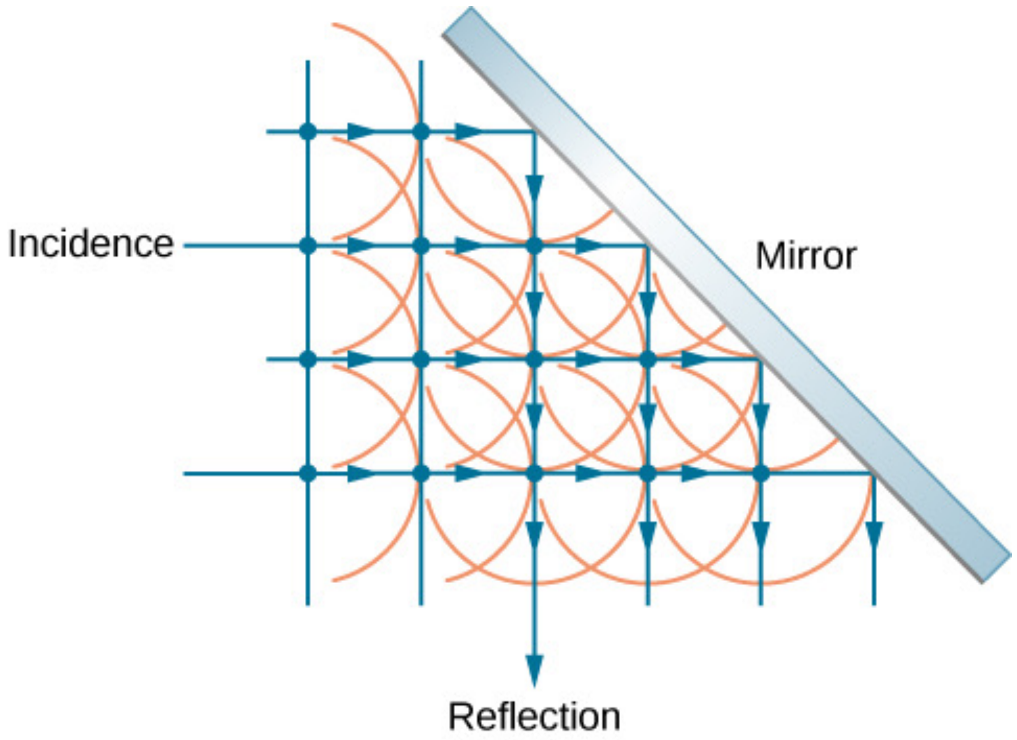


Huygens's principle applied to a straight wave front. Each point on the wave front emits a semicircular wavelet that moves a distance

