2.71/2.710 Optics

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Instructor: George Barbastathis

Units: 3-0-9, Prerequisites: 8.02, 18.03, 2.003

2.71: meets the Course 2 Restricted Elective requirement

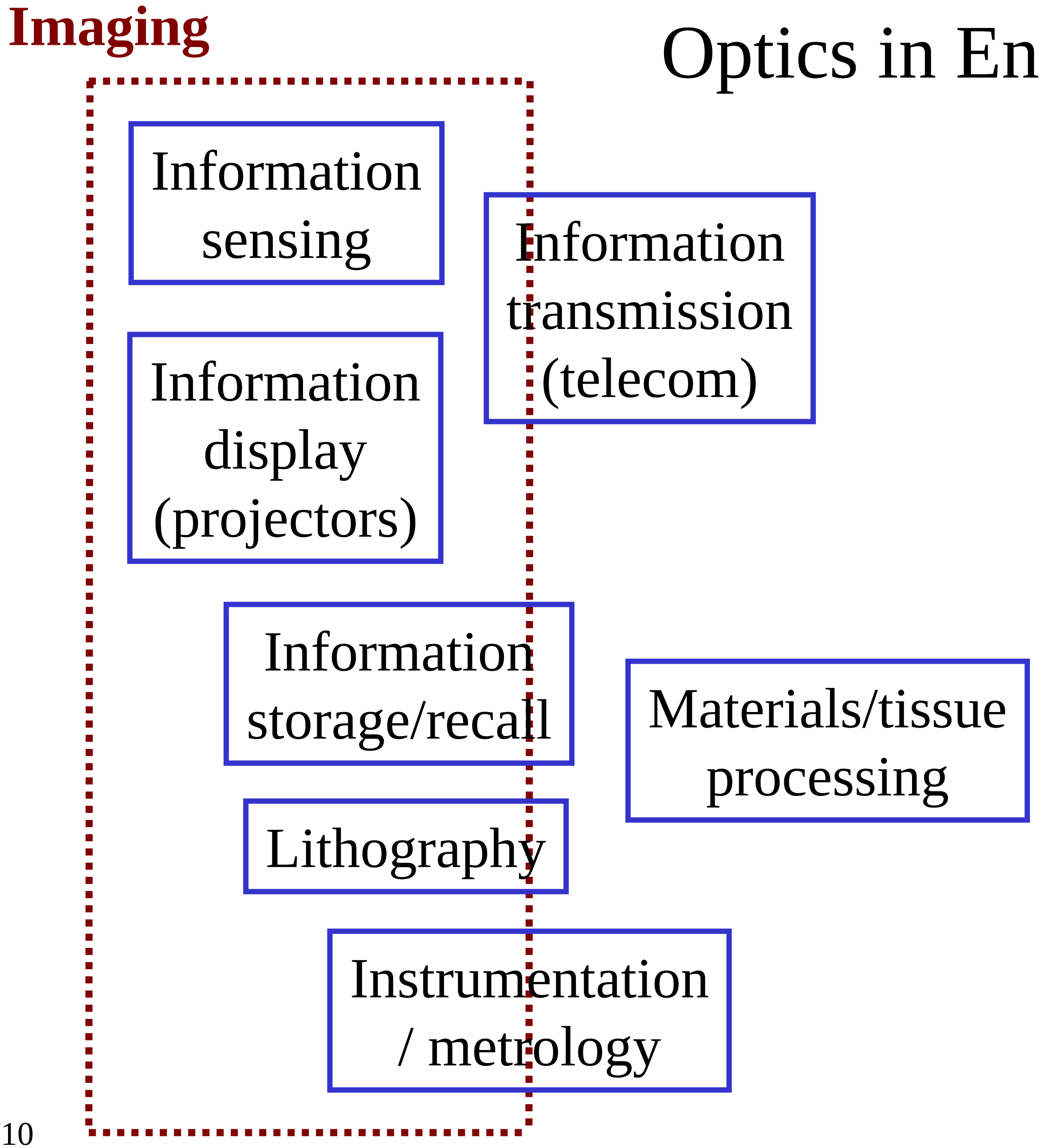
2.710: H-Level, meets the MS requirement in Design

"gateway" subject for Doctoral Qualifying exam in Optics

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

Optics in Engineering



Imaging

Information sensing

Information display (projectors)

Information transmission (telecom)

Information storage/recall

Materials/tissue processing

Lithography

Instrumentation / metrology

Topics

- Geometrical optics
  - Basic ray-tracing
  - Image formation and imaging systems
  - 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

What you need

- Absolutely necessary
  - Euclidean geometry
  - calculus with complex variables
  - Taylor series approximation
  - MATLAB or other computation/visualization software
  - linear systems (2.003 level, we will extensively review)
- Helpful if you know but we will cover here
  - basic electrodynamics
  - basic wave propagation
  - Fourier analysis

Class compass

- Textbooks: “Optics” by E. Hecht, 4th edition (Addison-Wesley)
    - “Introduction to Fourier optics” by J. W. Goodman, 2nd 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

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 5
  - selected among one of the application areas (topics soon TBA)
  - start on Mo. Nov. 1
  - weekly or so info meetings with instr/TA
  - oral presentation on Weds. Dec. 1

Applications / Projects

- 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)

Administrative: both

- Two quizes:
  - Quiz 1 on Monday Oct. 4, 10am (in class)
    - content: geometrical optics
  - Quiz 2 on Monday Nov. 22, 10am (in class)
    - content: wave (Fourier) optics
- Final exam:
  - scheduled by the Registrar
  - comprehensive on everything covered in class
- Practice problems will be posted before each quiz and the final
- Absence from quizes/final: Institute policies apply
- Grading: Institute definitions apply

Administrative: both (cont.)

- TA Office hours: Tuesday 1-3pm
- Unlimited email access (broadcasts encouraged), best effort to reply within 24hrs.
- Recitations during scheduled class hours
  - *most* Mondays (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)

- 18th–19th centuries
  - Fresnel, Young experimentally observe diffraction, defeat Newton's particle theory
  - Maxwell formulates electro-magnetic equations, Hertz verifies antenna emission principle (1899)
- 20th 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

- 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

What is light?

- Light is a form of **electromagnetic energy** – detected through its effects, e.g. heating of illuminated objects, conversion of light to current, mechanical pressure (“Maxwell force”) etc.

- Light energy is conveyed through particles: “photons”
  - ballistic behavior, e.g. shadows

- Light energy is conveyed through waves
  - wave behavior, e.g. interference, diffraction

- Quantum mechanics reconciles the two points of view, through the “wave/particle duality” assertion

Particle properties of light

Photon=elementary light particle

Mass=0

Speed c=3×10^8 m/sec

According to Special Relativity, a mass-less particle travelling at light speed can still carry energy (& momentum)!

Energy $E=h\nu$ $\Longrightarrow$ 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

Wave properties of light

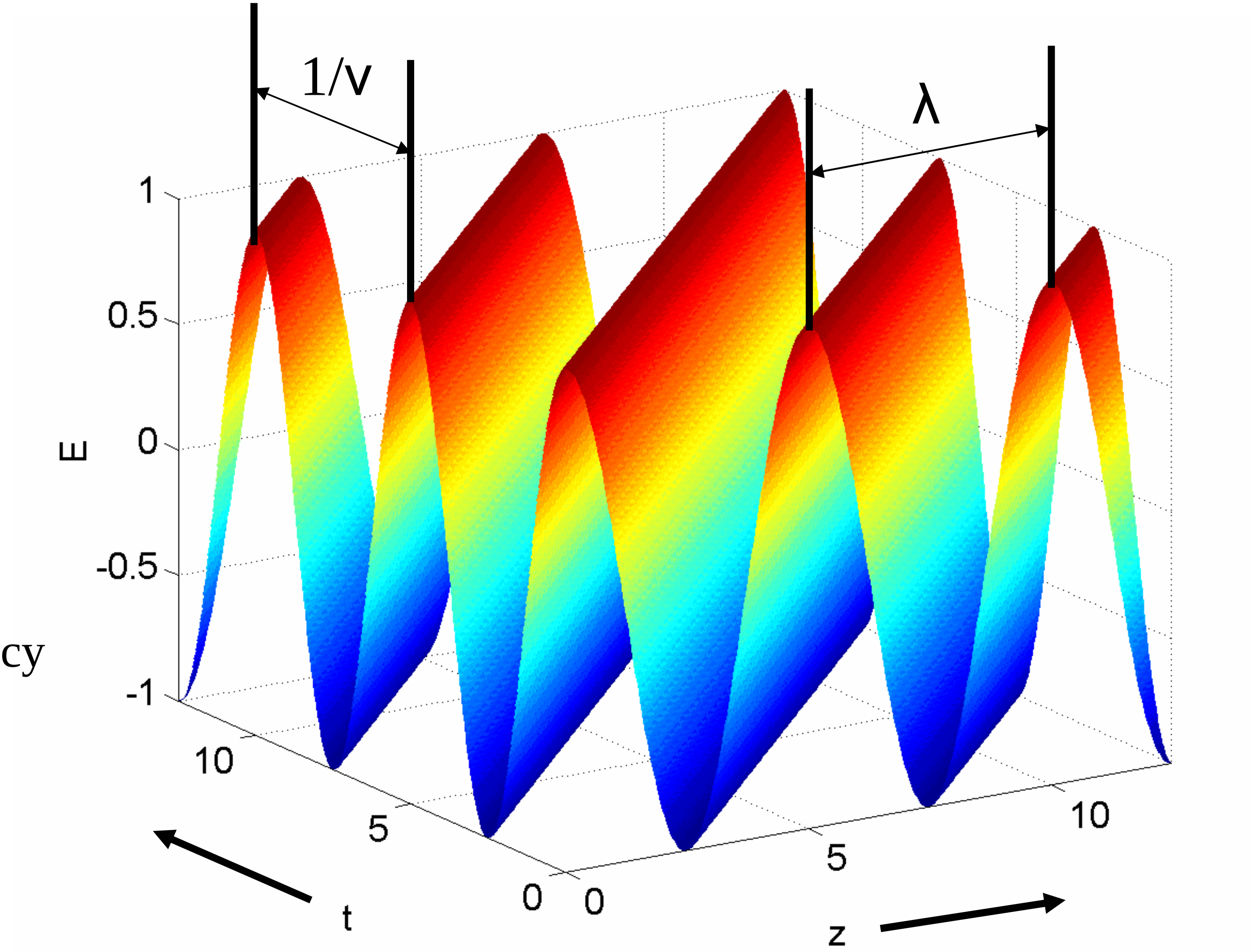
λ: **wavelength**
(spatial period)

