2.71/2.710 Optics

Units: 3-0-9, Prerequisites: 8.02, 18.03

2.71: meets the Department Elective requirement

2.710: H-Level, meets the MS requirement in Design

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 for data communications and computer interconnects
  - optical data storage
  - interface to human visual perception and learning
  - micro-optical adaptive components (optical MEMS)

What you need

- Absolutely necessary
  - Euclidean geometry
  - calculus with complex variables
  - Taylor series approximation
  - MATLAB or other computation/visualization software
- Helpful if you know but we will cover here
  - basic electrodynamics
  - basic wave propagation
  - linear systems and Fourier analysis

Topics

- Geometrical optics
  - Basic ray-tracing
  - Image formation and imaging systems
  - Optical design
- Wave optics
  - Scalar linear wave propagation
  - Wave properties of light
  - Polarization
  - Interference and interferometry
  - Fourier/systems approach to light propagation
  - Spatial filtering, resolution, coherent & incoherent image formation, inverse problems
  - Wavefront modulation/holography

Applications

- Confocal microscopy
  - optical slicing
  - fluorescence
  - two-photon
  - real-time
  - holographic
  - Spectroscopic
  - bio-imaging, imaging through turbulence
- Super-resolution
  - apodizing filters
  - hybrid (optics+signal processing) approaches
  - information-theoretic viewpoint
- Optical data storage
  - optical disks (CD's, DVD's, MO disks)
  - holographic memories
- Optical switching
  - optical MEMS
  - liquid crystals
  - thermo-optics
  - acousto-optics
- Statistical optics
  - Coherence imaging (van Cittert-Zernicke theorem, radio astronomy)
  - Optical coherence tomography
  - X-ray tomography (Slice Projection theorem, Radon transforms)

Class compass

- Broadcasts
  - 2.710@petrosian.mit.edu
- Textbooks: “Optics” by E. Hecht, 3rd edition (Addison-Wesley)
  - [2.710 only] “Introduction to Fourier optics” by J. W. Goodman, 2nd edition (McGraw-Hill)
- 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

Administrative: 2.71

- Grade: 30% homeworks, 40% quiz, 30% final exam
- Ten homeworks
  - each due 1 week after post date (see syllabus)
  - see website for collaboration & late policies
  - mainly “comprehension” problems
- Occasional lab demonstrations (optional)

Administrative: 2.710

- Grade: 25% homeworks, 30% quizes, 20% project, 25% final exam
- Ten homeworks
  - each due 1 week after post date (see syllabus)
  - see website for collaboration & late policies
  - both “comprehension” and “open-ended” problems
- Occasional lab demonstrations (optional)
- Project
  - teams of 2-3
  - selected among one of the application areas (topics soon TBA)
  - start first week of November
  - weekly or so info meetings with instr/TA
  - oral presentation and 3-page technical paper

Administrative: both

- Two quizes:
  - Quiz 1 on Wednesday Oct. 10, 10am (in class)
  - Quiz 1 content: geometrical optics, basic wave propagation
  - Quiz 2 on Wednesday Nov. 14, 10am (in class)
  - Quiz 2 content: Fourier optics
- Final exam:
  - scheduled by the Registrar
  - comprehensive on everything covered in class
- Absence from quizes/final: Institute policies apply
- Grading: Institute definitions apply

Administrative: both (cont.)

- Office hours: TBA
- Unlimited email access (broadcasts encouraged), best effort to reply within 24hrs.
- Recitations during scheduled class hours
  - *most* Wednesdays (some separate for 2.71 and 2.710)
  - broadcast by e-mail when not in syllabus
  - contents
    - example problems (usually before homeworks are due)
    - homework solutions (after homework due dates)
    - extended coverage of some special topics (e.g., optical design software; 2D Fourier transforms)
    - suggestions welcome

Brief history of optics

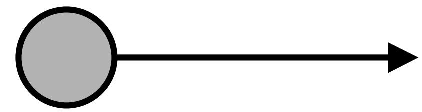
- Ancient Greeks (~5-3 century BC)
  - Pythagoras (rays emerge from the eyes)
  - Democritus (bodies emit "magic" substance, simulacra)
  - Plato (combination of both of the above)
  - Aristotle (motion transfer between object & eye)
- Middle Ages
  - Alkindi, Alhazen defeat emission hypothesis (~9-10 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

