Introduction to Optical Modeling

Friedrich-Schiller-University Jena
Institute of Applied Physics

Lecturer:
Prof. Uwe D. Zeitner (Part 1)
Prof. Frank Wyrowski (Part 2)

Seminar

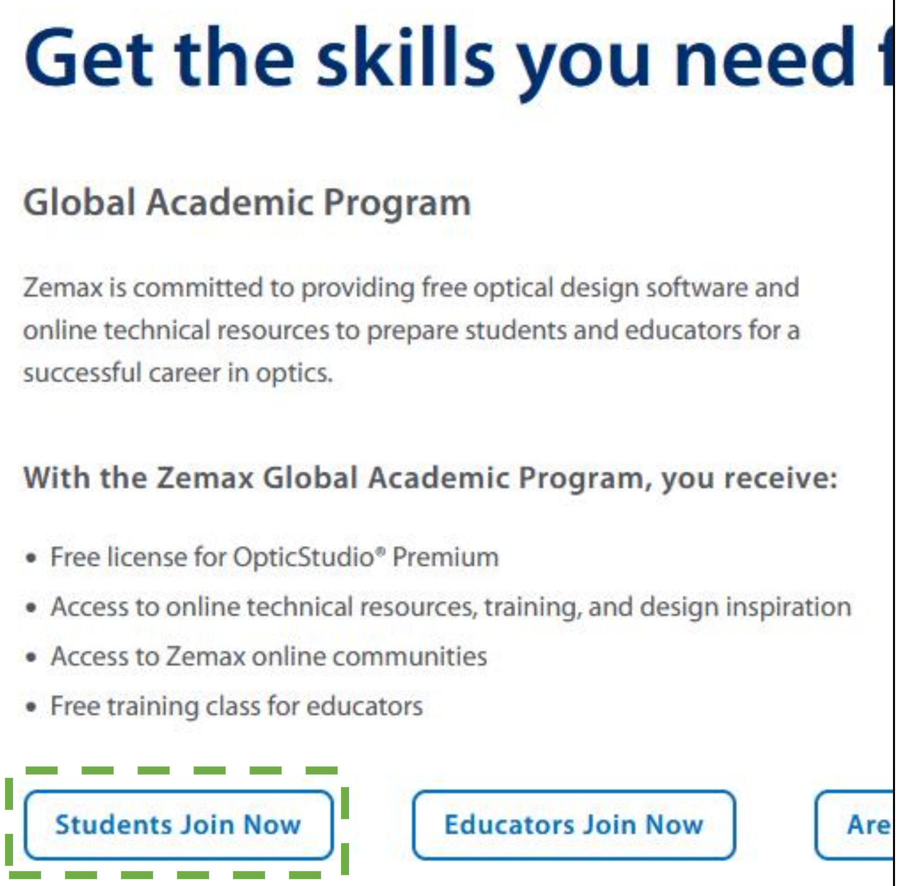
Bi-weekly → 4 groups (about 15 students each)

Monday:	12:00 – 14:00	Start:	25.10.	Group 4
			1.11.	Group 3
Friday:	10:00 – 12:00	Start:	29.10.	Group 2
			5.11.	Group 1