k=2π/λ
wavenumber

ν: temporal
frequency

ω=2πν
angular frequency

E: electric
field



Wave/particle duality for light

Photon=elementary light particle

Energy $E=h\nu$

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

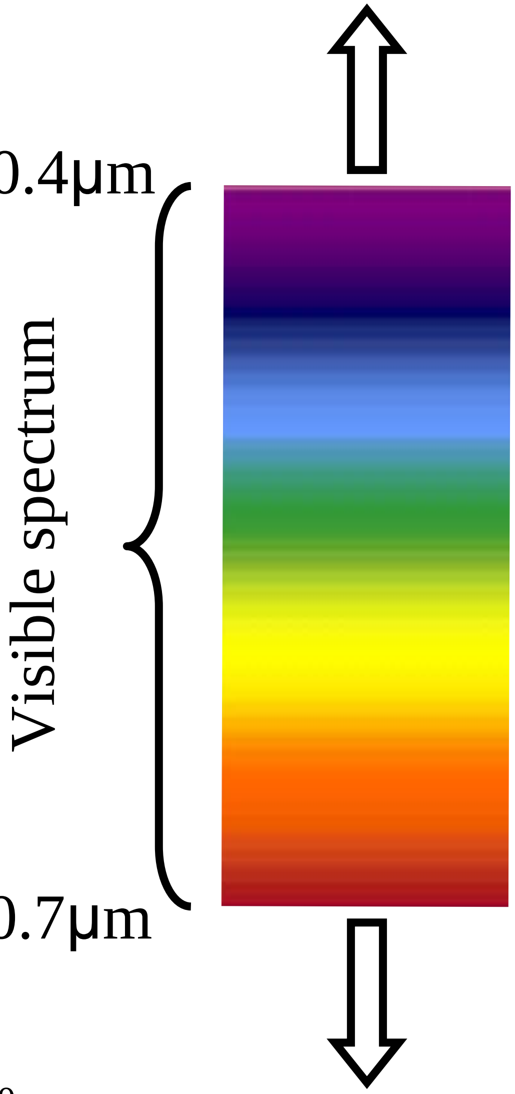
ν=frequency (sec^{-1})
λ=wavelength (m)

$$\boxed{c=\lambda\nu}$$

"Dispersion relation"

(holds in vacuum only)

The light spectrum



Ultra-violet

~0.4µm

Blue, $\lambda \sim 488$nm; $\nu \sim 6.1\times10^{14}$Hz

Visible spectrum

Green, $\lambda \sim 532$nm; $\nu \sim 5.5\times10^{14}$Hz

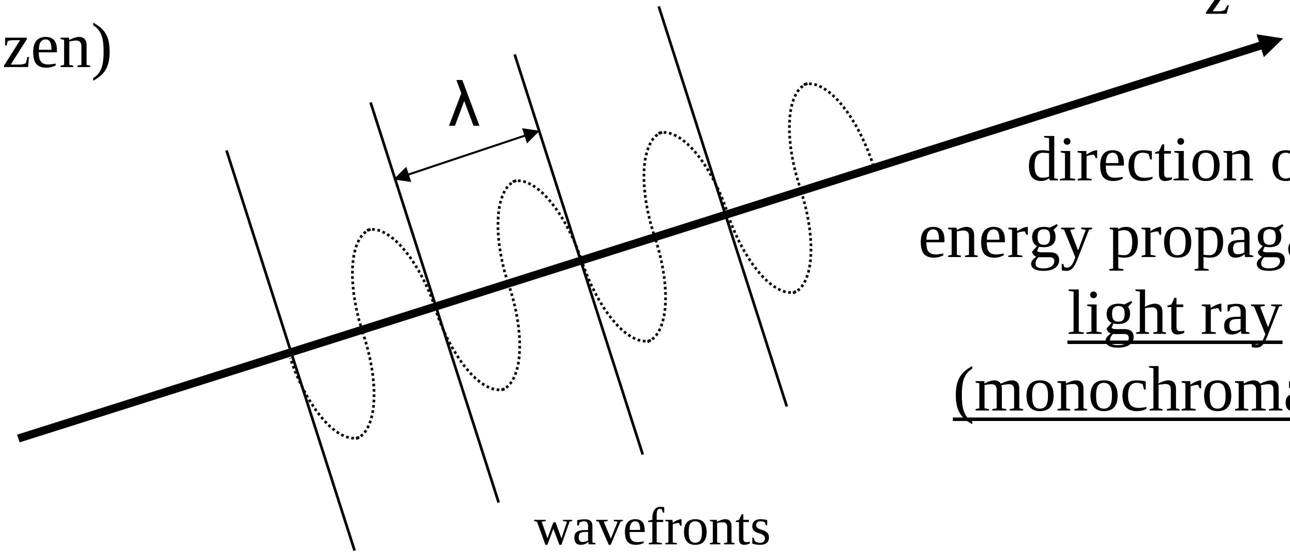
Red, $\lambda \sim 633$nm; $\nu \sim 4.8\times10^{14}$Hz

~0.7µm

Infra-red

Light in vacuum: rays

t=0
(frozen)