Particle properties of light

Photon=elementary light particle



Mass=0
Speed $c=3\times10^8$ m/sec

$$c=\lambda\nu$$

"Dispersion relation"

Energy $E=h\nu$ ⟹ relates the dual particle & wave nature of light;

h=Planck's constant
$=6.6262\times10^{-34}$ J sec

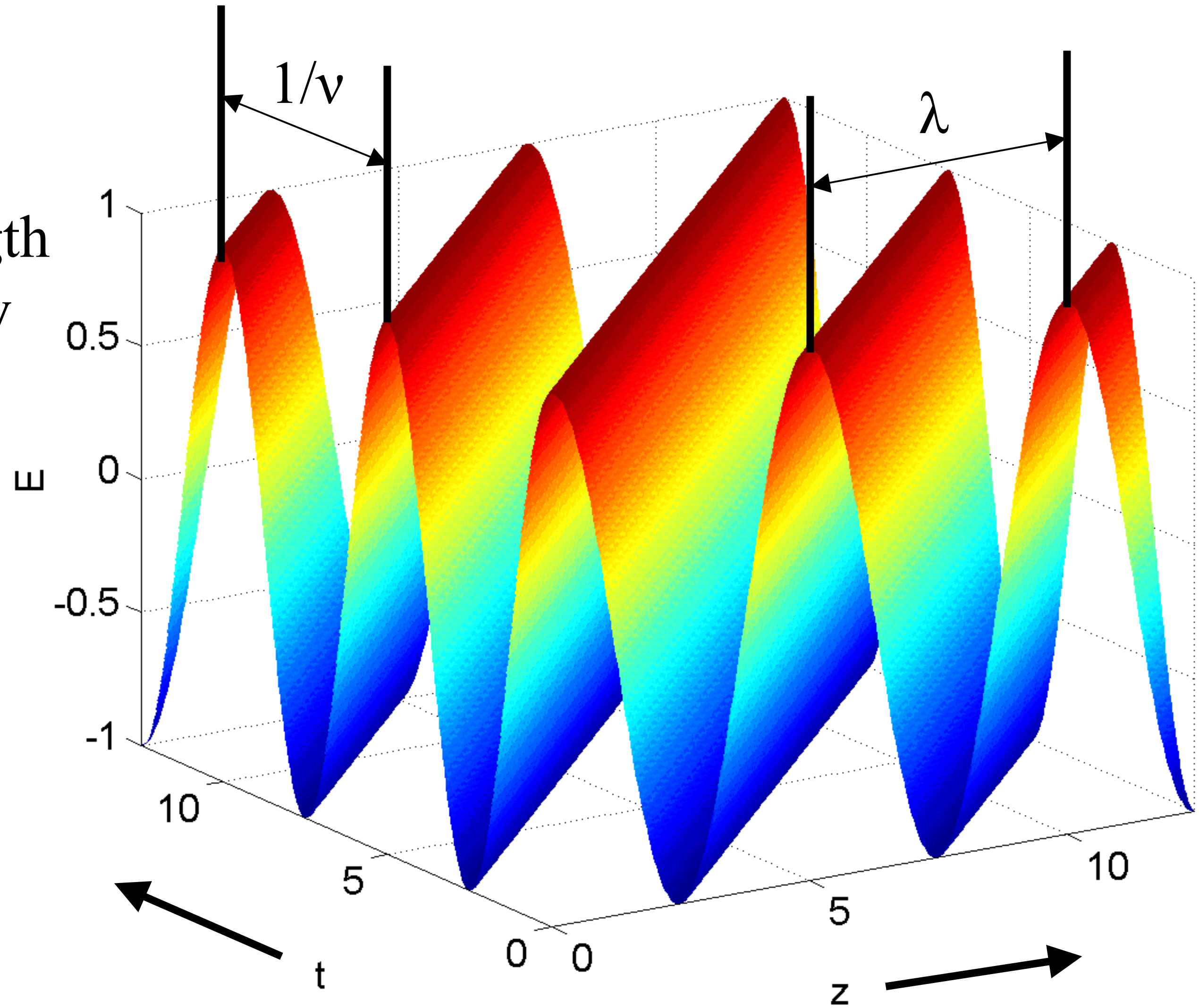
ν is the temporal oscillation frequency of the light waves

