2.71/2.710 Optics

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- Admin. Assistant: Kate Anderson
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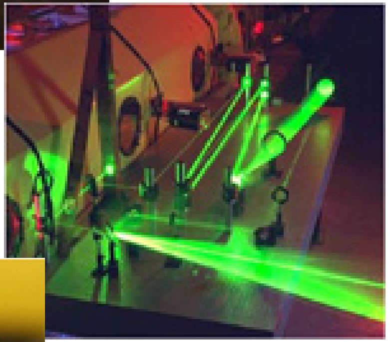
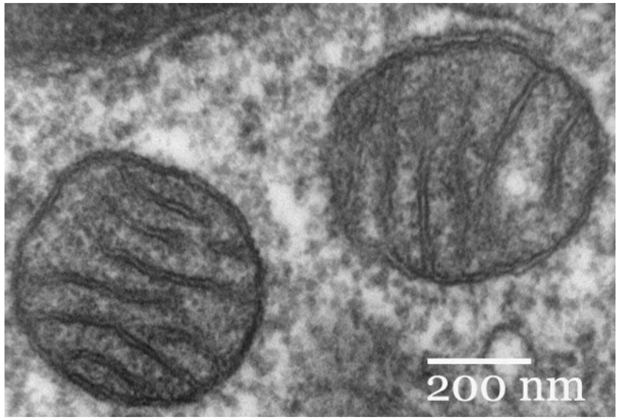
- Units: 3-0-9, Prerequisites: 8.02, 18.03, 2.004
- 2.71: meets the Course 2 Restricted Elective requirement
- 2.710: H-Level, meets the MS requirement in Design
- “gateway” subject for Doctoral Qualifying exam in Optics
- MIT lectures (EST): Mo 8-9am, We 7:30-9:30am
- NUS lectures (SST): Mo 9-10pm, We 8:30-10:30pm





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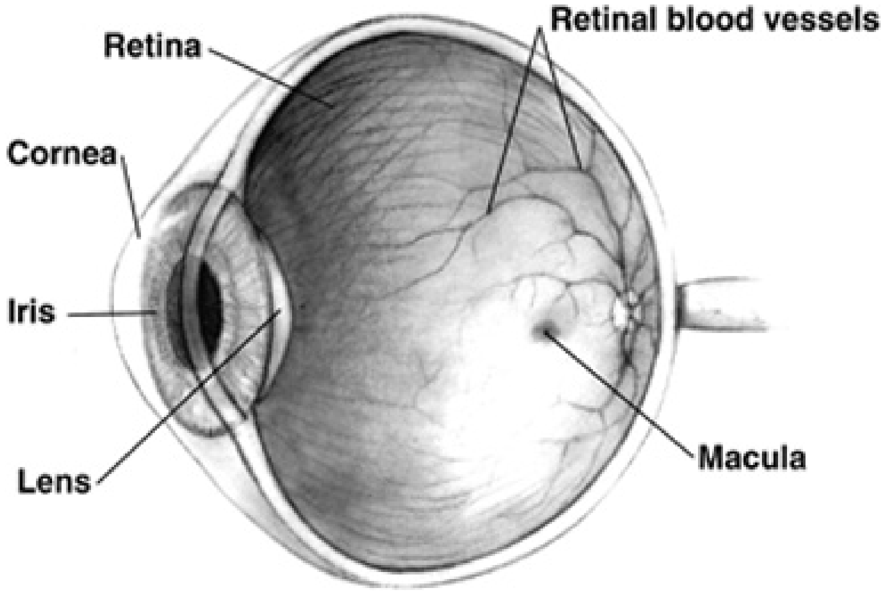
Natural & artificial imaging systems



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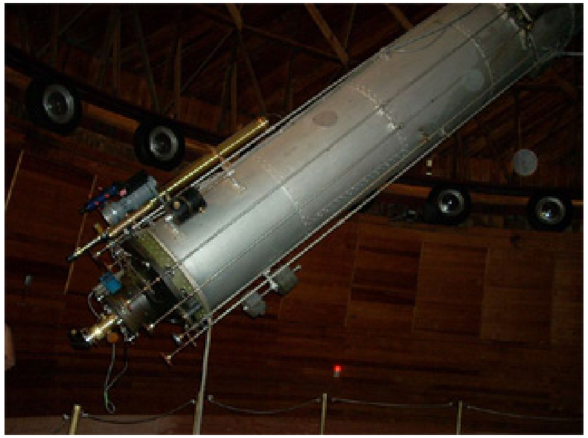

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Class objectives

- Cover the fundamental properties of light propagation and interaction with matter under the approximations of geometrical optics and scalar wave optics, emphasizing
  - physical intuition and underlying mathematical tools
  - *systems* approach to analysis and design of optical systems
- Application of the physical concepts to topical engineering domains, chosen from
  - high-definition optical microscopy
  - optical switching and routing for data communications and computer interconnects
  - optical data storage
  - interface to human visual perception and learning

What you need

- Absolutely necessary
  - Euclidean geometry, trigonometry
  - calculus with complex variables
  - Taylor series approximation
  - MATLAB or other computation/visualization software
  - linear systems (2.004 level, we will extensively review)
- Helpful if you know but we will cover here
  - basic electrodynamics (Maxwell's equations)
  - basic wave propagation
  - Fourier analysis

Learning resources

- Announcements, notes, assignments, solutions, links, broadcast
- Textbooks:
  - “Optics” by E. Hecht, 4th edition (Addison-Wesley)
  - “Introduction to Fourier optics” by J. W. Goodman, 3rd edition (McGraw-Hill)
- Other recommended texts:
  - “Waves and fields in optoelectronics” by H. A. Haus
  - “Optics” by Klein and Furtak
  - “Fundamentals of photonics” by Saleh and Teich
  - “Fundamentals of optics” by Jenkins and White
  - “Modern Optical Engineering” by W. J. Smith
- Experimental demonstrations (in class, almost weekly)

Administrative: 2.71

- Grade: 30% homeworks, 30% quizes,
  40% final exam
- Eight homeworks
  - each due 3 lectures after post date (see syllabus)
  - see website for collaboration & late policies
  - mainly “comprehension” problems

Administrative: 2.710

- Grade: 30% homeworks, 20% quizes, 20% project,
  30% final exam
- Eight homeworks
  - each due 3 lectures after post date (see syllabus)
  - see website for collaboration & late policies
  - both “comprehension” and “open-ended” problems
- Project
  - teams of 3-5
  - two project types: I. Read & Lecture; II. Research
  - selected among one of available topics or self-selected
  - start early March
  - weekly or so info meetings with project assistants
  - oral presentation on Weds. May 6

Administrative: both

- Two quizes:
  - Quiz 1 on Monday March 9th, in class
    - content: geometrical optics
  - Quiz 2 on Monday April 27th, in class
    - content: scalar wave optics
- Final exam:
  - scheduled by the Registrar
  - comprehensive on all material covered in class
- Practice problems will be available before each quiz and the final
- Absence from quizes/final: Institute policies apply
- Grading: Institute definitions apply

Administrative: both (cont.)