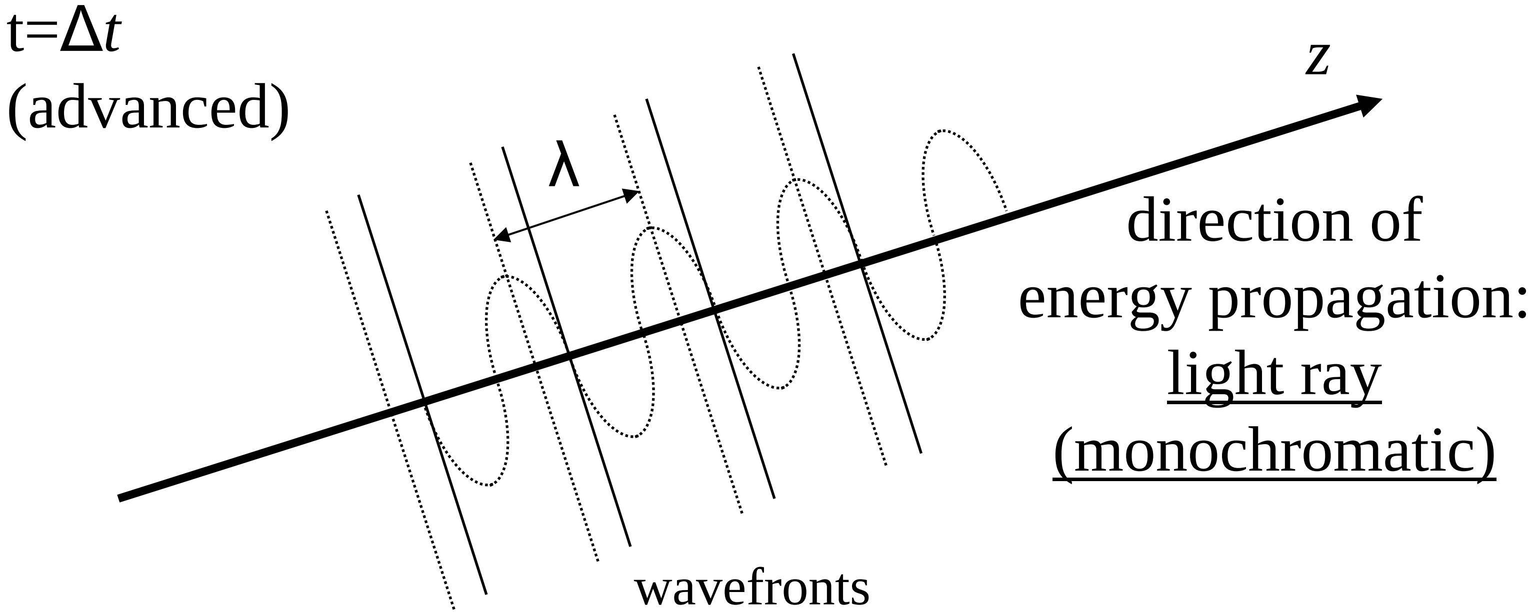


direction of
energy propagation:
<u>light ray</u>
<u>(monochromatic)</u>

wavefronts

In homogeneous media,
light propagates in rectilinear paths

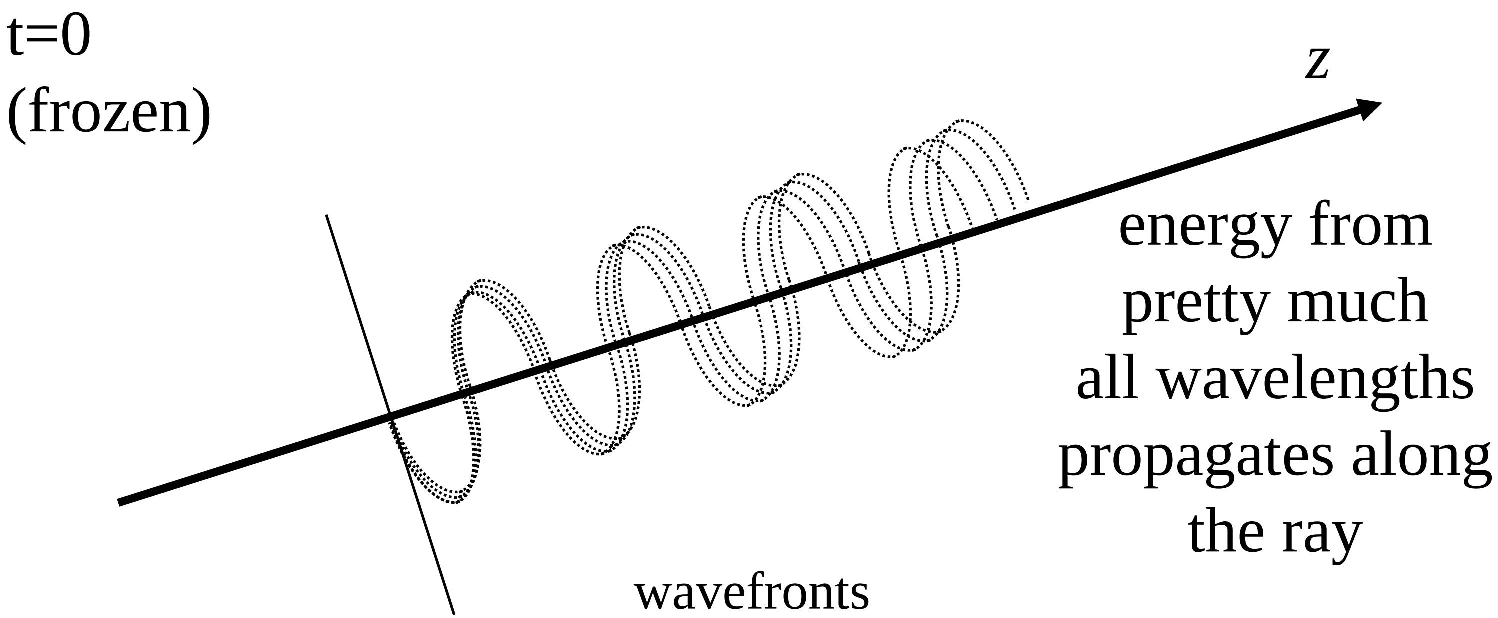
Light in vacuum: rays



direction of
energy propagation:
light ray
(monochromatic)

In homogeneous media,
light propagates in rectilinear paths

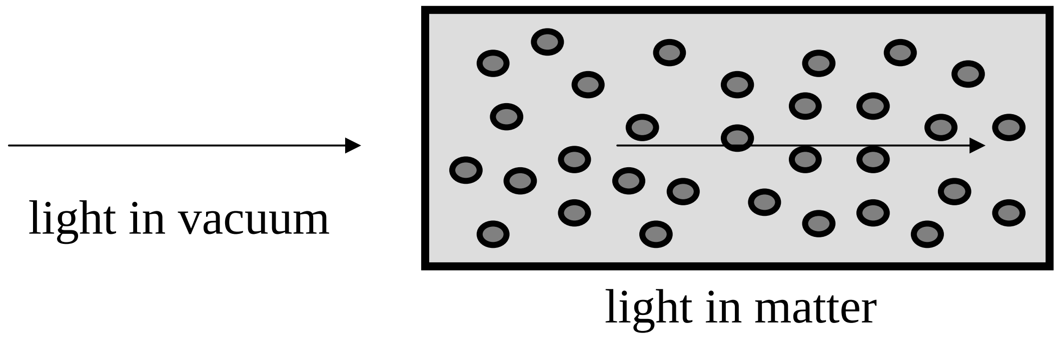
Polychromatic rays



energy from
pretty much
all wavelengths
propagates along
the ray

In homogeneous media,
light propagates in rectilinear paths

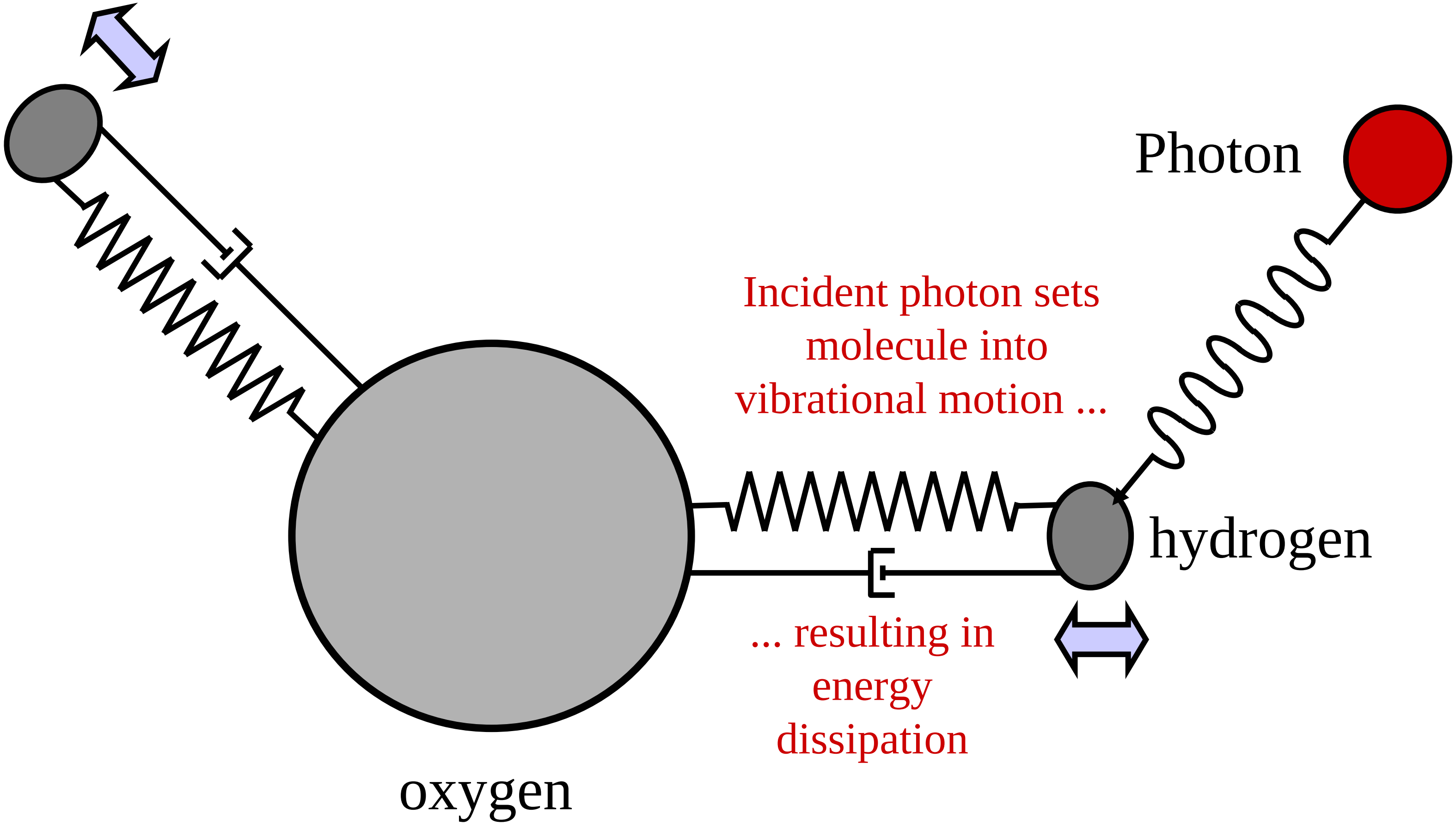
Light in matter: refraction/absorption



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 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