ν=frequency (sec^{-1})
λ=wavelength (m)

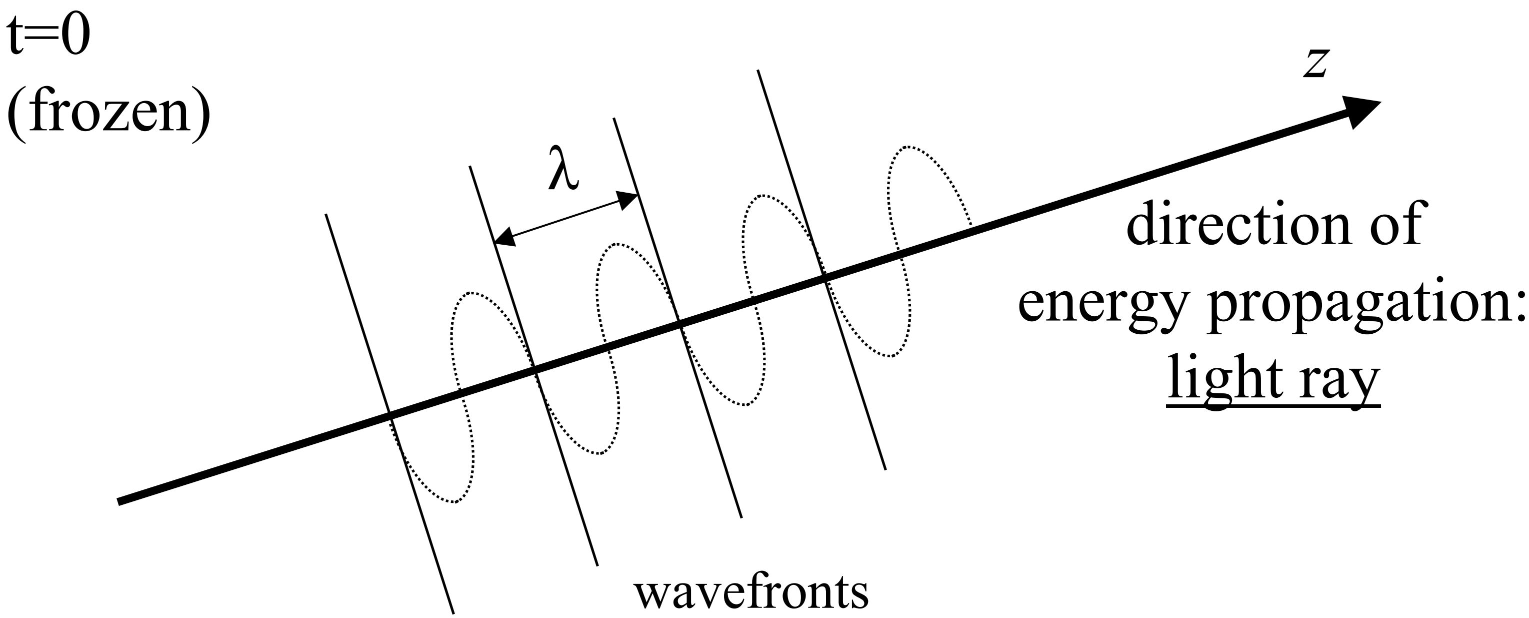
λ is the spatial period of the light waves