- **Please study lecture notes and book reading assignments <u>before class</u>**

- Questions: the most important part of learning
  - In class
  - During office hours (time/location TBA)
  - After hours: please use course discussion web site – **No email**
- Logistic/administrative questions: please email instructor team (faster response)
- No recitations
  - Some math revision sessions scheduled Mo or We, 7pm+ (MIT only)
  - In class problem solving in teams

Topics

- Geometrical optics
  - Basic ray-tracing
  - Image formation and imaging systems
  - Advanced ray-tracing: Hamiltonian optics
  - Optical system design
- Wave optics
  - Scalar linear wave propagation
  - Wave properties of light
  - Polarization
  - Interference and interferometers
  - Fourier/systems approach to light propagation
  - Spatial filtering, resolution, coherent & incoherent image formation, space-bandwidth product
  - Wavefront modulation, holography, diffractive optics
  - Subwavelength optics: “nanophotonics,” “metamaterials”

Brief history of Optics

- Ancient Greeks (~5-3 century BC)
  – Pythagoras (rays emerge from the eyes)
  – Democritus (bodies emit "magic" substance, simulacra)
  – Plato (combination of both of the above)
  – Aristotle (motion transfer between object & eye)
- Middle Ages
  – Alkindi, Alhazen defeat emission hypothesis (~9-10 century AD)
  – Lens is invented by accident (northern Italy, ~12th century AD)
  – Della Porta, da Vinci, Descartes, Gallileo, Kepler formulate geometrical optics, explain lens behavior, construct optical instruments (~15th century AD)
- Beyond the middle ages:
  – Newton (1642-1726) and Huygens (1629-1695) fight over nature of light

Brief history of Optics (cont'ed)

- 18^{th}–19^{th} centuries
  - Fresnel, Young experimentally observe diffraction, defeat Newton's particle theory
  - Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)
- 20^{th} century
  - Quantum theory explains wave-particle duality
  - Invention of holography (1948)
  - Invention of laser (1956)
  - Optical applications proliferate
    - computing, communications, fundamental science, medicine, manufacturing, entertainment

Nobel Laureates in the field of Optics

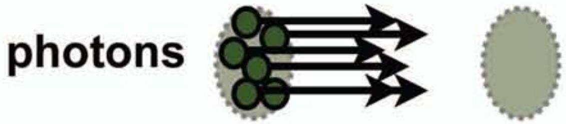
- O. Shinomura, M. Chalfie, R. Y. Tsien – Chemistry 2008
- Roy J. Glauber, John L. Hall, Theodor W. Hänsch – Physics 2005
- W. Ketterle (**MIT**), E. Cornell, C. Wieman – Physics **2001**
- Z. Alferov, H. Kroemer, J. Kilby – Physics 2000
- A. Zewail – Chemistry 1999
- S. Chu, C. Cohen-Tannoudji, W. Phillips – Physics 1997
- E. Ruska – Physics 1986
- N. Bloembergen, A. Schawlaw, K. Siegbahn – Physics 1981
- A. Cormack, G. Housefield – Biology or Medicine 1979
- M. Ryle, A. Hewish – Physics 1974
- D. Gabor – Physics 1971
- A. Kastler – Physics 1966 C. Townes (**MIT**), N. Basov, A. Prokhorov – Physics 1964
- F. Zernicke – Physics 1953
- C. Raman – Physics 1930
- W. H. Bragg, W. L. Bragg – Physics 1915
- G. Lippman – Physics 1908
- A. Michelson – Physics 1907
- J. W. Strutt (Lord Rayleigh) – Physics 1904
- H. Lorentz, P. Zeeman – Physics 1902
- W. Röntgen – Physics 1901

The dual particle/wave nature of light

A beam of light can be thought of as ...

... a flux of particles

(Newton/Planck/Einstein)



Zero mass, speed: $c = 3 \times 10^8 \mathrm{m/sec}$

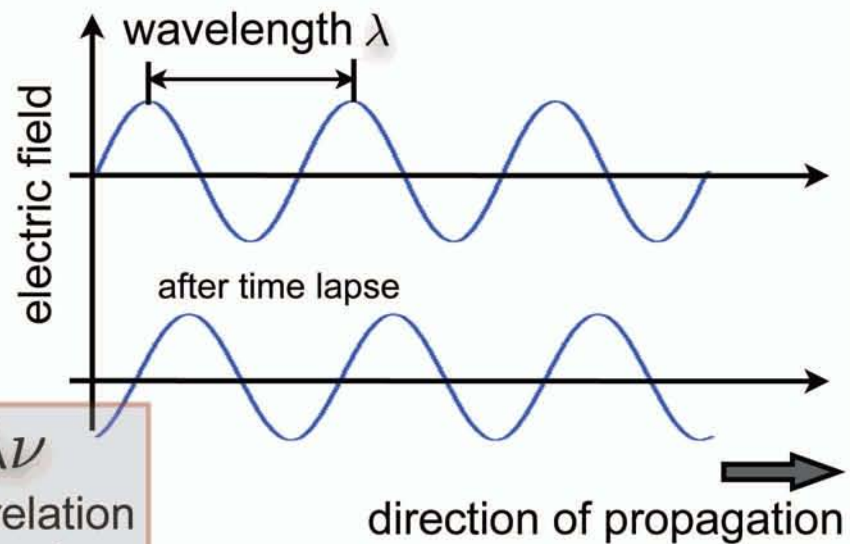
Energy carried by each particle: $E = h\nu$

$h = 6.6262 \times 10^{-34} \mathrm{J \cdot sec}$ (Planck's const.)