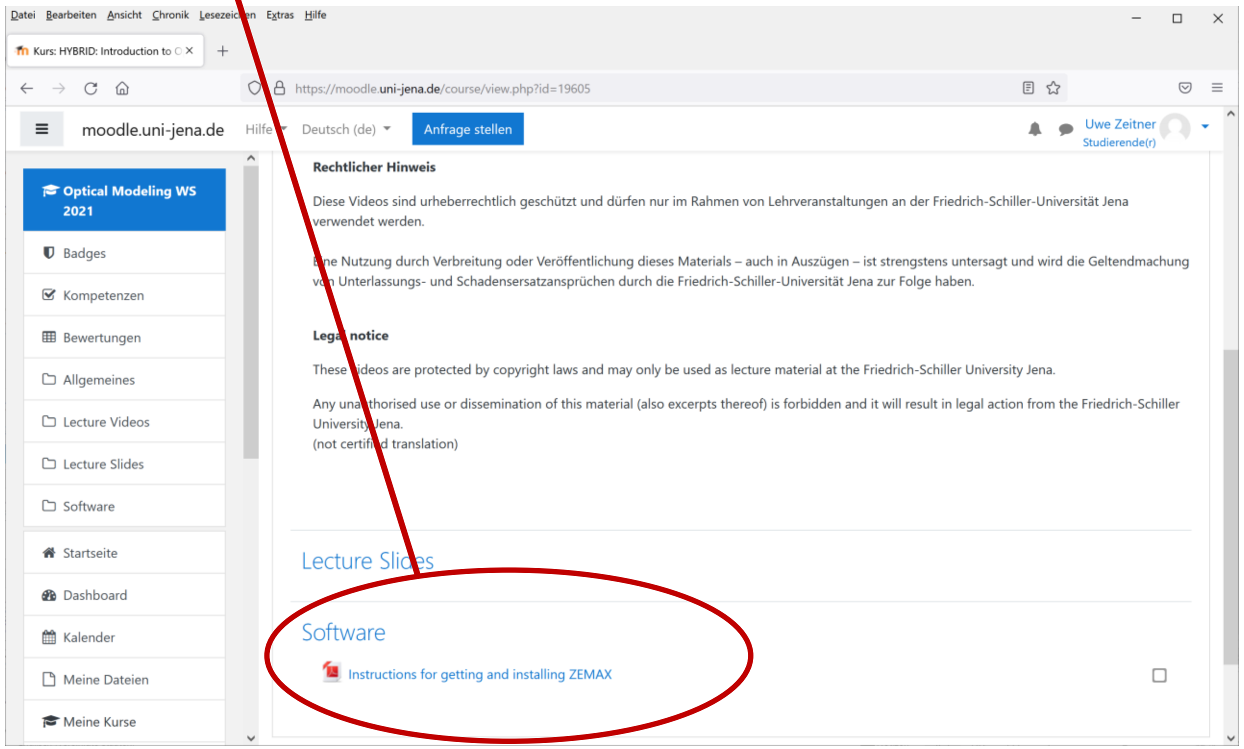
Required: **Zemax-Account** (see next slide)

Register for academic license

https://www.zemax.com/pages/get-the-skills-you-need-for-a-future-in-optics



All additional information on the Moodle platform



Course Overview

Part 1: Geometrical optics based modeling and design (U.D. Zeitner)

1. Introduction (today)
2. Paraxial approximation / Gaussian optics
3. ABCD-matrix formalism
4. Real lenses
5. Optical materials
   - glass types, dispersion
   - chromatic aberrations
6. Imaging systems
   - apertures/stops, entrance-/exit-pupil
   - wavefront aberrations

Part 2: Wave-optics based modeling (F. Wyrowski)

Additional Literature

H. Gross, “Handbook of Optical Systems,” Wiley-VCH
in particular Vol. 1 & 2

W.J. Smith, “Modern Optical Engineering,” SPIE Press

J. Goodman, “Introduction to Fourier Optics,” Roberts & Company Publishers

1 Introduction

Topic of the course: Optical Modeling and Design

→ understanding of optical systems

Canon EF400

Examples of optical systems:

- energy → photovoltaics
- medicine → microscopes, photodynamic therapy, …
- datacom → fiber-optical information transport, cell-phone camera, …
- technology → fabrication of computer chips, laser material processing …
- …