Photon flux: a light wave

λ: wavelength
ν: frequency
E: electric field

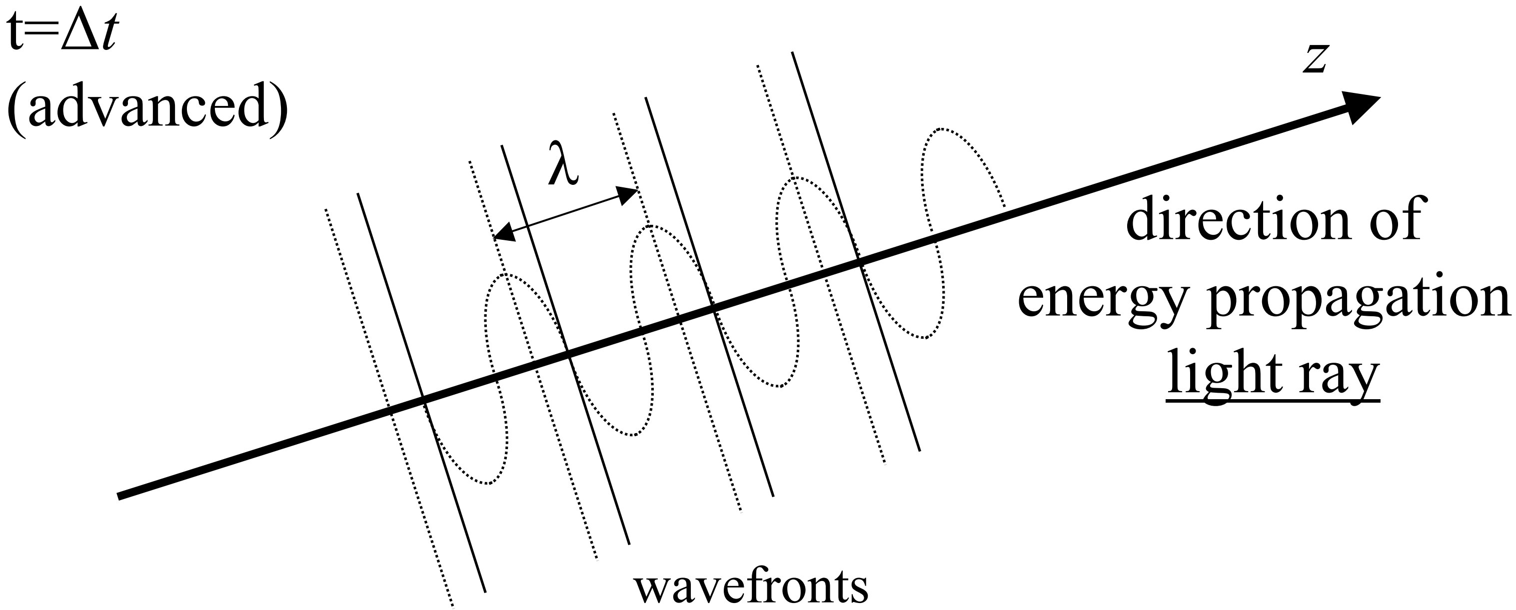


The concept of a "ray"



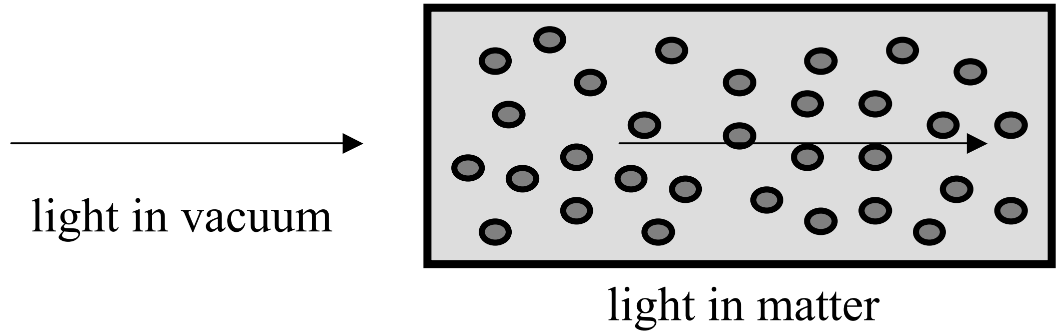
In homogeneous media,
light propagates in rectilinear paths

The concept of a "ray"