$\nu \text{ (frequency)} = \dfrac{1}{T \text{ (period)}}$

... an electromagnetic wave

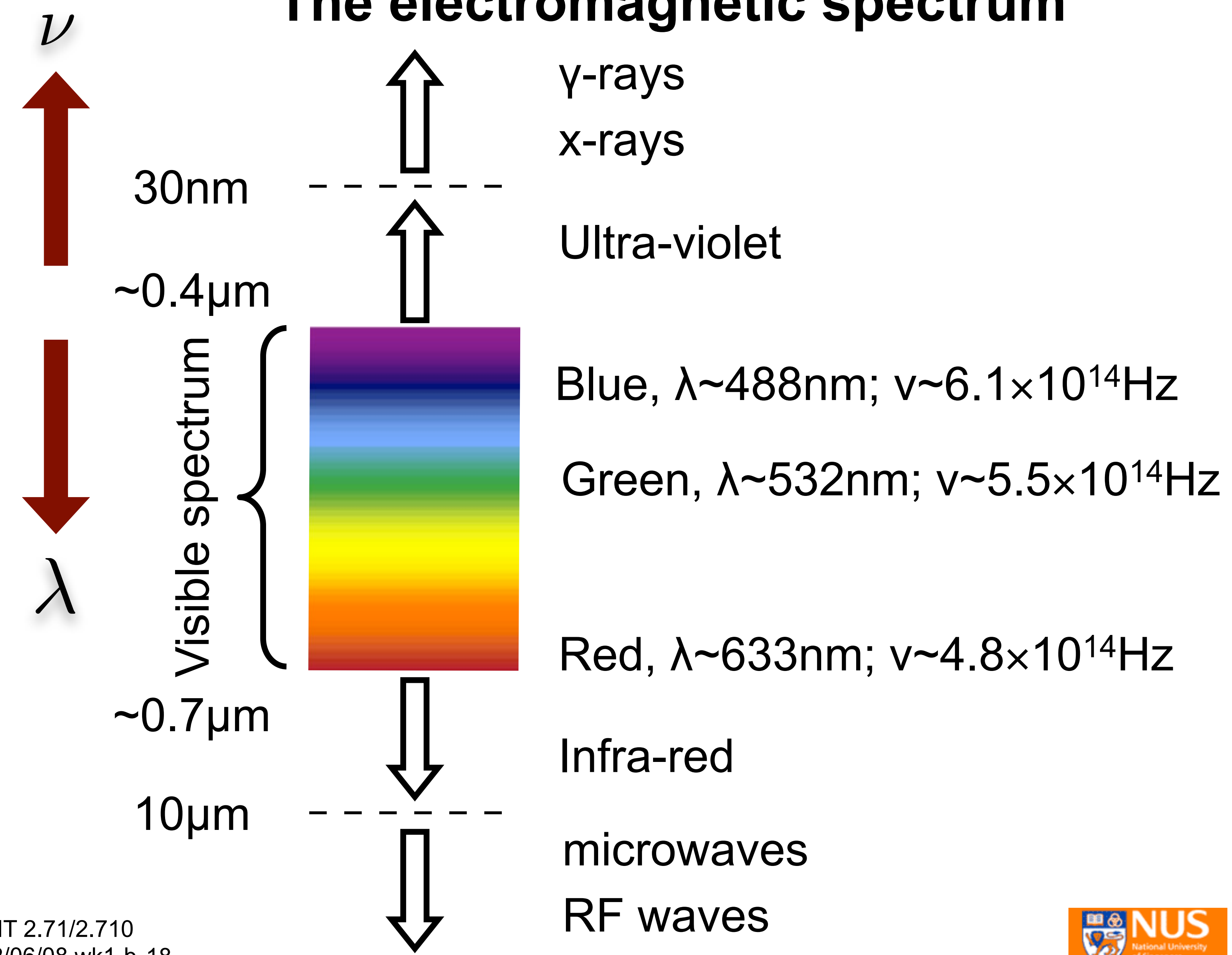
(Huygens/Maxwell/Hertz)



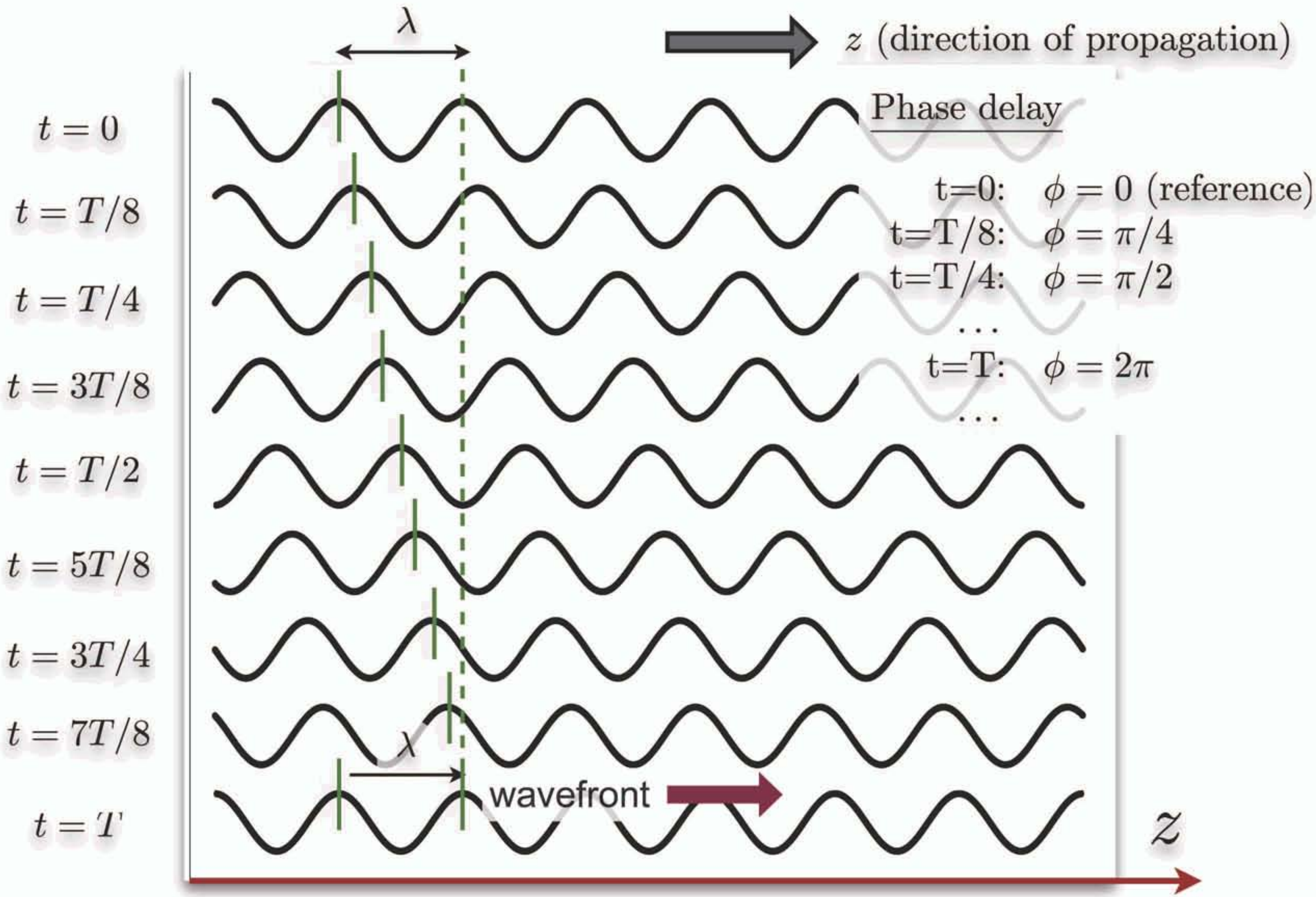
$$c = \lambda\nu$$

Dispersion relation
(free space)