$$s = vt$$

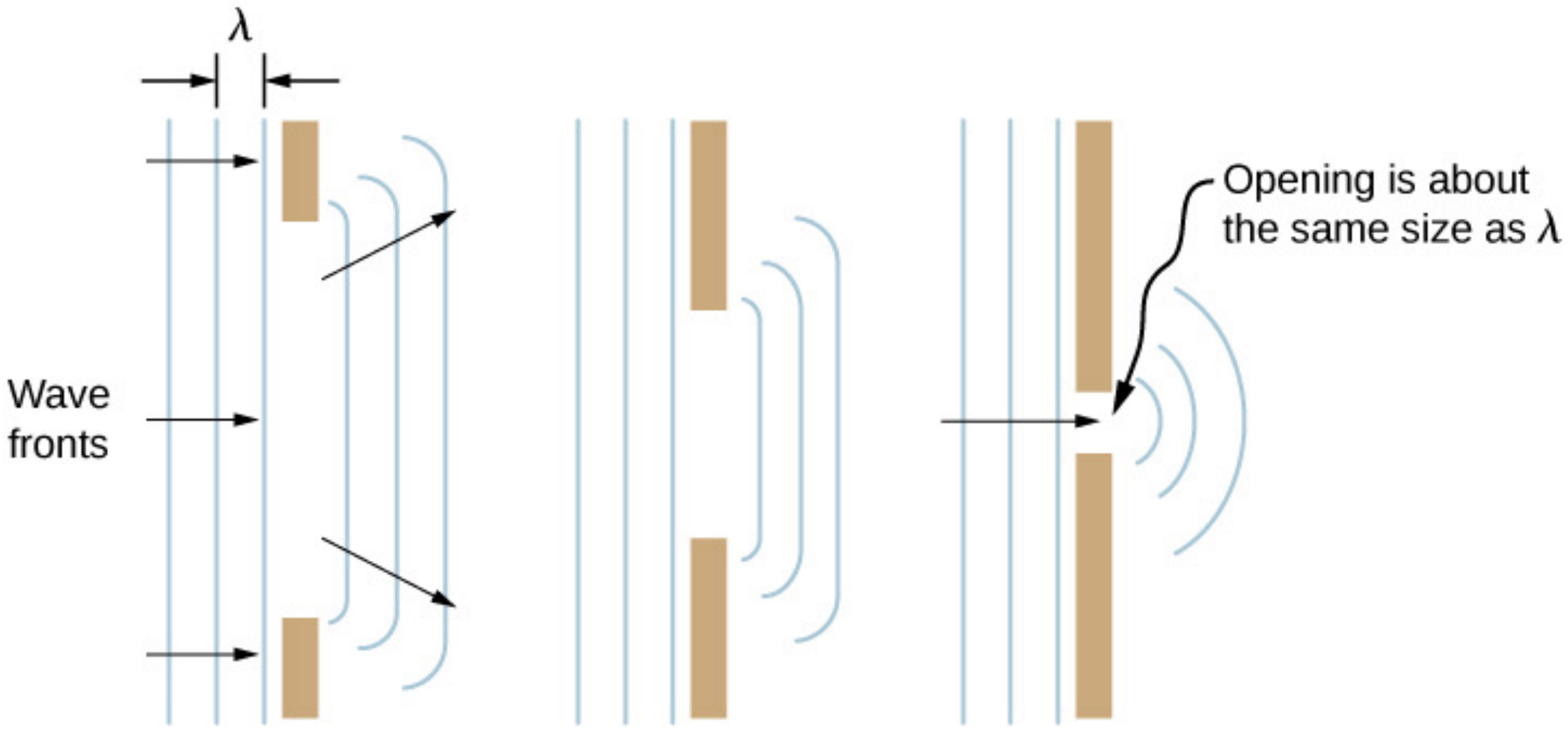
The new wave front is a line tangent to the wavelets.

Wave nature of Light



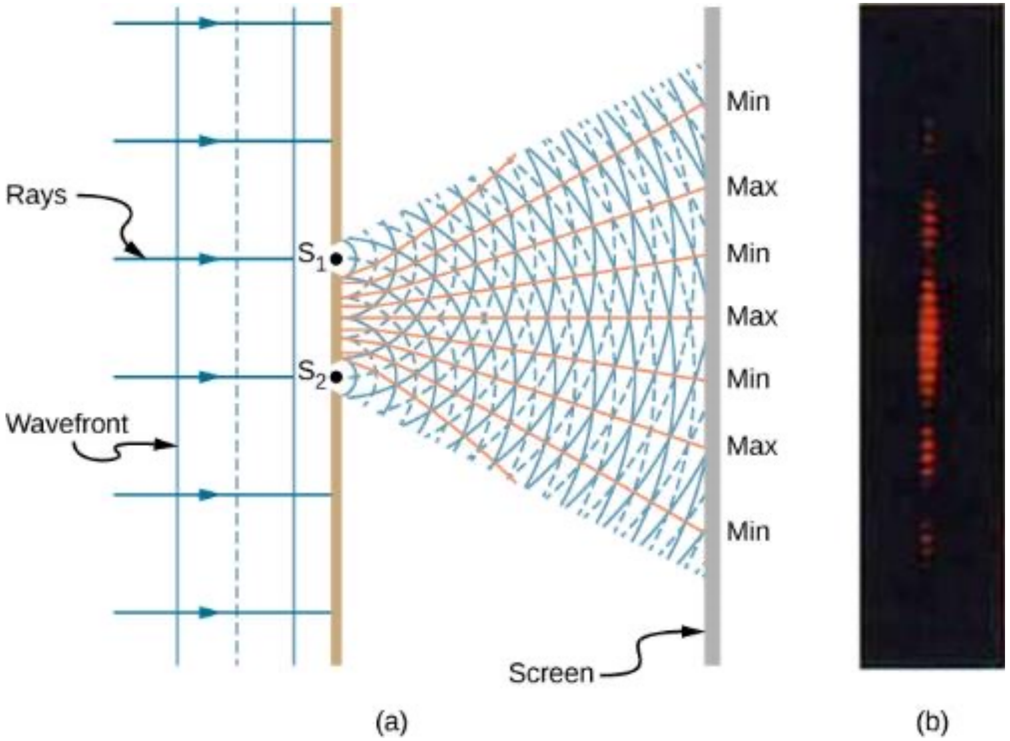
Huygens's principle applied to a plane wave front striking a mirror. The wavelets shown were emitted as each point on the wave front struck the mirror. The tangent to these wavelets shows that the new wave front has been reflected at an angle equal to the incident angle. The direction of propagation is perpendicular to the wave front, as shown by the downward-pointing arrows.