In homogeneous media,
light propagates in rectilinear paths

Light in matter



Speed $c=3\times10^8$ m/sec

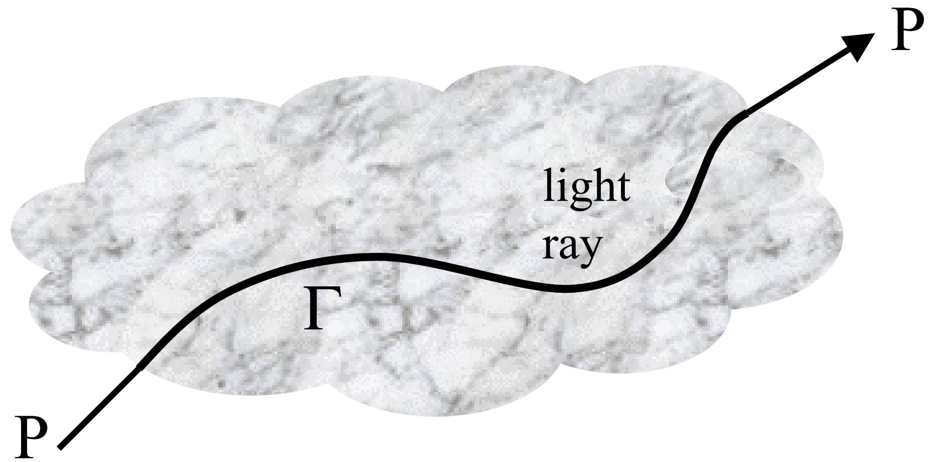
Speed c/n
n : refractive index
(or index of refraction)

Absorption coefficient 0

Absorption coefficient α
energy decay coefficient,
after distance L : $e^{-2\alpha L}$