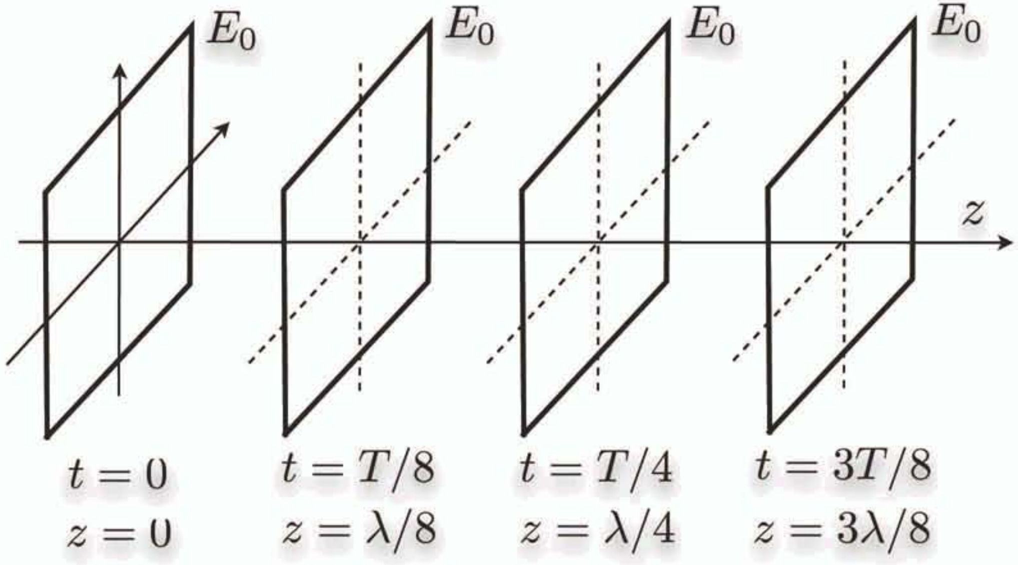
The electromagnetic spectrum



1D wave propagation



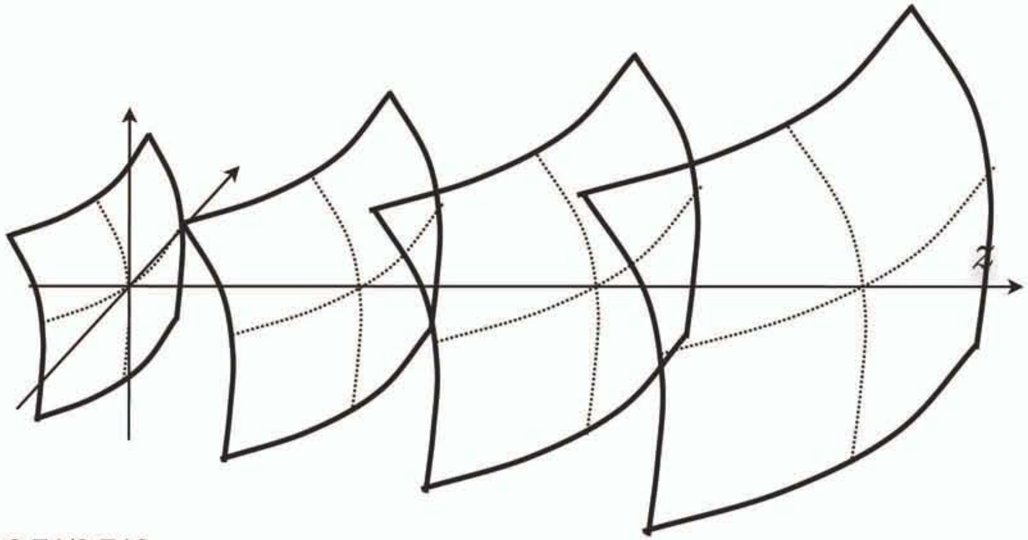
Wavefronts in 3D



Planar wavefront (plane wave):

The wave phase is constant along a planar surface (the wavefront).

As time evolves, the wavefronts propagate at the wave speed without changing; we say that the wavefronts are *invariant to propagation* in this case.

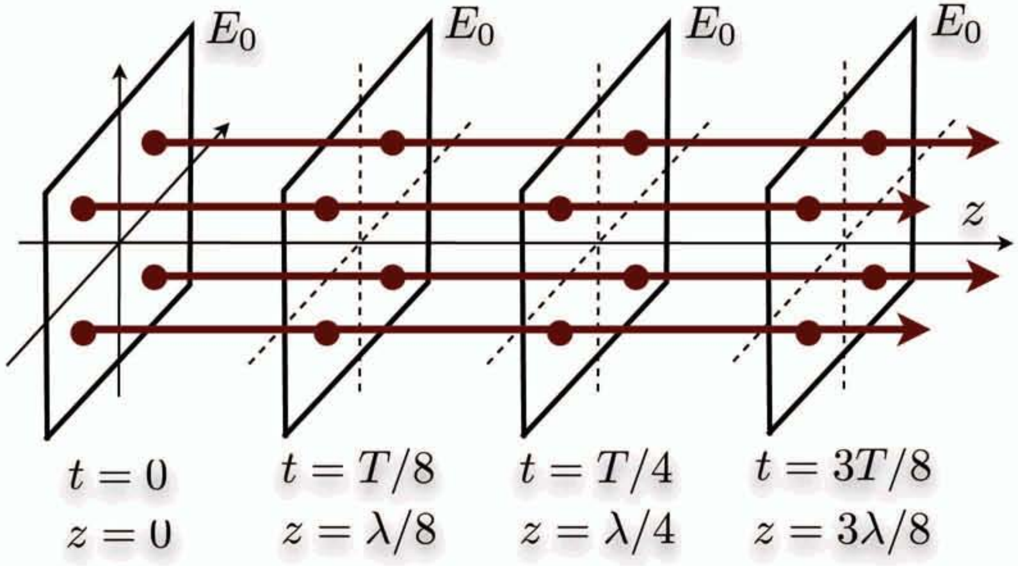


Spherical wavefront (spherical wave):

The wave phase is constant along a spherical surface (the wavefront).

As time evolves, the wavefronts propagate at the wave speed and expand outwards while preserving the wave's energy.