Wave nature of Light in action



Huygens's principle applied to a plane wave front striking an opening. The edges of the wave front bend after passing through the opening, a process called diffraction. The amount of bending is more extreme for a small opening, consistent with the fact that wave characteristics are most noticeable for interactions with objects about the same size as the wavelength.

Wave nature of Light in action

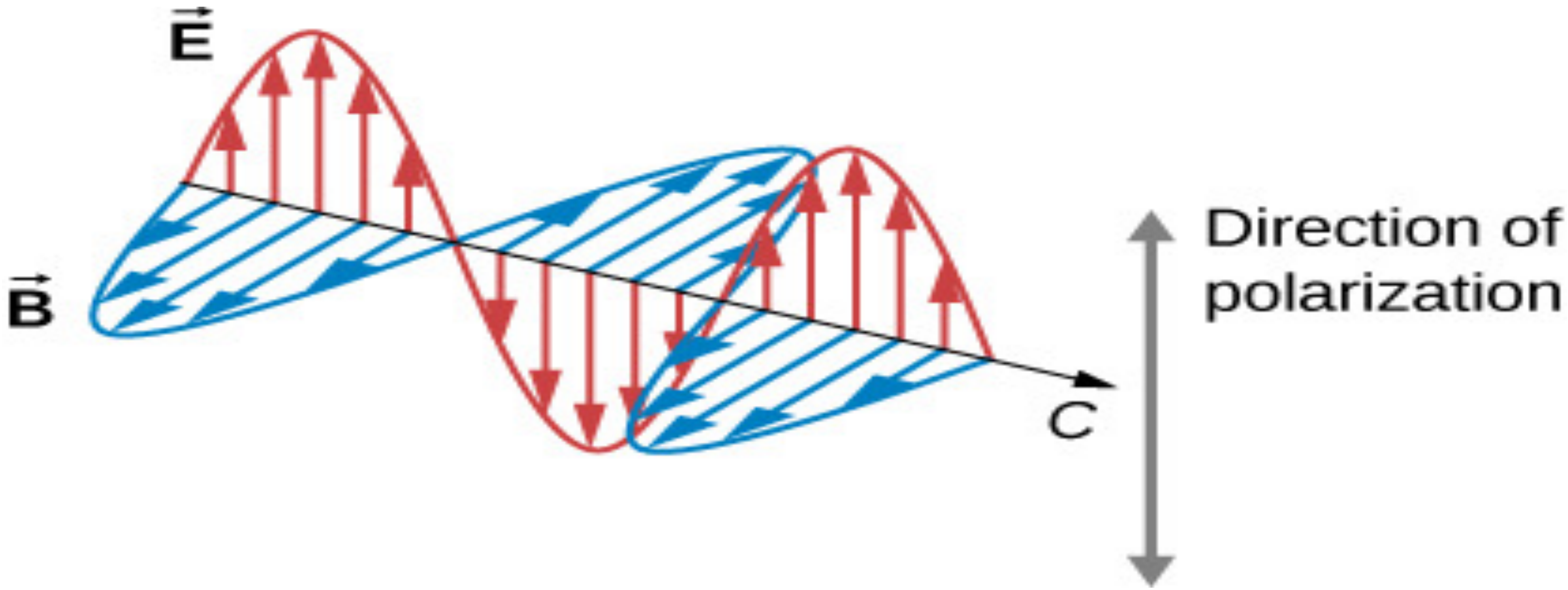


Double slits produce two coherent sources of waves that interfere.