E.g. glass has $n\approx1.5$, glass fiber has $\alpha\approx0.25$dB/km=0.0288/km

The minimum path principle

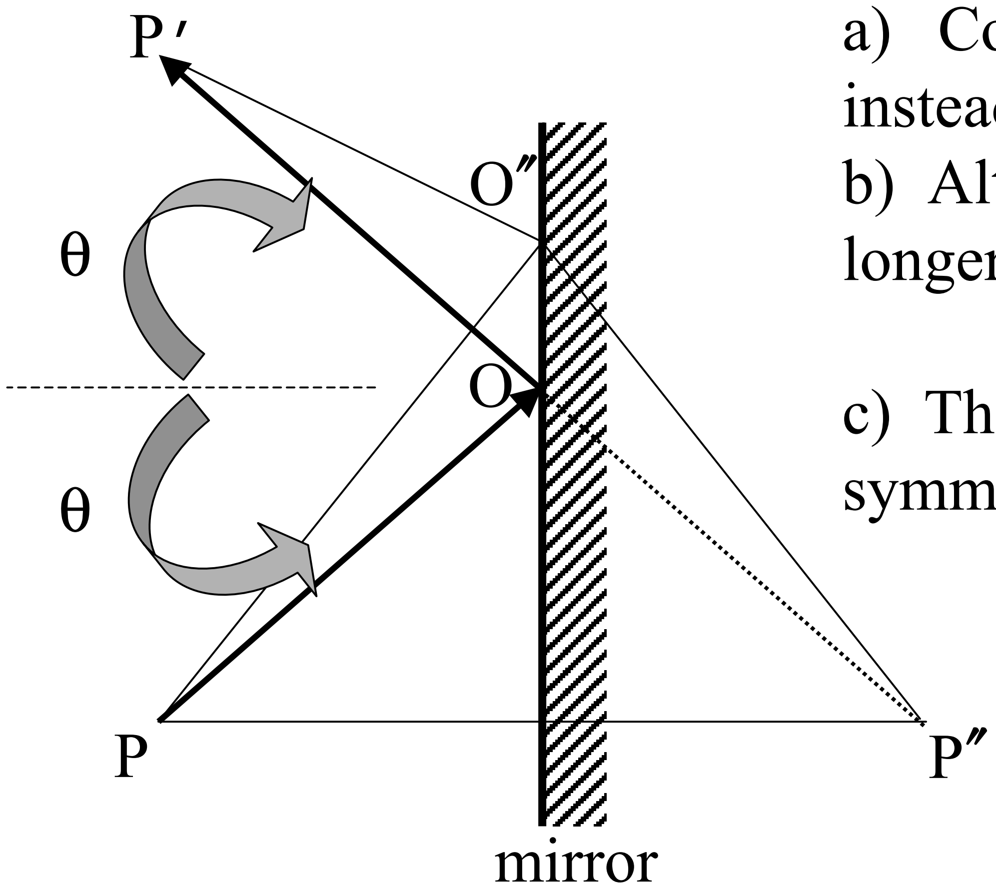


$$\int_{\Gamma} n(x, y, z)\, \mathrm{d}l$$

Γ is chosen to minimize this "path" integral, compared to alternative paths

(aka **Fermat**'s principle)
Consequences: law of reflection, law of refraction

The law of reflection

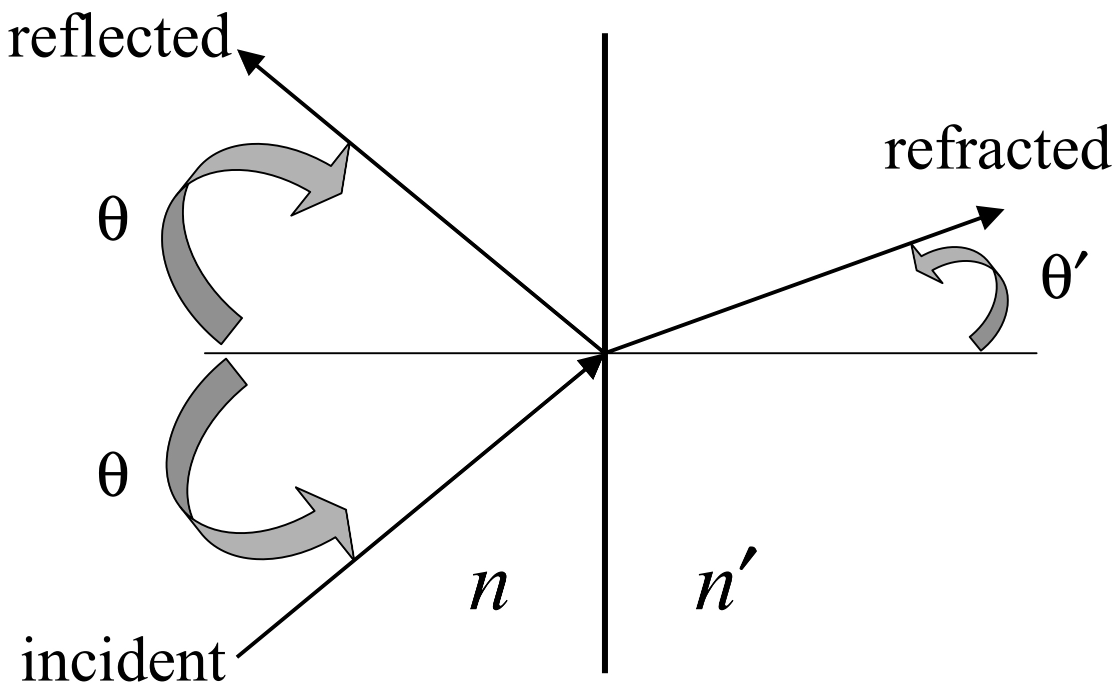


a) Consider virtual source P” instead of P

b) Alternative path P”O”P’ is longer than P”OP’

c) Therefore, light follows the symmetric path POP’.