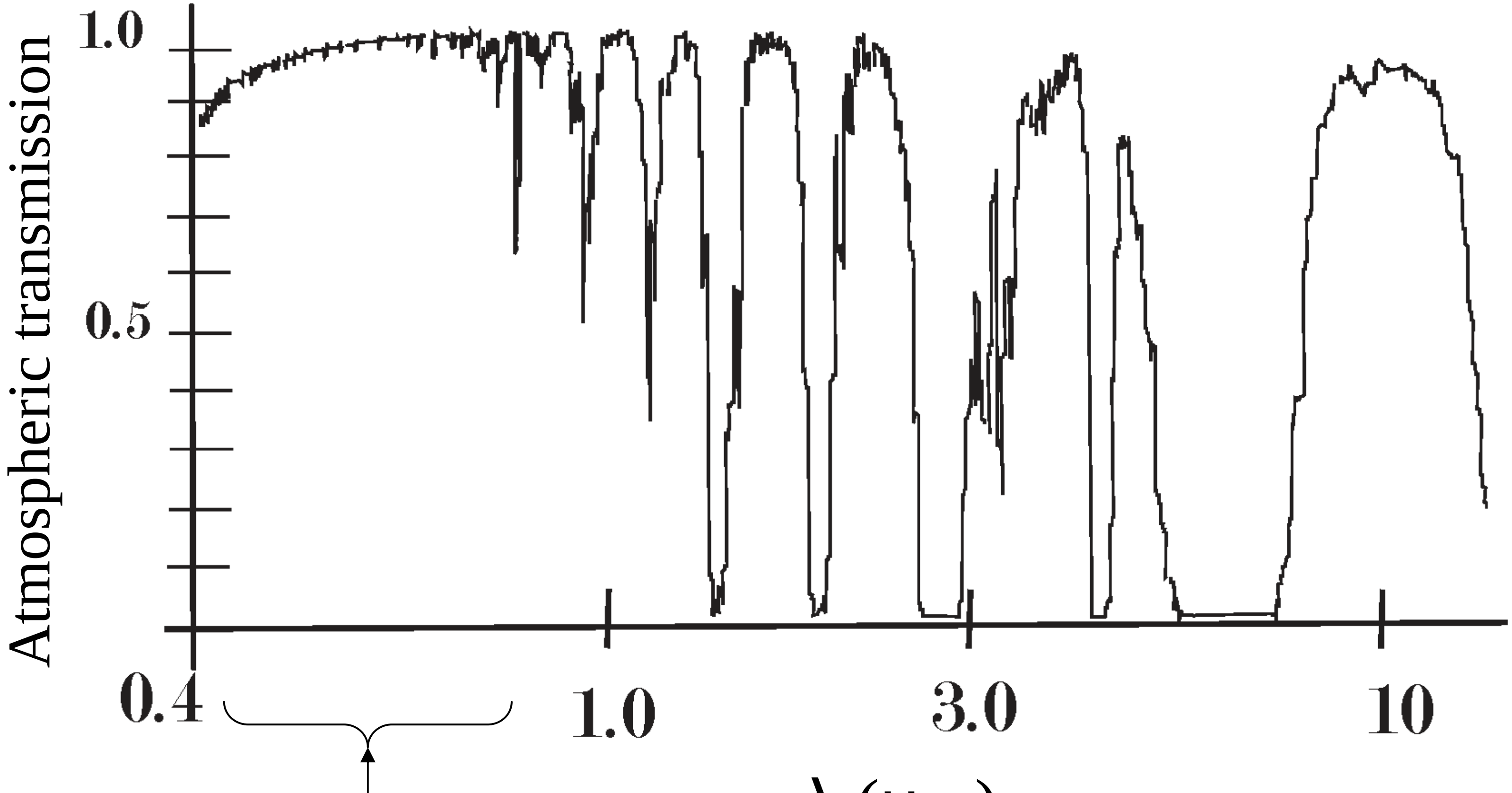
Molecular model of absorption



Incident photon sets molecule into vibrational motion …

… resulting in energy dissipation

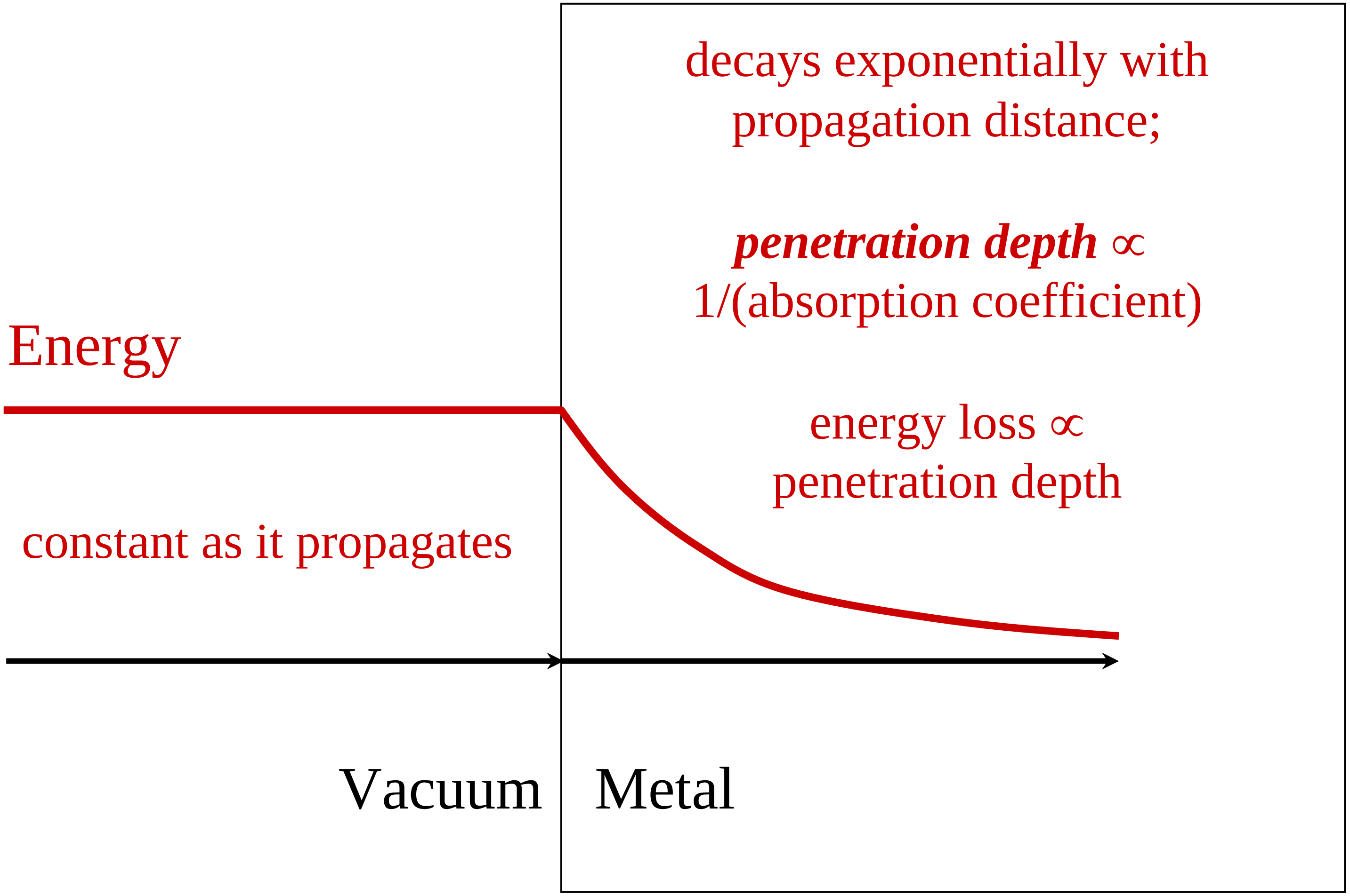
Light transmission through the atmosphere



human vision

Light in metals

light generates current ⇒ energy dissipation



decays exponentially with
propagation distance;

penetration depth ∝
1/(absorption coefficient)