(a)Light spreads out (diffracts) from each slit, because the slits are narrow. These waves overlap and interfere constructively (bright lines) and destructively (dark regions). We can only see this if the light falls onto a screen and is scattered into our eyes.

(b)When light that has passed through double slits falls on a screen, we see a pattern such as this.

Wave nature of Light



An EM wave, such as light, is a transverse wave. The electric **E** and magnetic fields **B** are perpendicular to the direction of propagation. The direction of polarization of the wave is the direction of the electric field.

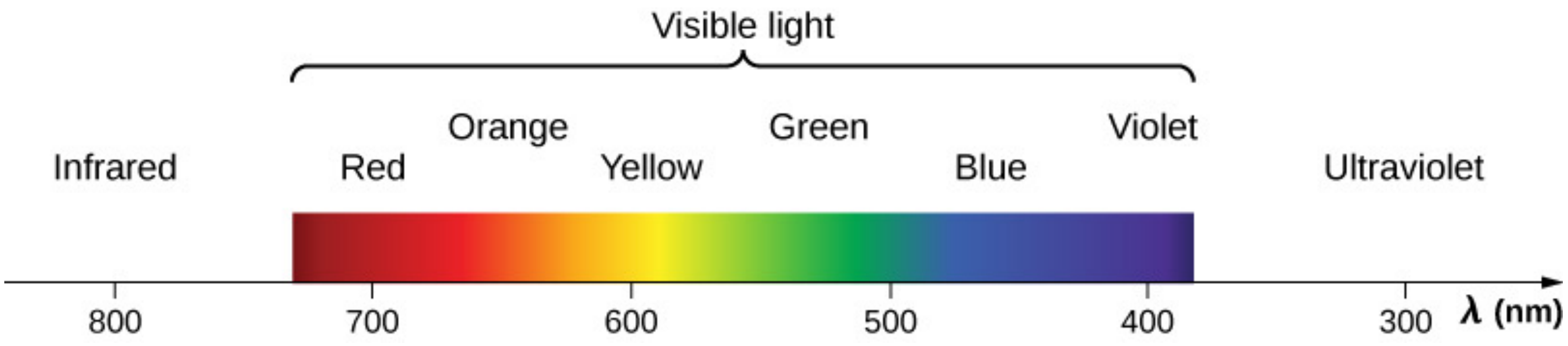
The Electromagnetic Spectrum

- All electromagnetic waves travel in a vacuum with a speed *c* given by:

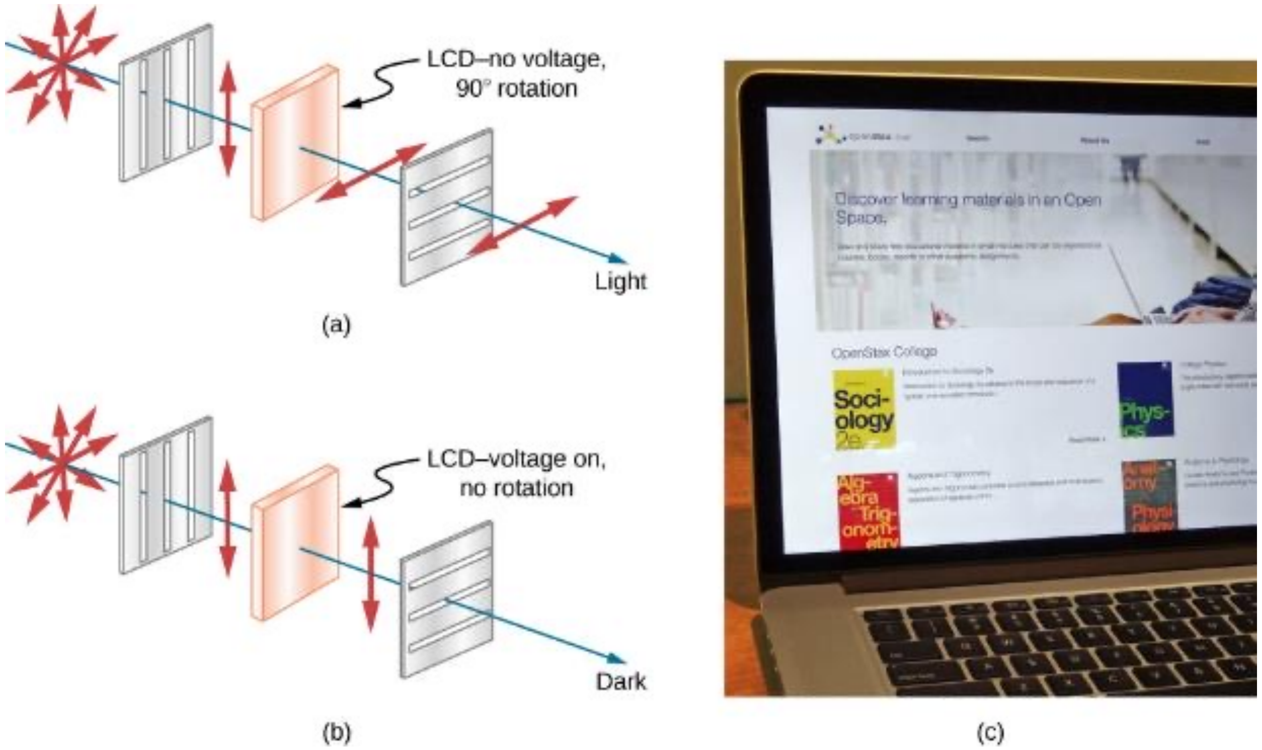
$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \lambda f$$

(where μ_0 and ε_0 are the respective permeability and permittivity of "free" space)