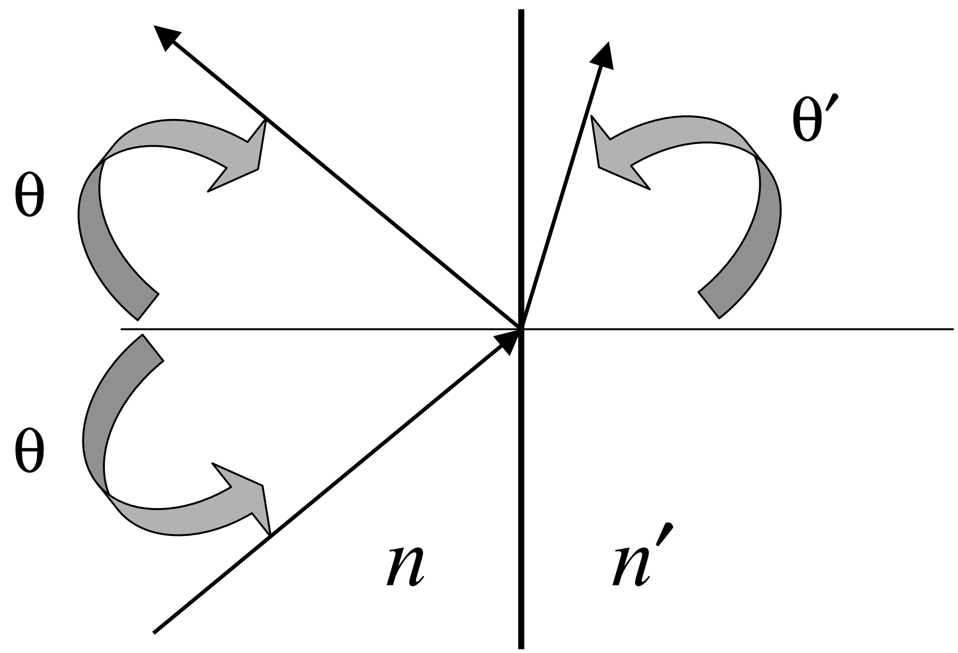
The law of refraction



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

Snell's Law of Refraction

Total Internal Reflection (TIR)

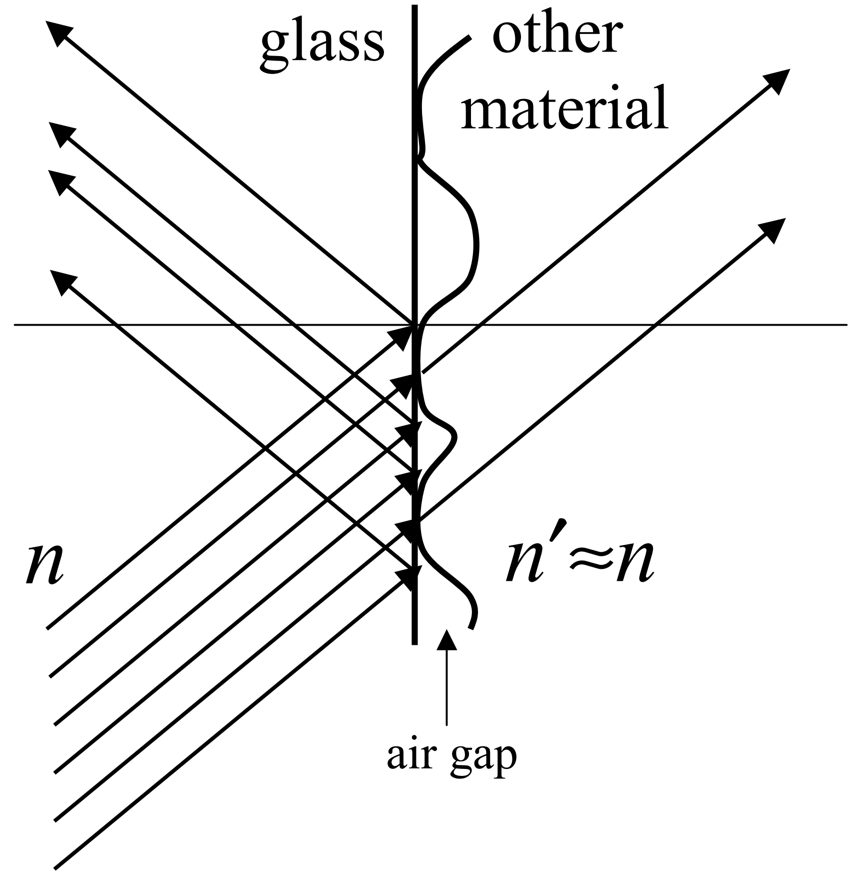


$$n > n' \Rightarrow \theta' \text{ becomes imaginary when } \theta > \theta_{\text{crit}} = \sin^{-1}\frac{n'}{n}$$

$\Rightarrow$ refracted beam disappears, all energy is reflected

Frustrated Total Internal Reflection (FTIR)

Reflected rays are missing where index-matched surfaces touch ⇒ shadow is formed



Angle of incidence exceeds critical angle