Rays



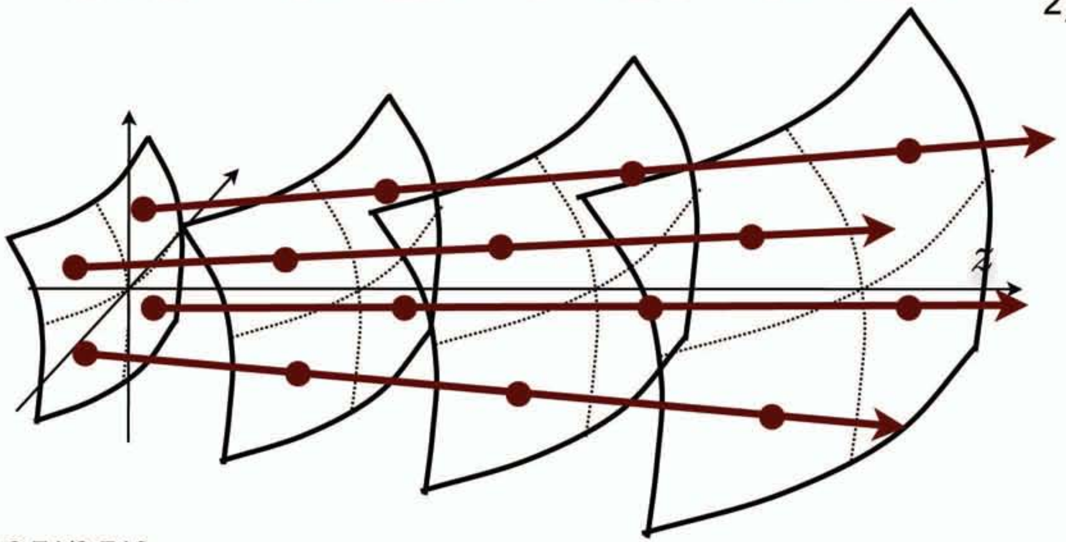
Rays are:

1) normals to the wavefront surfaces
2) trajectories of “particles of light”

Properties of rays:

1) Continuous and piece-wise differentiable
2) Ray trajectories are such as to minimize the “optical path”

⇒ in free space, ray trajectories are straight lines



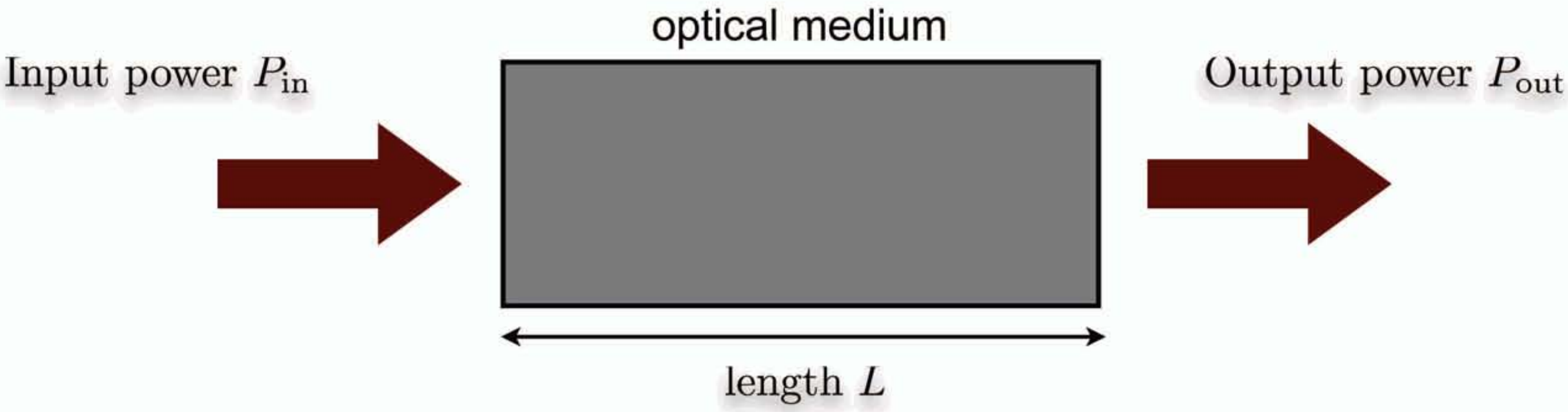
Light interaction with matter

- We will consider three basic types of light-matter interaction:
  - absorption
  - scattering
  - refraction

- The type of interaction that occurs depends on
  - the wavelength of the light
  - other wave attributes of the light, e.g. polarization
  - the atomic/molecular structure of matter
  - the amount of incident light energy

- At high energies, “nonlinear” interactions occur, e.g. florescence and multi-photon scattering or even ionization; we will mention them briefly later in this class, but we will not cover them in detail.

Absorption



Physical origin of absorption: conversion of light energy to heat (Ohmic losses)

Beer's Law:

$$P_{out} = P_{in} e^{-2\alpha L}$$

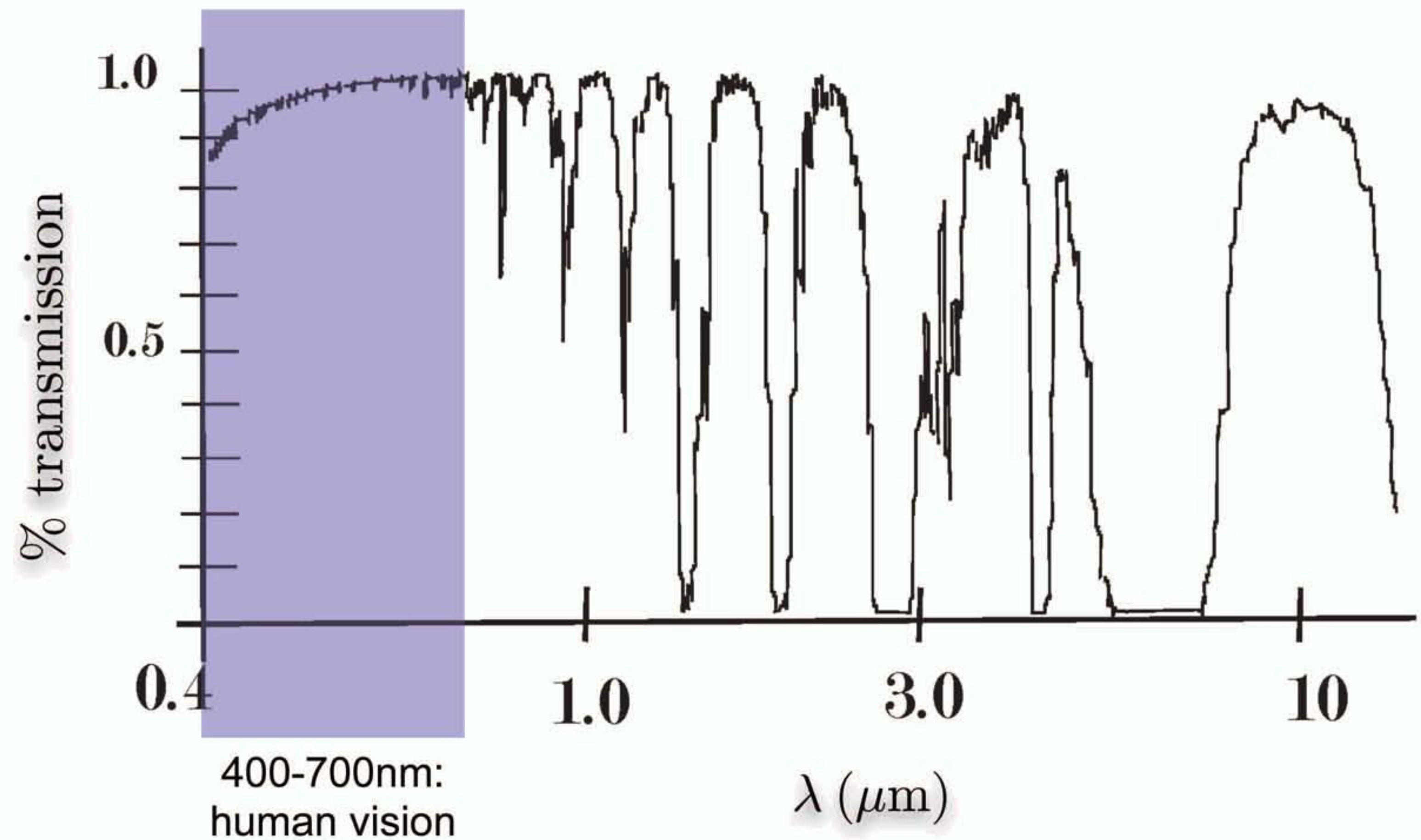
Conductors: very high absorption,

$\alpha \sim 10 \text{dB}/\mu\text{m}$ or higher in metals

Dielectrics: very low absorption,

$\alpha \sim 0.1 \text{dB}/\text{km}$ or lower in optical fibers

Light absorption through the atmosphere



Refraction: light speed in vacuum and matter

In free space:

$c = 3 \times 10^8 \mathrm{m/sec.}$

In dielectric materials
(e.g. water, glass):

$$\frac{c}{n}, \qquad \text{where}$$

the quantity n is referred to as
the *refractive index*
(aka *index of refraction*)

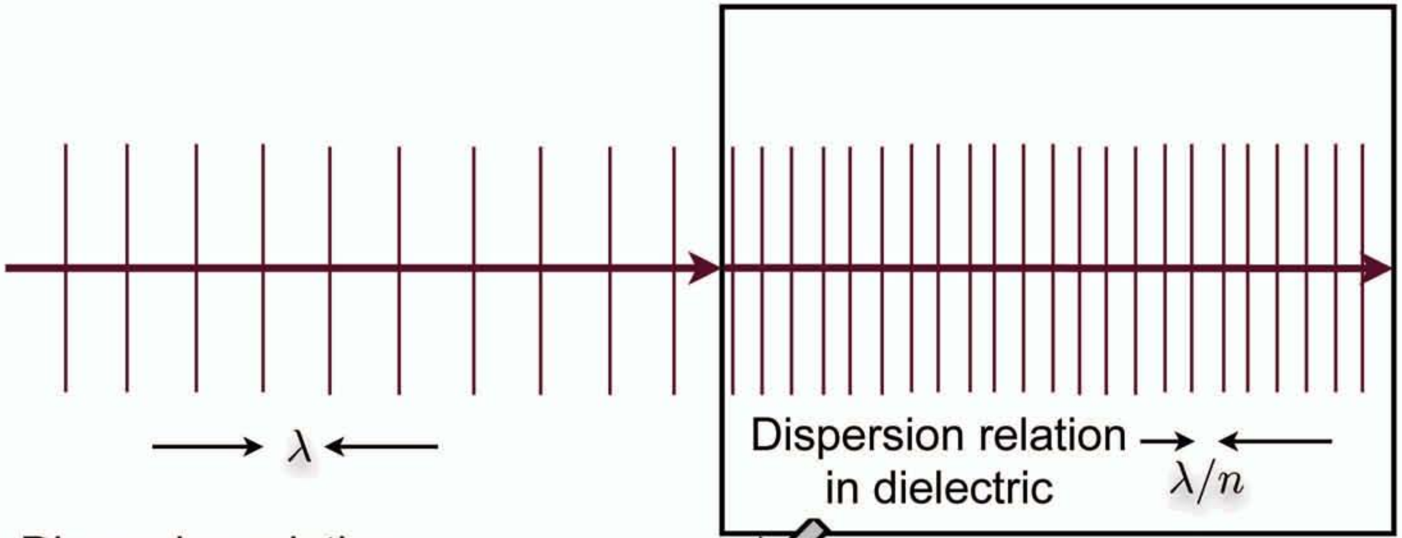
The refractive index expresses the optical "density" of a dielectric medium

Refractive index values of commonly used dielectrics:

air≈ 1
water≈ 1.3
glass≈ 1.5

We accept the definition of refractive index n as a phenomenological quantity. We will explain its physical origins more rigorously when we discuss the electromagnetic description of light in more detail.

Refraction: wavelength in vacuum and matter



Dispersion relation in vacuum

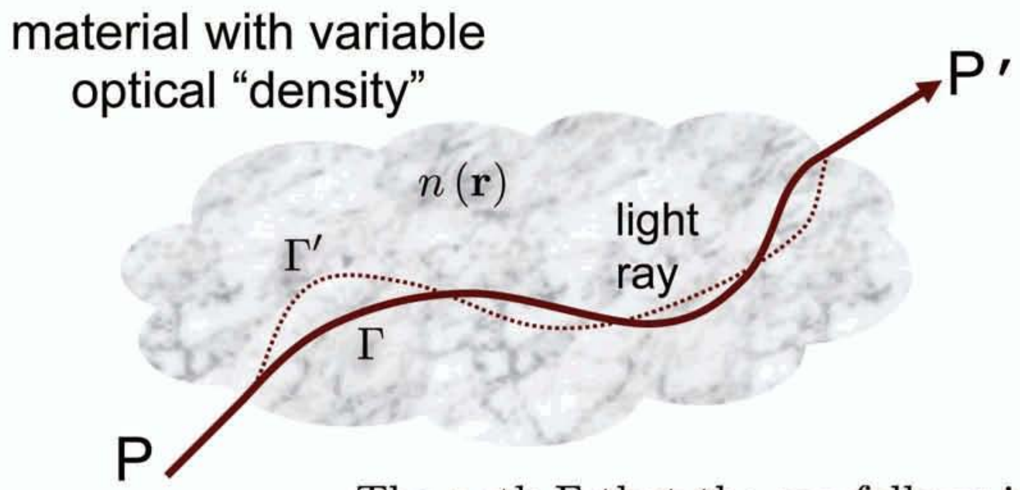
$$c = \lambda\nu \Rightarrow \frac{c}{n} = \left(\frac{\lambda}{n}\right)\nu$$