Basic Building Blocks

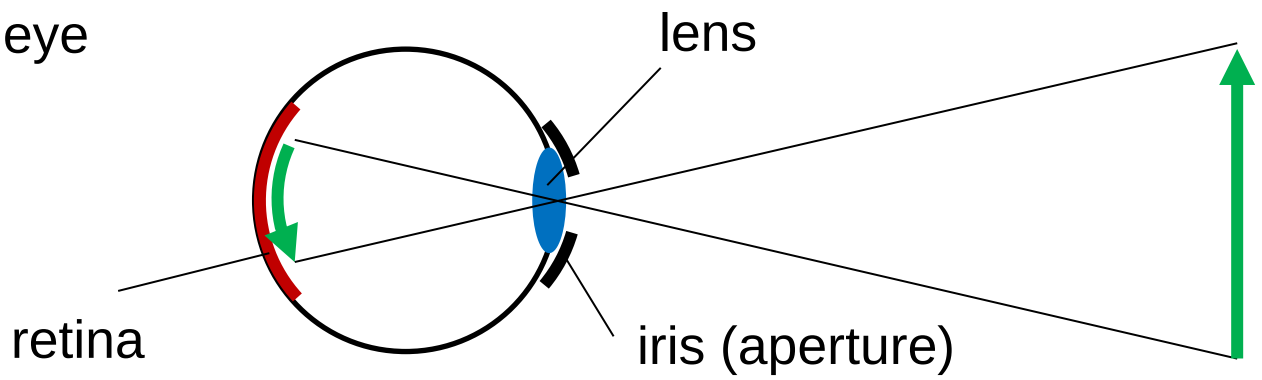
each optical system is composed of 3 basic building blocks:

Source of photons → photon transport and “manipulation” → Detector

- active: lamp, laser
- passive: reflected light

- eye
- CCD-camera
- film
- chlorophyll
- …

Simple example: the human eye



Modeling vs. Design

Understanding the function of a <u>given</u> optical system → **Modeling**

source → optical system → ???

requires:
- models for proper **representation of light**
- models for **interaction of light and matter**

Modify / optimize the function of an optical system or <u>build</u> a complete <u>new one</u>

→ **Design**

source → ??? → detector

requires:
- modeling of the system
- concepts for **improvements** or ideas for good solutions
- decision **criteria** for good solutions

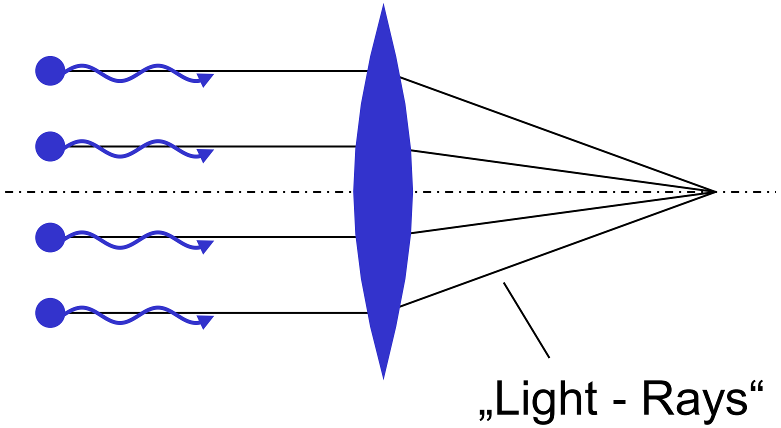
not trivial!
→ an inverse problem

1.1 Light Representation

Fundamental Question: What is Light?