- Visible light covers only a small range of the total electromagnetic spectrum



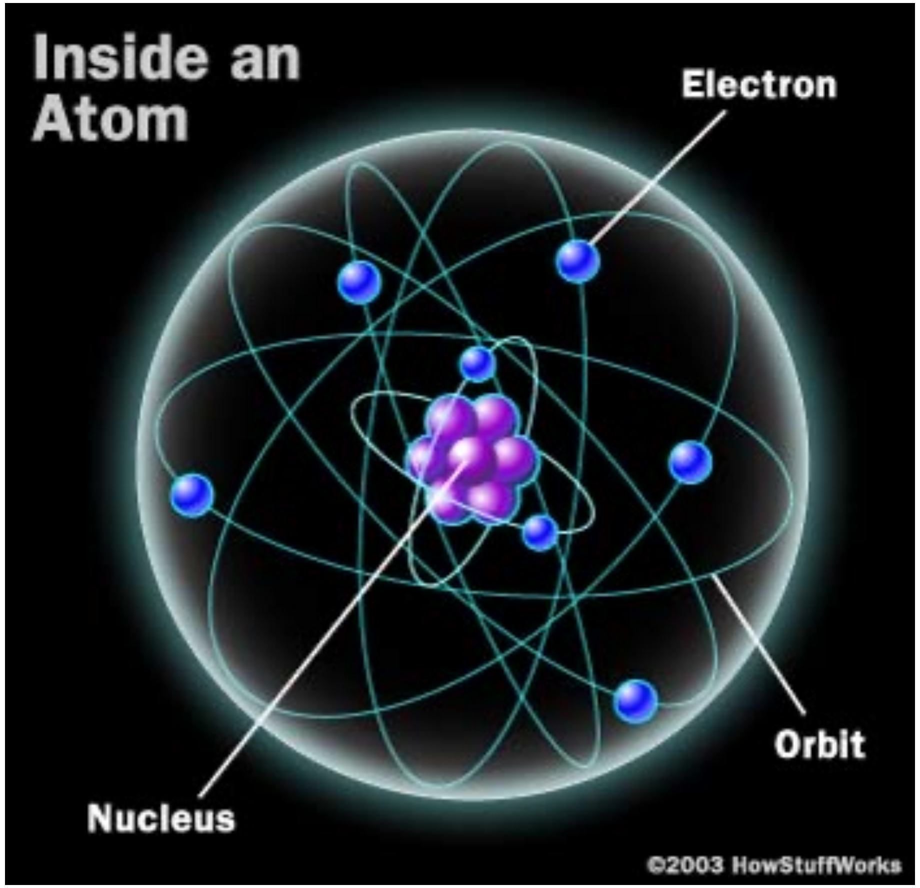
Wave nature of Light in action



(a) The direction of polarization of the wave is the direction of the electric field. Polarized light is rotated 90° by a liquid crystal and then passed by a polarizing filter that has its axis perpendicular to the direction of the original polarization.
(b) When a voltage is applied to the liquid crystal, the polarized light is not rotated and is blocked by the filter, making the region dark in comparison with its surroundings.
(c) LCDs can be made color specific, small, and fast enough to use in laptop computers and TVs.