The temporal frequency ν is the same, independent of the material; this is because ν is determined by the photon energy $E = h\nu$

Light speed in dielectric of refractive index n

Light wavelength in dielectric of refractive index n

The minimum path (Fermat) principle



"optical path length"

$$\int_{\Gamma} n(\mathbf{r})\,\mathrm{d}l$$

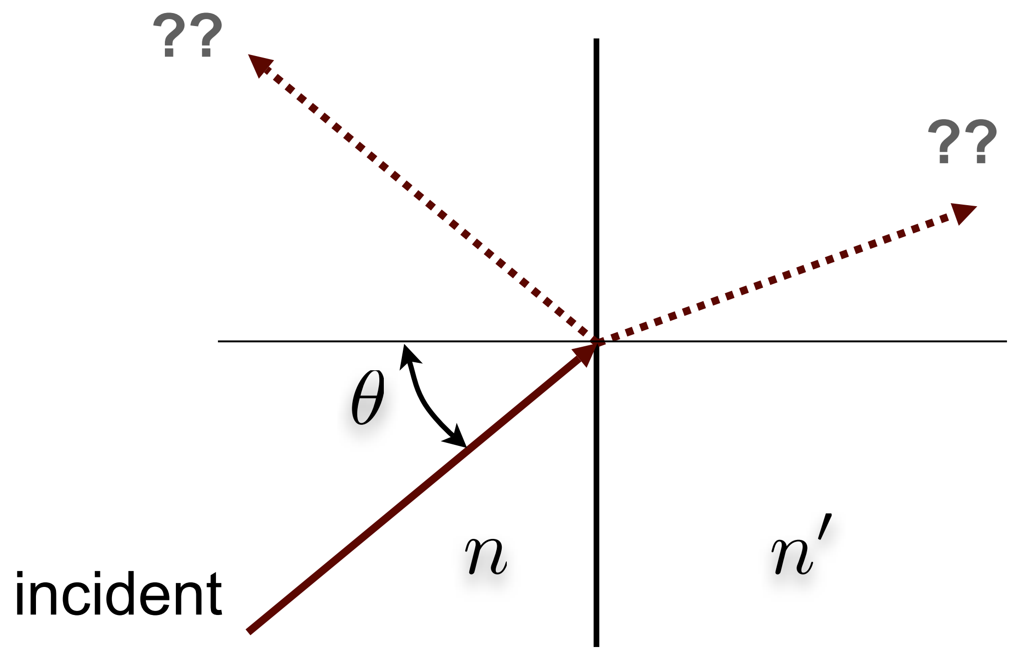
The path Γ that the ray follows is such that the value of the path integral of refractive index $n(\mathbf{r})$ along Γ is smaller than all other possible paths Γ'.

Analogy from mechanics: the minimum action (Lagrangian) principle

Corollary: In free space or uniform space of constant refractive index n, light propagates in a *straight line*.

Consequences: the laws of reflection and refraction

Incidence at dielectric interface



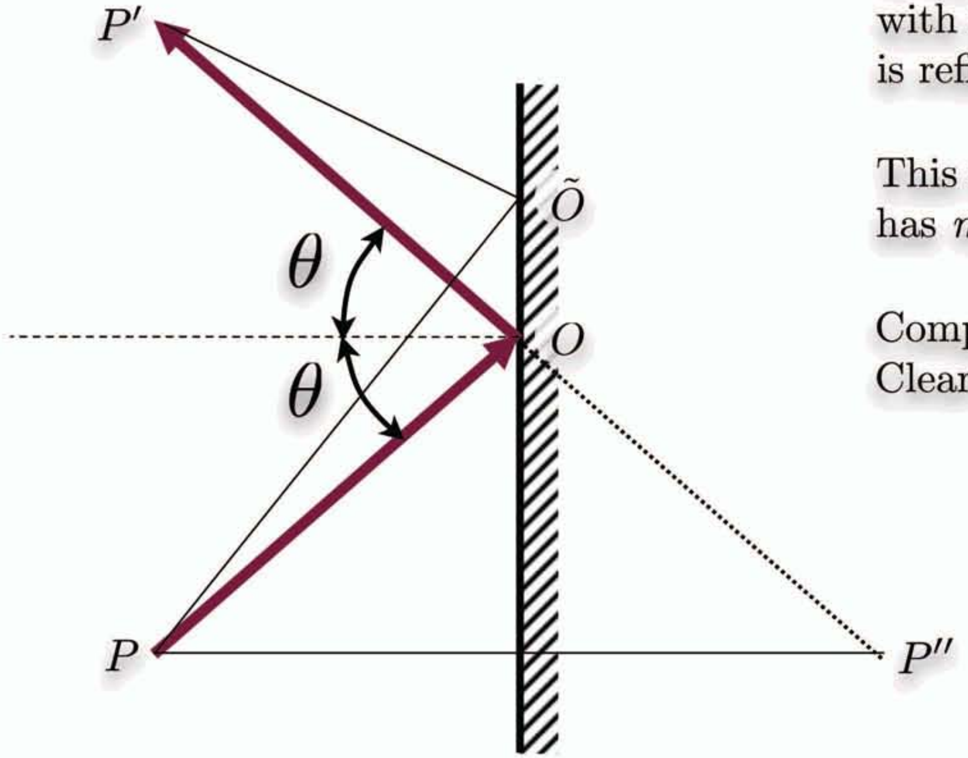
When a light ray is incident at a dielectric interface,

part of the light energy is *reflected* back into the material on the left-hand side

part of the light energy is *refracted* towards the material on the right-hand side

Here, we seek to determine the directions of propagation of the reflected and refracted rays. The fraction of energy that is reflected or refracted requires electromagnetics, so we'll postpone its calculation for later.