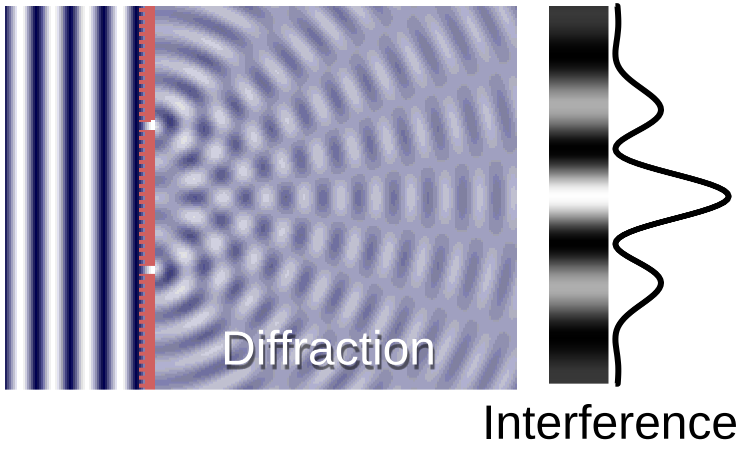
Newton

Particle / Photon



Huygens / Maxwell

Wave (electromagnetic ~)



Wave – Particle Dualism

Here: consider light as electromagnetic wave

Maxwell's Equations

Time domain:

$$\nabla \times \vec{E}(\vec{r},t) = -\frac{\partial}{\partial t}\vec{B}(\vec{r},t)$$

$$\nabla \times \vec{H}(\vec{r},t) = j(\vec{r},t) + \frac{\partial}{\partial t}\vec{D}(\vec{r},t)$$

$$\nabla \vec{D}(\vec{r},t) = \rho(\vec{r},t)$$

$$\nabla \vec{B}(\vec{r},t) = 0$$

$\vec{E}(\vec{r},t)$ … electric field
$\vec{B}(\vec{r},t)$ … magn. induction
$\vec{H}(\vec{r},t)$ … magn. field
$\vec{D}(\vec{r},t)$ … dielectric displacement

$j(\vec{r},t)$ … current density
$\rho(\vec{r},t)$ … charge density

<u>linear</u> matter equations:

$$j(\vec{r},t) = \sigma \overrightarrow{\cdot E}(\vec{r},t)$$

$$\vec{D}(\vec{r},\omega) = \varepsilon_0 \varepsilon_r(\omega)\vec{E}(\vec{r},\omega)$$

$$\vec{B}(\vec{r},\omega) = \mu_0 \mu_r(\omega)\vec{H}(\vec{r},\omega)$$

(frequency domain)

σ … conductivity

Wave Equation

Linear, homogeneous, isotropic medium, no free charges:

$$\nabla^2 \vec{E}(\vec{r},t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}(\vec{r},t) = 0 \qquad (1.1)$$

Wave equation for the electric field $\vec{E}(\vec{r},t)$

c … velocity of light in the medium

c_o … velocity of light in vacuum

$$c = \frac{c_0}{\sqrt{\varepsilon\mu}} = \frac{c_0}{n}$$

One solution of this equation:

$$\vec{E}(\vec{r},t) = \vec{E}(\vec{r}) \cdot e^{-i\omega t} \qquad (1.2)$$

→ field with harmonic time dependence

$\omega = 2\pi f$

f … time frequency of oscillation

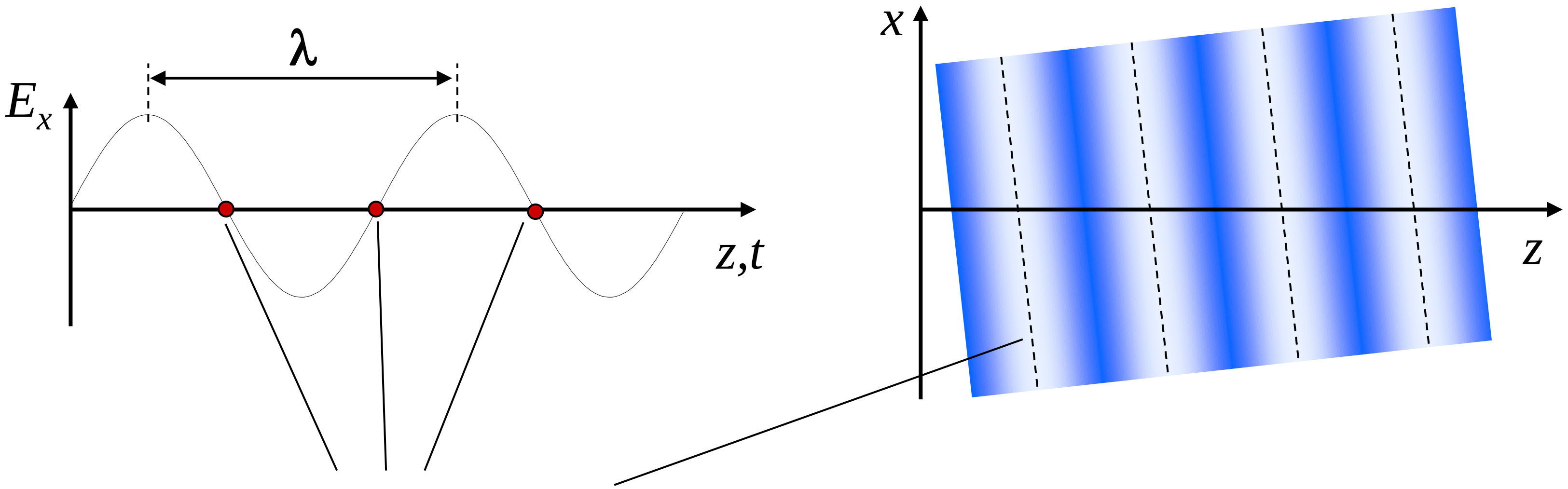
Light as a harmonic wave

1D Representation:

$$\vec{E} = \vec{A} \cdot \cos\left[\underbrace{2\pi \cdot \left(f \cdot t - \frac{z}{\lambda} \right)}_{\text{Phase}} \right]$$

$$f = \frac{c}{\lambda}$$ Frequency → Color

2D:



Points / Lines of equal phase → **Wave-Fronts!**

Time-free wave equation

inserting (1.1) in (1.2) leads to the simplification

$$\nabla^2 \vec{E}(\vec{r}) + \frac{\omega^2}{c^2}\vec{E}(\vec{r}) = 0 \qquad (1.3)$$

$\Rightarrow$ **Helmholtz - Equation**

$$\frac{\omega^2}{c^2} = k^2 = \left(\frac{2\pi}{\lambda}\right)^2$$

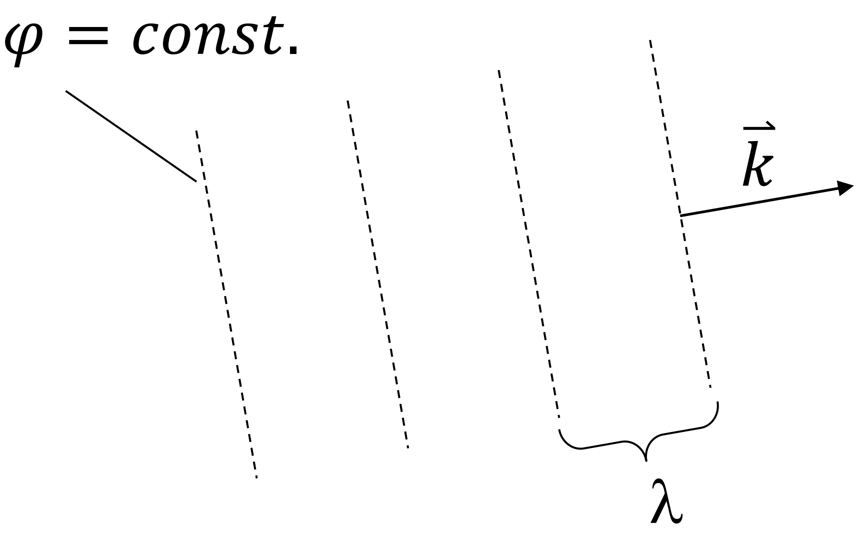
k … modulus of the k-vector

Fundamental solutions of Helmholtz's Equation, I

First basic solution of (1.3):