energy loss ∝
penetration depth

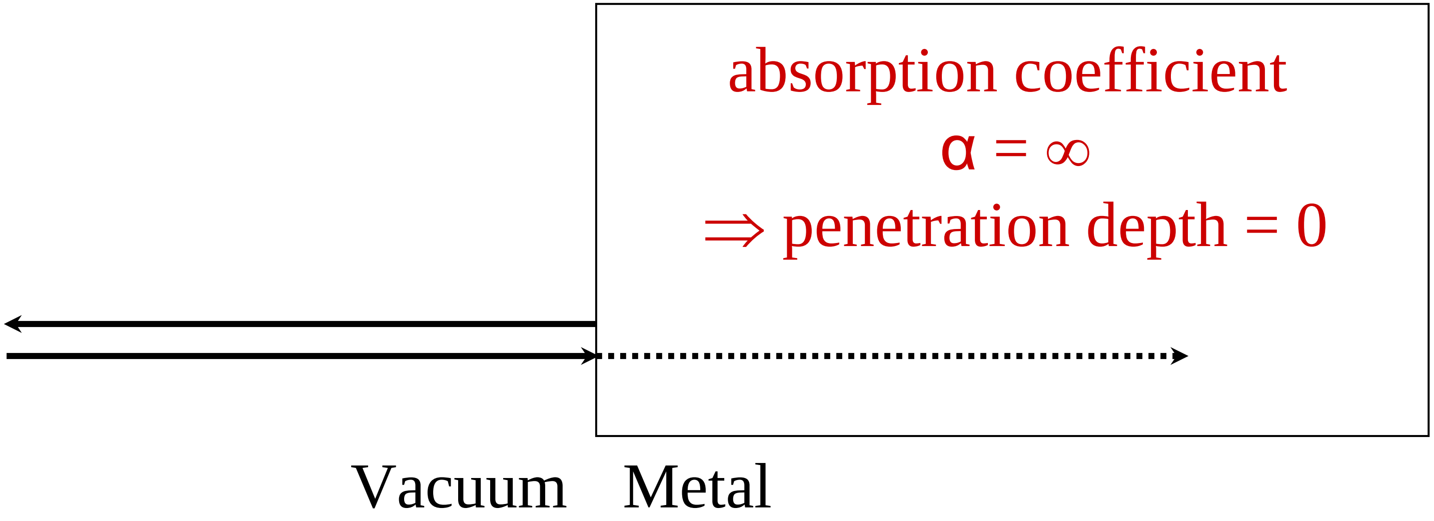
Energy

constant as it propagates

Vacuum

Metal

Ideal metals



absorption coefficient

$\alpha = \infty$

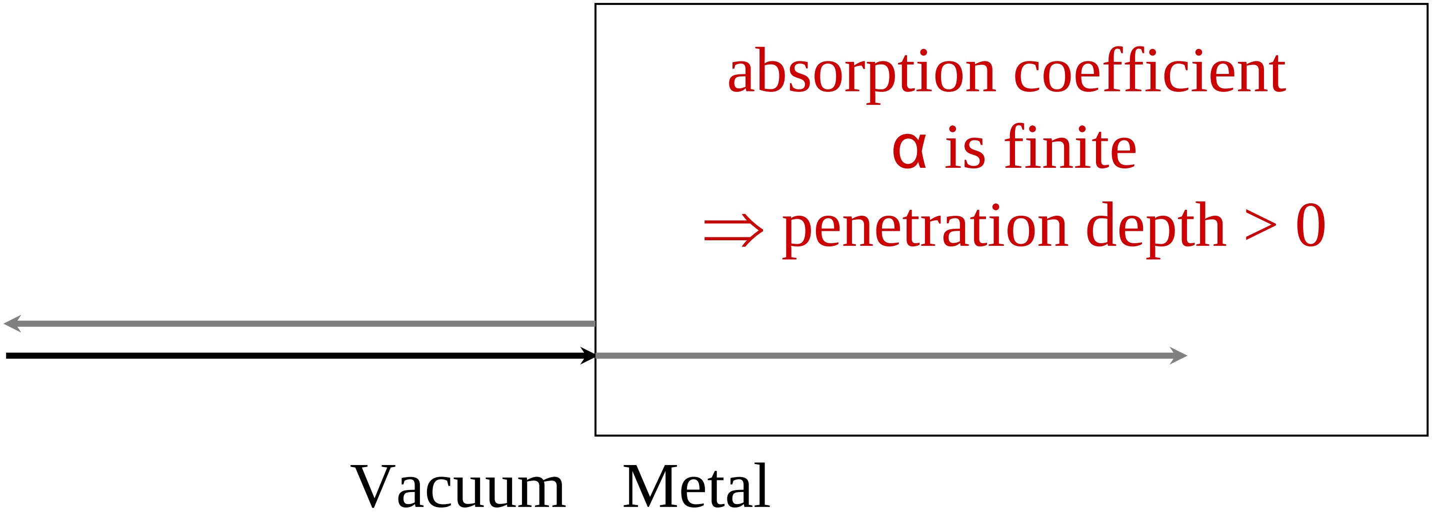
$\Rightarrow$ penetration depth = 0

Light never enters the ideal

$\Rightarrow$ all of it gets reflected

$$\begin{pmatrix}\text{Reflection}\\ \text{coefficient}\end{pmatrix} = \frac{\text{Reflected power}}{\text{Incident power}} = 1$$

Non-ideal metals



absorption coefficient

α is finite

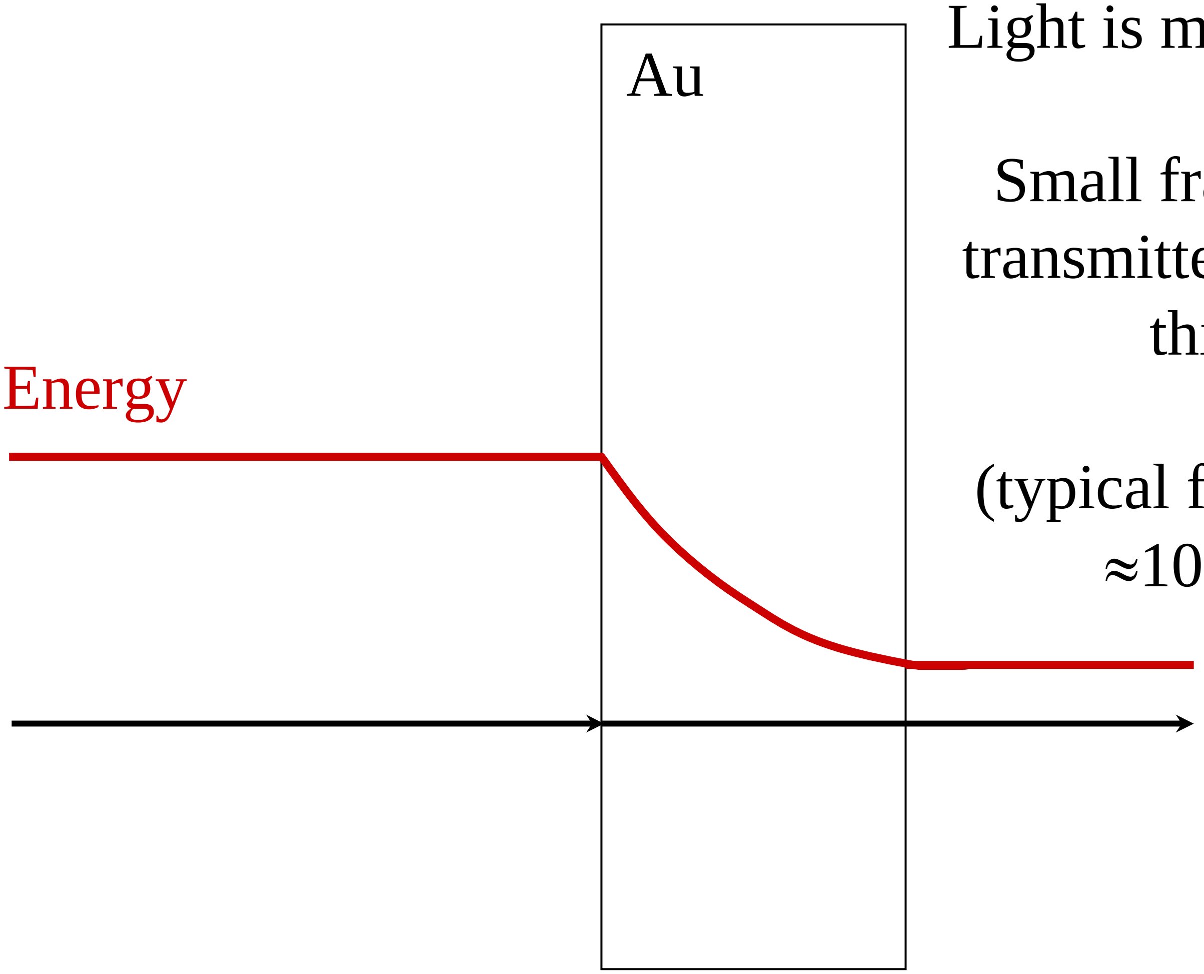
⇒ penetration depth > 0

Vacuum Metal

Fraction of light energy that enters the metal is lost (converted to heat)

$$\begin{pmatrix}\text{Reflection}\\ \text{coefficient}\end{pmatrix} = \frac{\text{Reflected power}}{\text{Incident power}} < 1$$

Thin metal films



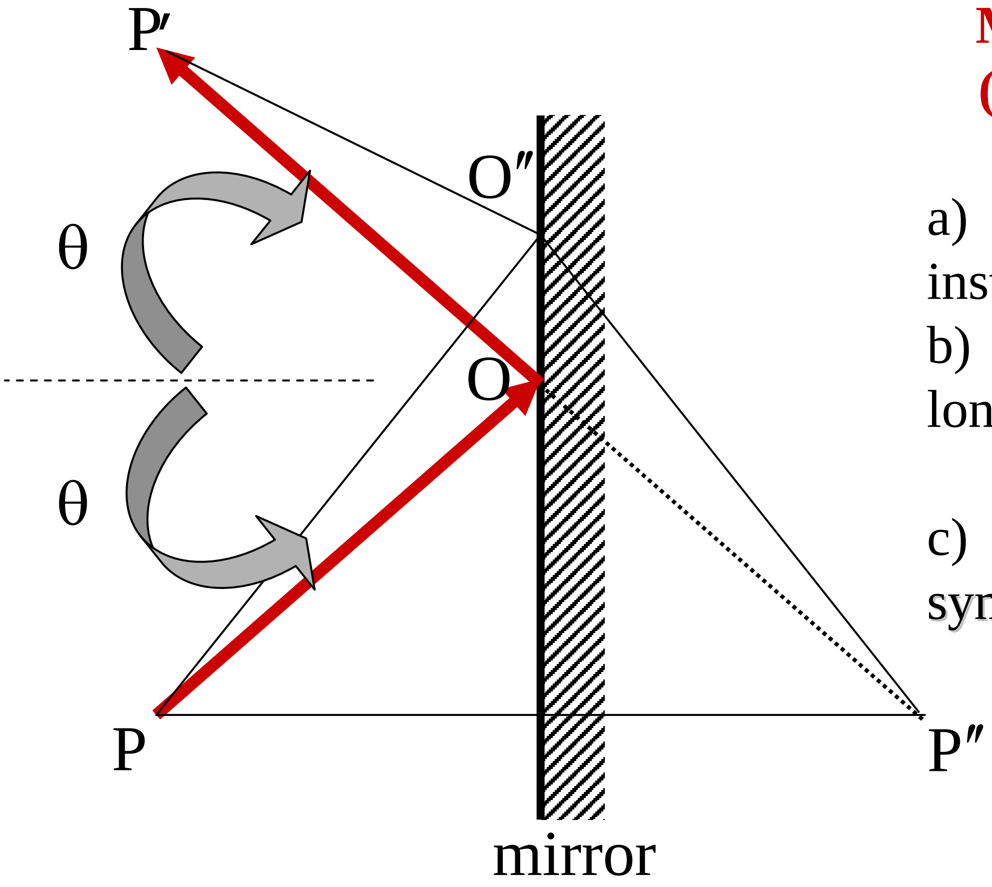
Light is mostly reflected

Small fraction is still transmitted through the thin film

(typical film thickness ≈10s of nm)