The law of reflection



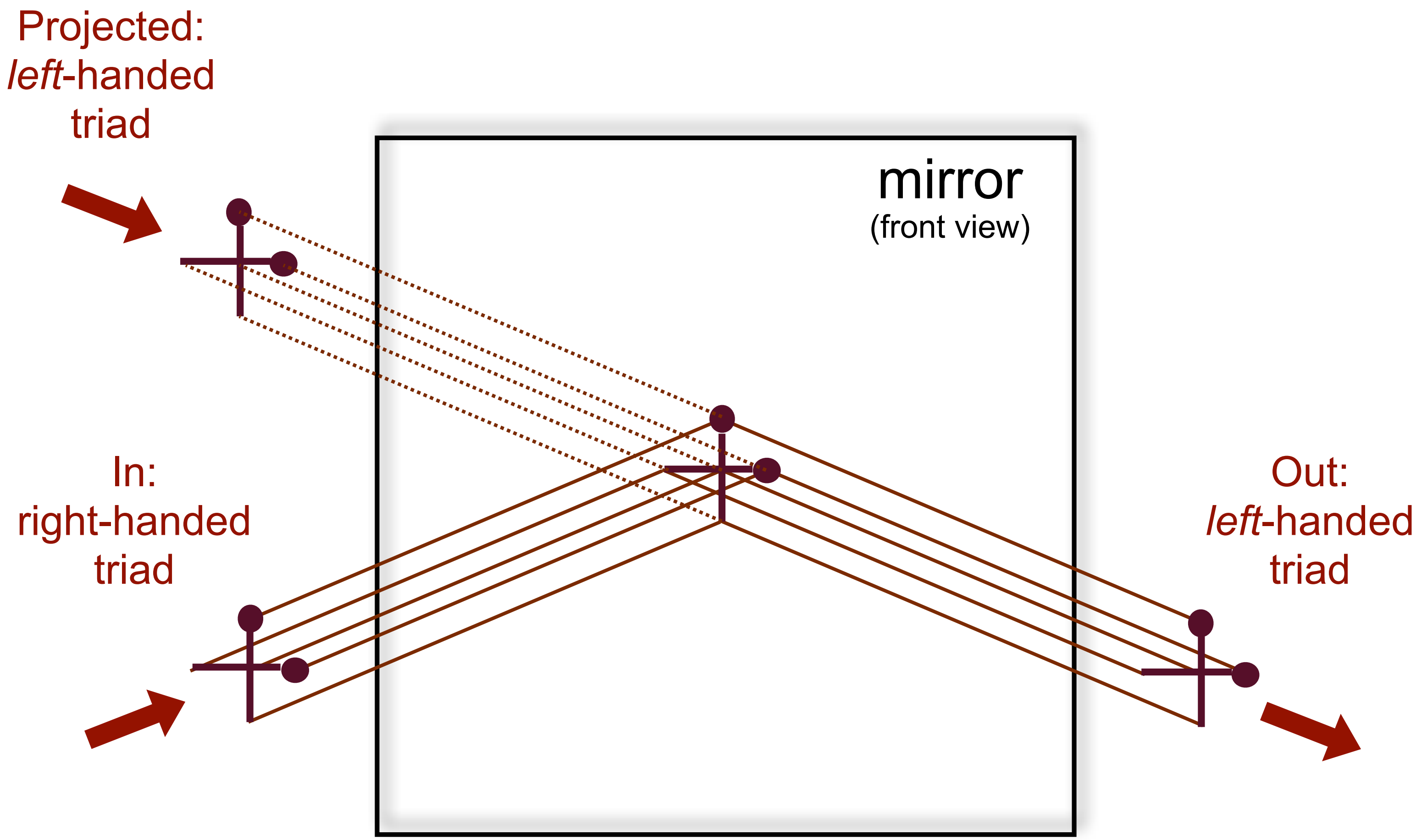
A ray departing from P in the direction θ with respect to the mirror normal is reflected symmetrically at the same angle θ.

This is because the symmetric path POP' has *minimum length*.

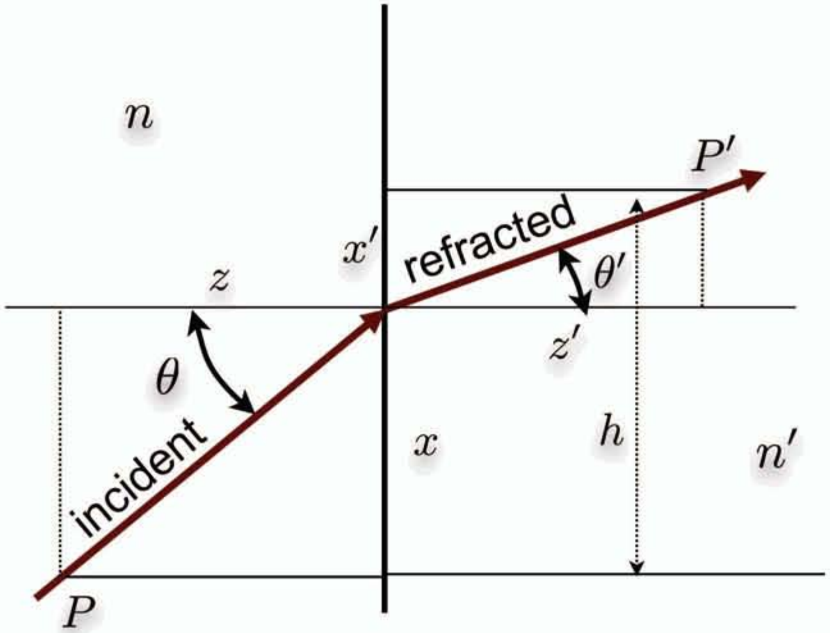
Compare, for example, the alternative $P\tilde{O}P'$. Clearly, $|PO| + |OP'| < |P\tilde{O}| + |\tilde{O}P'|$.

Consider the continuation of OP' *backwards* through the mirror. To an observer in the direction of P', the ray will appear to have originated at P''.

Reflection from mirrors



The law of refraction (Snell's Law)



Let P, P' denote two points along the ray trajectory. According to the Fermat principle, the angle θ must be such as to minimize the optical path length between PP'.

This is expressed as

$$(\text{OPL}) = n\sqrt{x^2+z^2} + n'\sqrt{(h-x)^2+z'^2}.$$

Taking derivatives with respect to x,

$$\frac{\partial(\text{OPL})}{\partial x} = n\frac{x}{\sqrt{x^2+z^2}} - n'\frac{h-x}{\sqrt{(h-x)^2+z'^2}} = n\sin\theta - n'\sin\theta' = 0$$

$$\Rightarrow n\sin\theta = n'\sin\theta'$$

This result is known as *Snell's Law*, or *Law of Refraction*.

Summary of today's lecture

- Dual particle/wave nature of light
  - wave description: wavelength, frequency, wavefronts, dispersion relation
  - particle description: rays
- Absorption (Beer's law)
- Refraction: phenomenological interpretation of the refractive index
- Fermat's principle
- Corollaries of Fermat's principle:
  - law of reflection
  - law of refraction (Snell's law)

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Spring 2009