Unresolved questions in late 19^{th} century

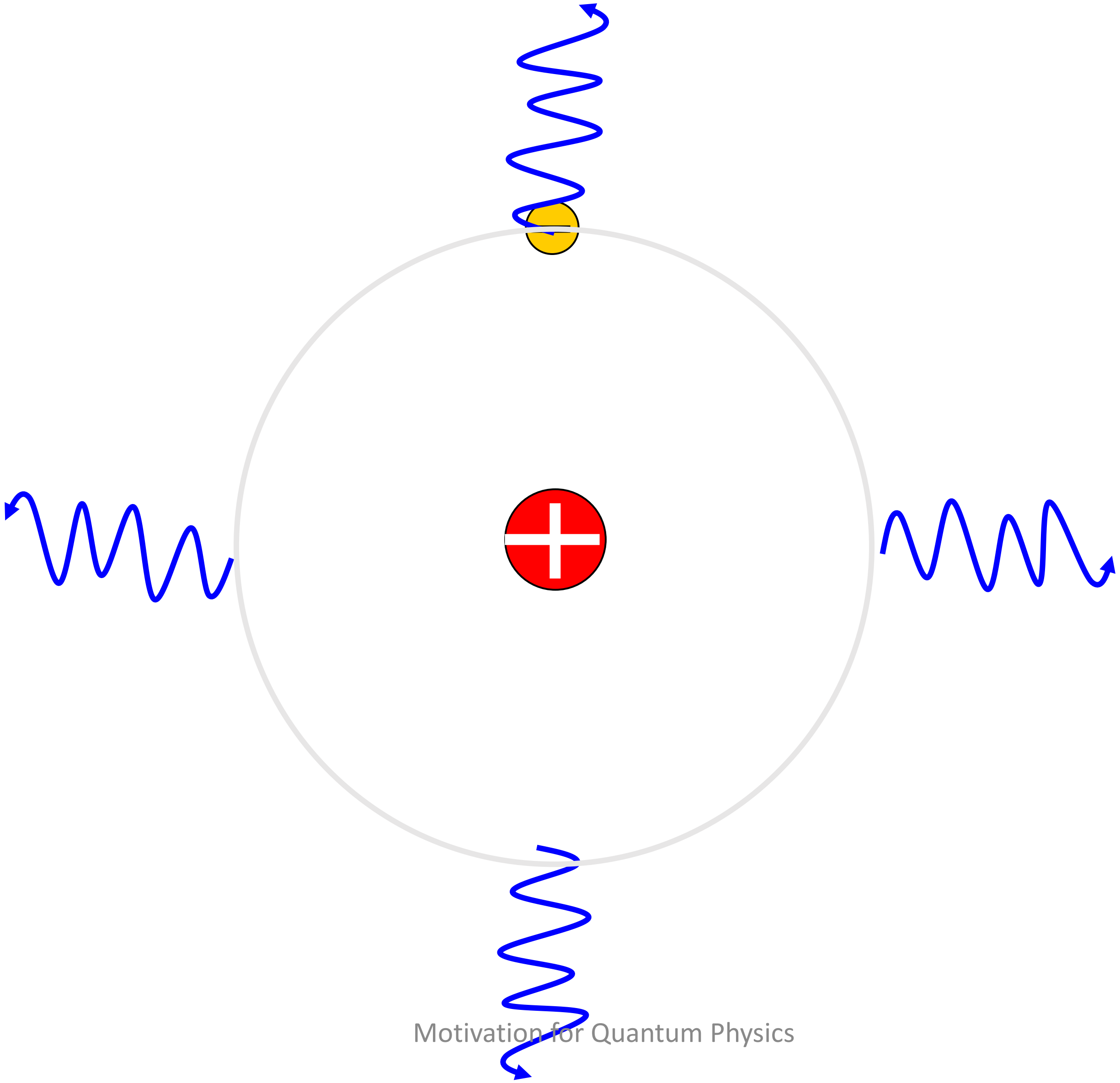
Atoms and classical physics



- According to the laws of mechanics and electromagnetism, an orbiting electron in an atom should continually radiate away energy as electromagnetic waves.

- Very quickly the electron would loose all of its energy and there would be no atoms!

Accelerated charges radiate energy



Problems with Newton's Laws

- Newton's laws, while successful in explaining the behavior of macroscopic objects including planets, can not explain atomic-level phenomena.

- This is not surprising since Newton's laws were discovered by considering the behavior of macroscopic objects, like planets.

Modern Physics is based on the following principle:

Physical "laws" may always have a limited range of applicability, and must be continually tested to find their limitations.

Three fundamental problems

- The question of the existence of an electromagnetic medium
- The problem of observed differences in the electric and magnetic field between stationary and moving reference systems
- The failure of classical physics to explain blackbody radiation.

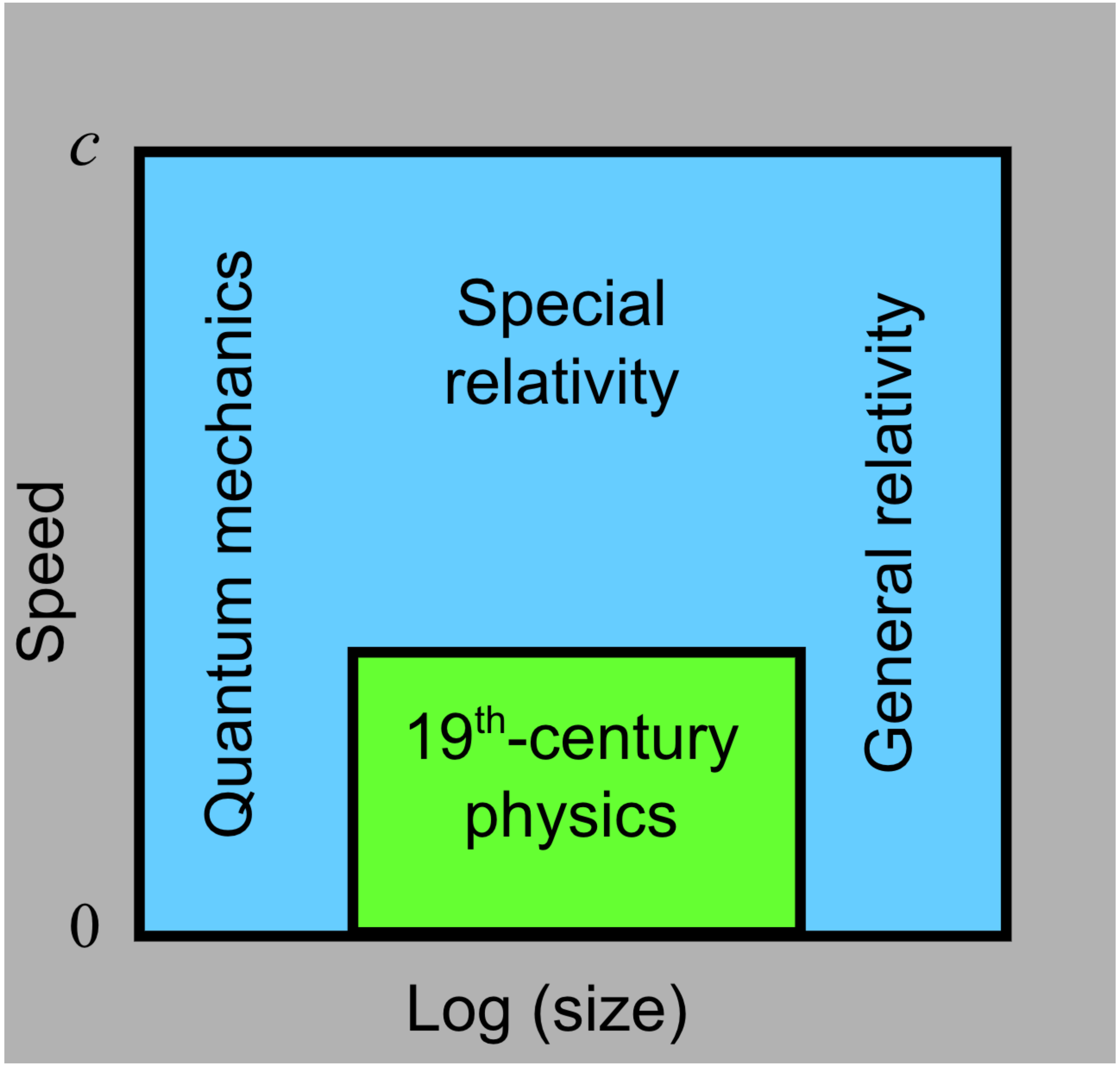
Additional Discoveries Contribute to the Complications