The law of reflection

oblique incidence

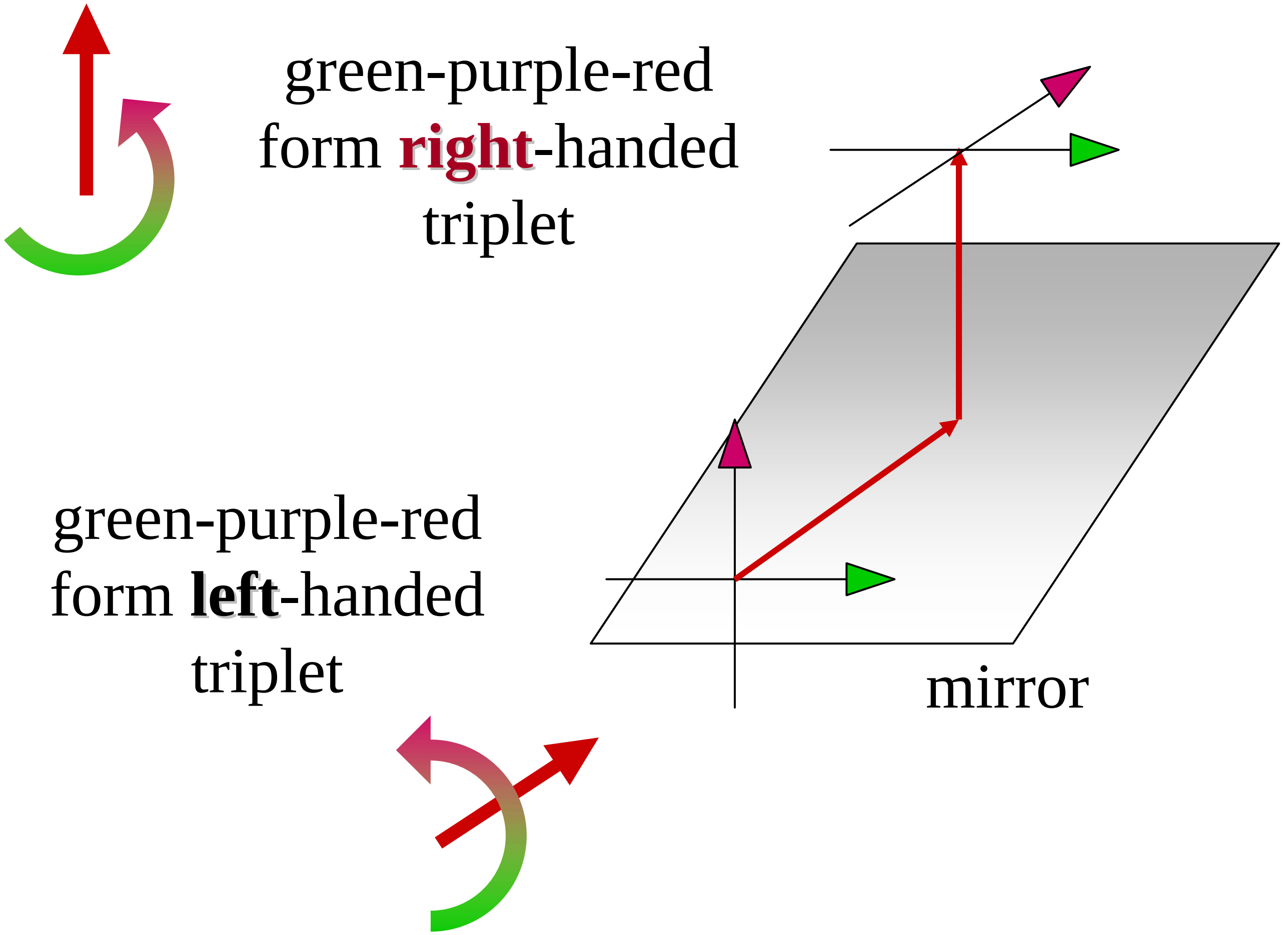


Minimum path principle (aka Fermat's principle)

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'.

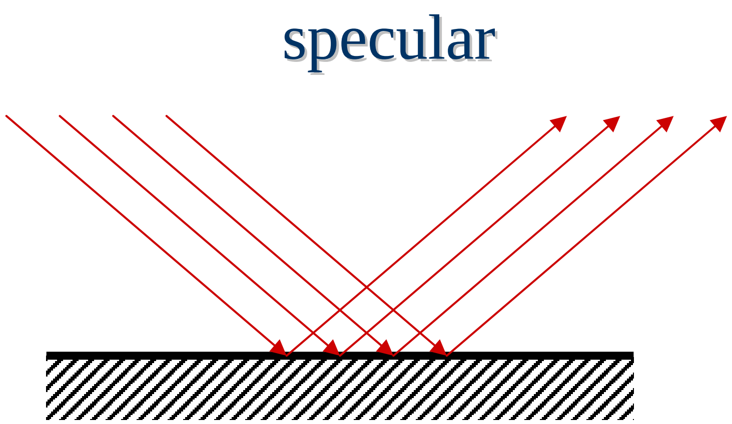
Inversion upon reflection

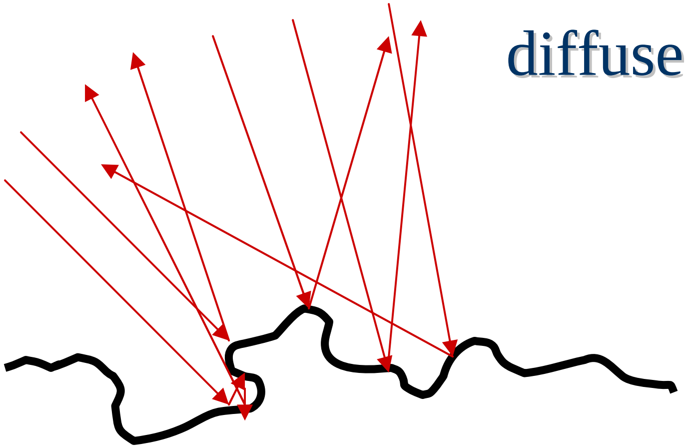


green-purple-red
form **right**-handed
triplet

green-purple-red
form **left**-handed
triplet

Specular *vs* diffuse reflection



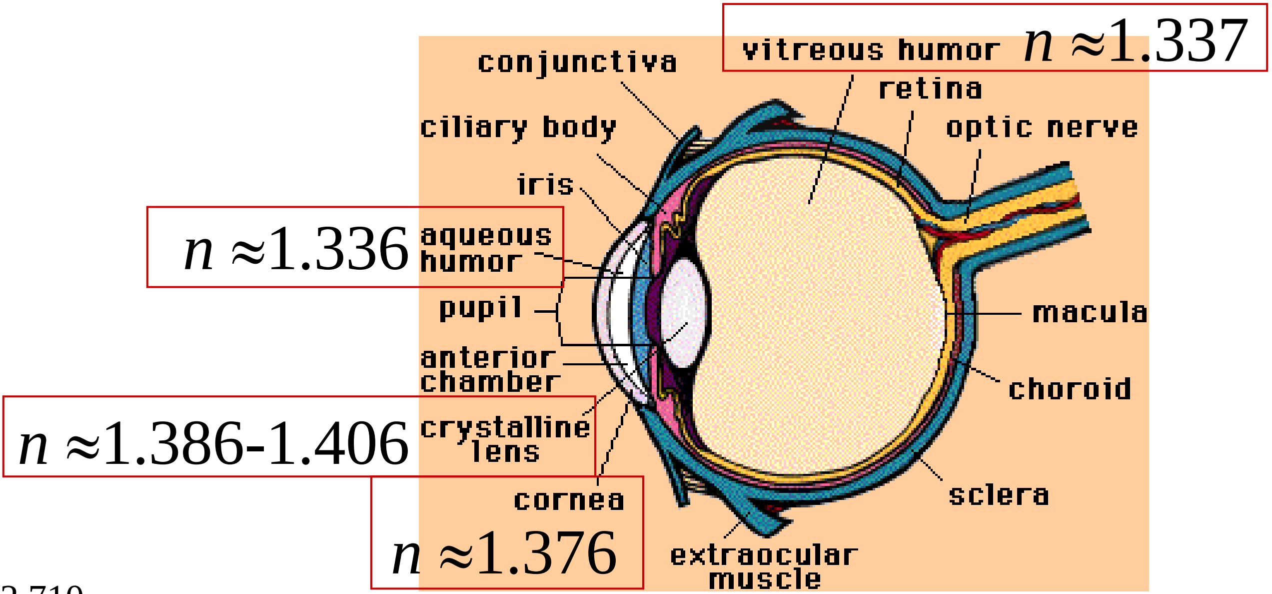


flat (ideal) surface:
orderly reflection
clear image
(e.g. well-polished mirror)

rough surface:
disorderly reflection
diffuse image
increased absorption
due to multiple reflections
(e.g. aluminum foil)

Common dielectrics

- Air, n slightly higher than 1(most commonly assumed $\approx$1 for all practical purposes)
- Water, $n \approx 1.33$
- Glass, $n \approx 1.45\text{-}1.75$
- Photorefractive crystals, e.g. lithium niobate $n \approx 2.2\text{-}2.3$



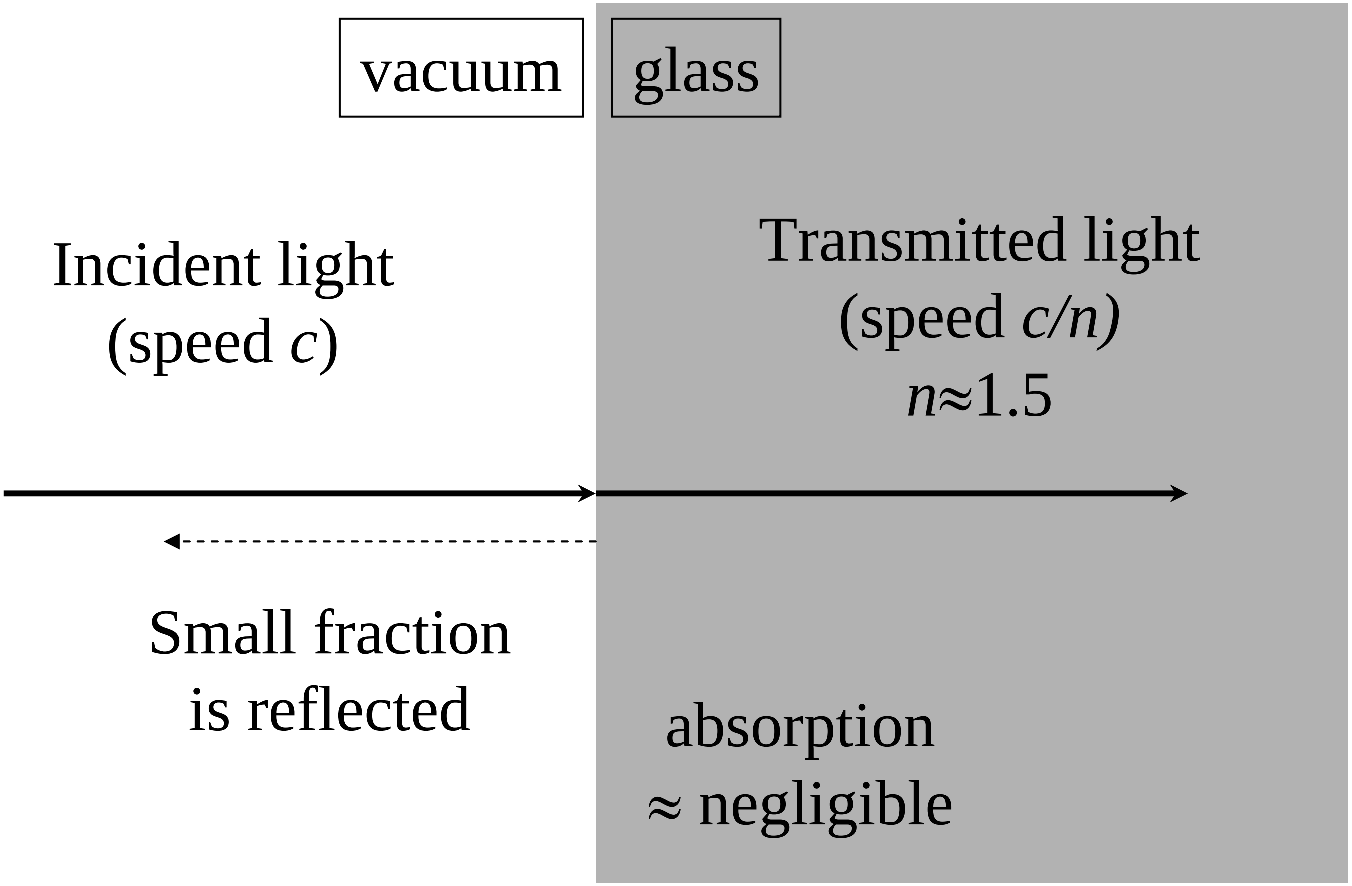
$n \approx 1.337$

$n \approx 1.336$

$n \approx 1.386\text{-}1.406$

$n \approx 1.376$

Light in air/glass interface



vacuum

glass

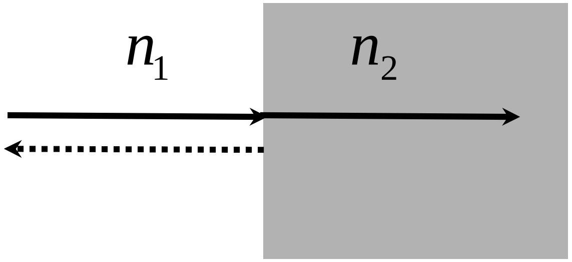
Incident light
(speed *c*)

Transmitted light
(speed *c/n*)
$n \approx 1.5$

Small fraction
is reflected

absorption
≈ negligible

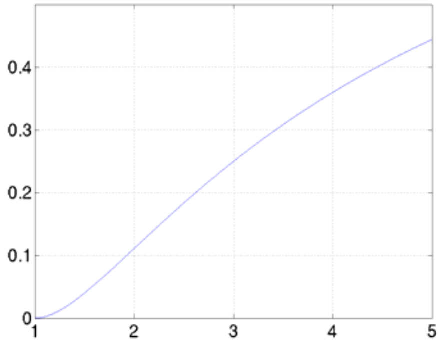
Transmission/reflection coefficients



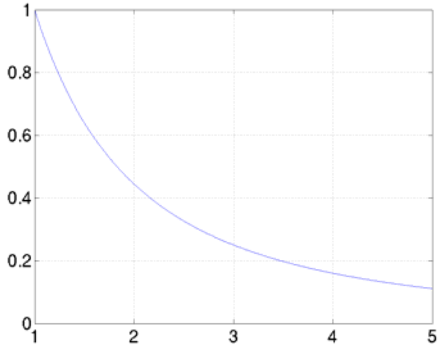
Normal incidence only

(oblique incidence requires wave optics)

n_1=1

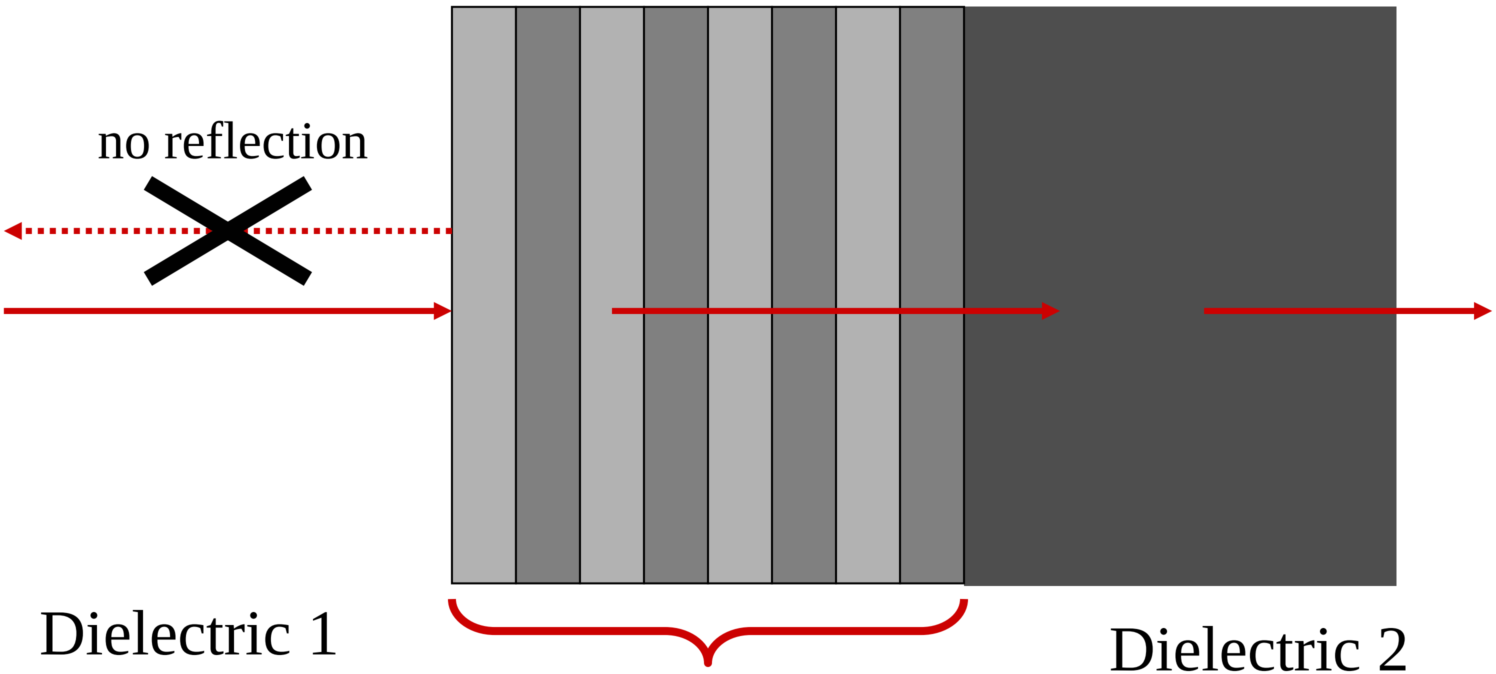


$$\begin{pmatrix}\text{Reflection}\\ \text{coefficient}\end{pmatrix} = \frac{\text{Reflected power}}{\text{Incident power}} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$



$$\begin{pmatrix}\text{Transmission}\\ \text{coefficient}\end{pmatrix} = \frac{\text{Transmitted power}}{\text{Incident power}} = \left(\frac{2n_1}{n_2 + n_1}\right)^2$$