- Discovery of x-rays
- Discovery of radioactivity
- Discovery of the electron
- Discovery of the Zeeman effect

Birth of Modern Physics

- These new discoveries and the many resulting complications required a revision of the fundamental physical assumptions of mechanics and atoms.

- Theory of Relativity and Quantum mechanics are the starting point of this fascinating revision.

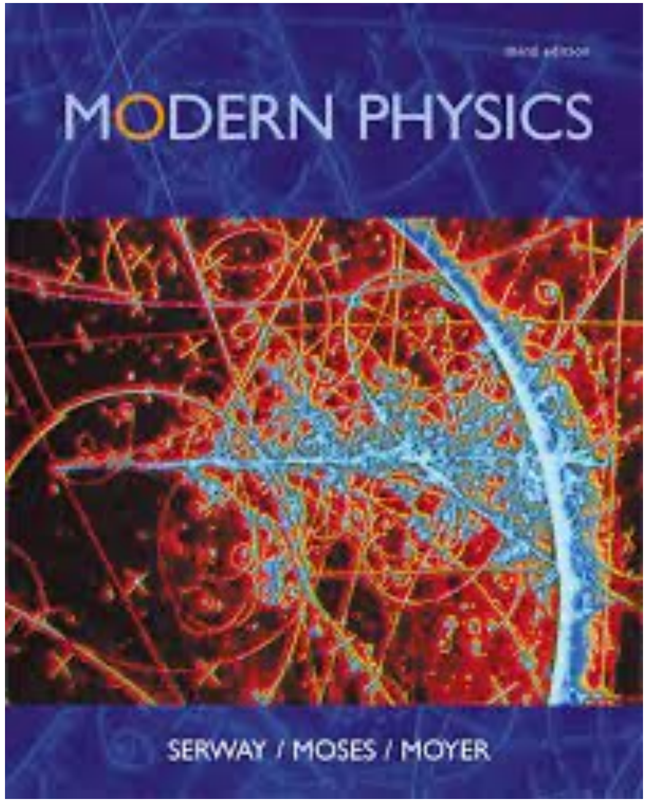


Reference Book for the course:

Modern Physics:

R. A. Serway, C. J. Moses, C. A. Moyer,

Thomson Learning Inc. 2005 Third Edition



Recommended Reading:

1. Photoelectric effect, section 3.4 in page 80.

2. The Bohr atom, section 4.3 in page 125.