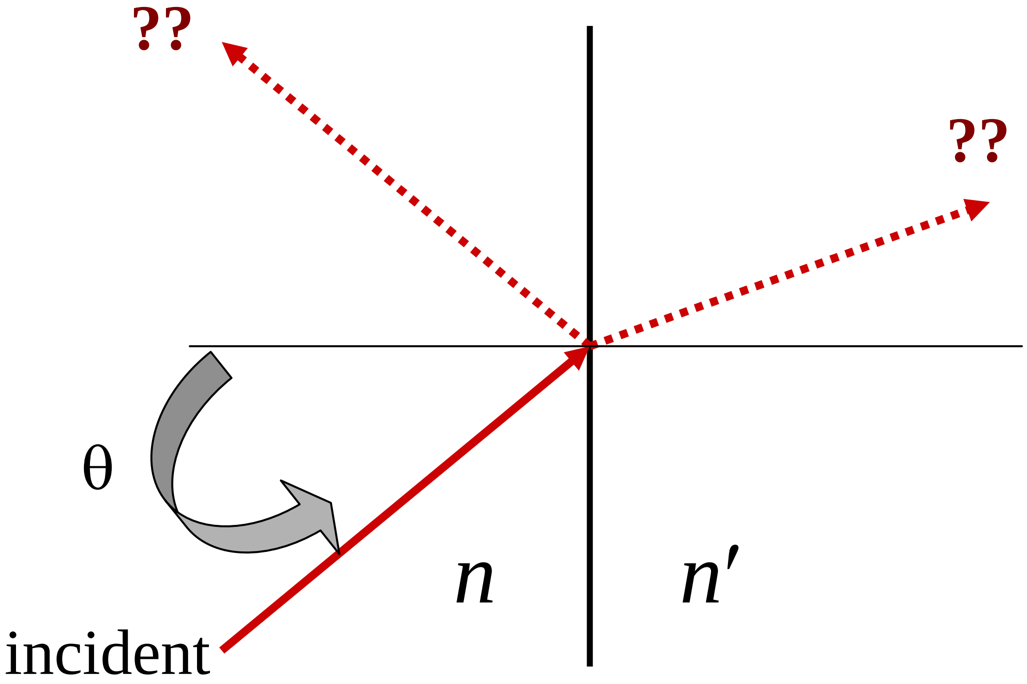
Anti-reflection coatings



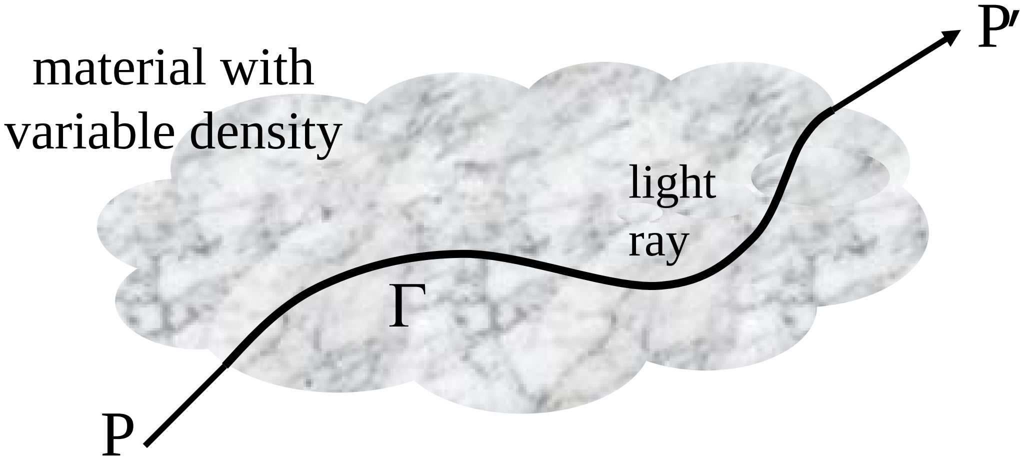
Dielectric stack
“periodically stratified medium”

With proper design, the stack cancels the reflection for a *wide* range of incidence angles

Incidence at dielectric interface



The minimum path principle

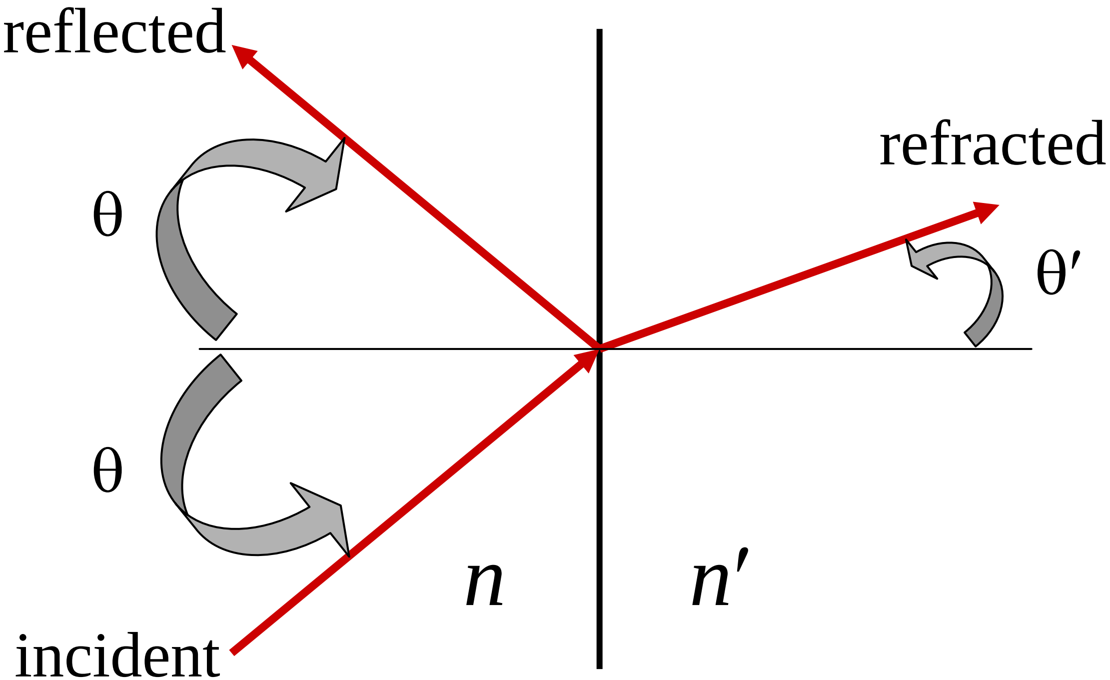


$$\int_{\Gamma} n(x, y, z)\, \mathrm{d}l$$

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

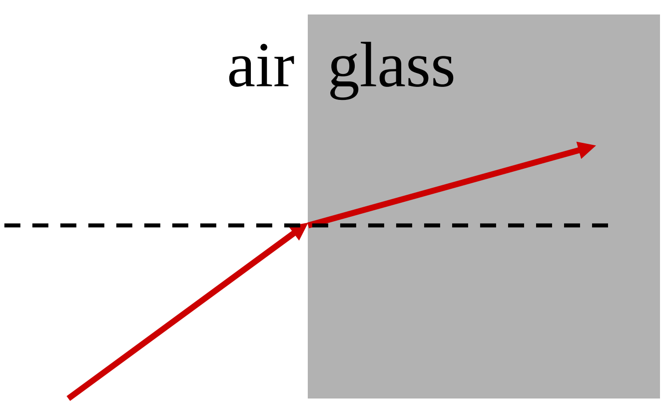
(aka **Fermat**'s principle)
Consequences: law of reflection, law of refraction

The law of refraction



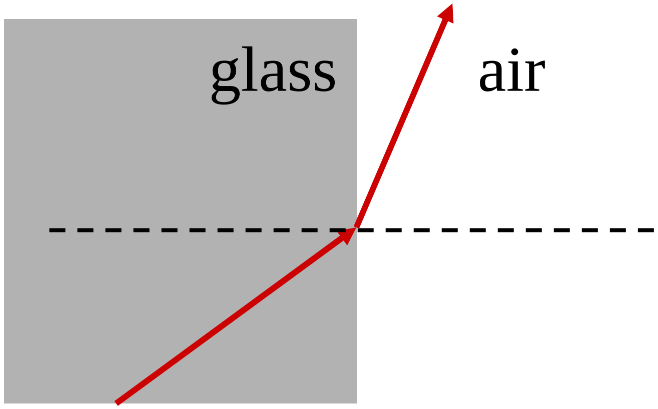
$$\boxed{n \sin\theta = n' \sin\theta'}$$ Snell’s Law of Refraction

Two types of refraction



from low to higher index
(towards optically denser material)

angle wrt normal decreases



from high to lower index
(towards optically less dense material)

angle wrt normal increases