$$\vec{E}(\vec{r}) = \vec{E}_0 \cdot e^{i\vec{k}\cdot\vec{r}} = \vec{E}_0 \cdot e^{i\varphi} \qquad (1.4)$$

$$\varphi = \vec{k} \cdot \vec{r}$$ → equation describing a plane



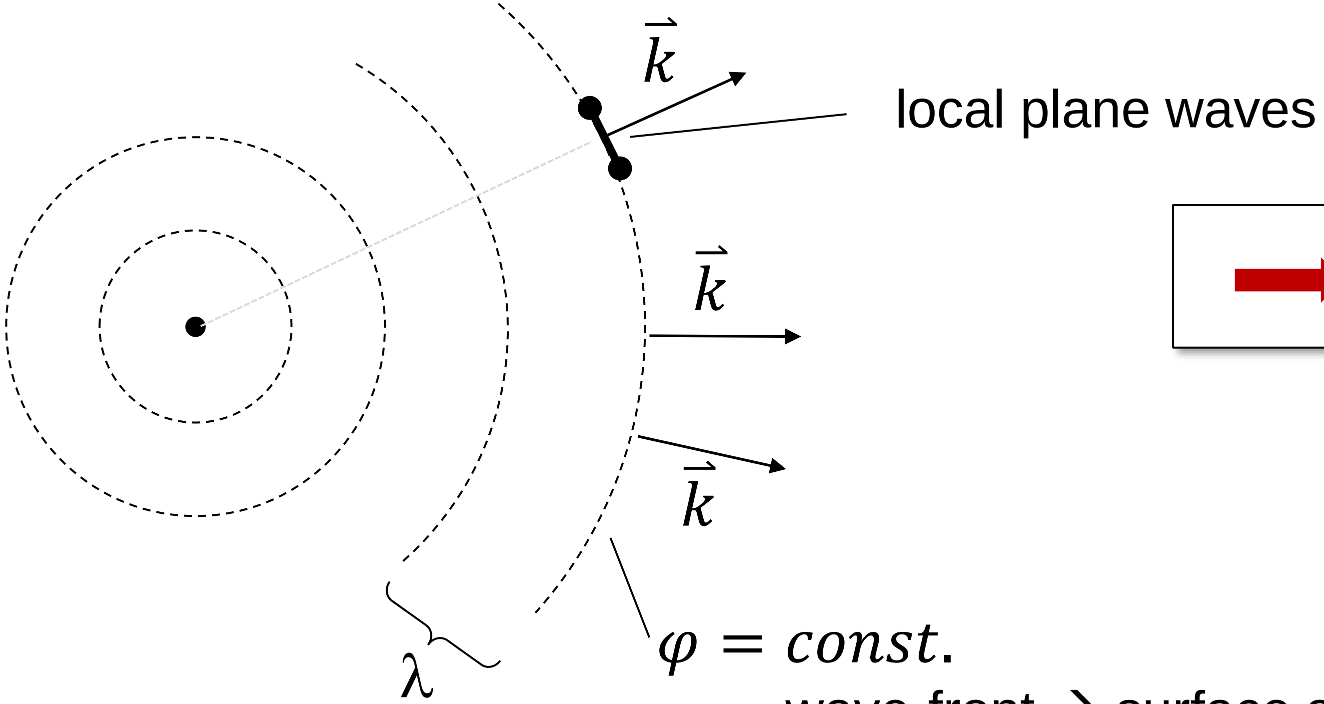
→ plane wave (propagating in direction of $\vec{k}$)

Fundamental solutions of Helmholtz's Equation, II

Second basic solution of (1.3):

$$E(\vec{r}) = \frac{E_0}{r} \cdot e^{ik \cdot r} \tag{1.5}$$

→ **spherical wave (from a point source)**

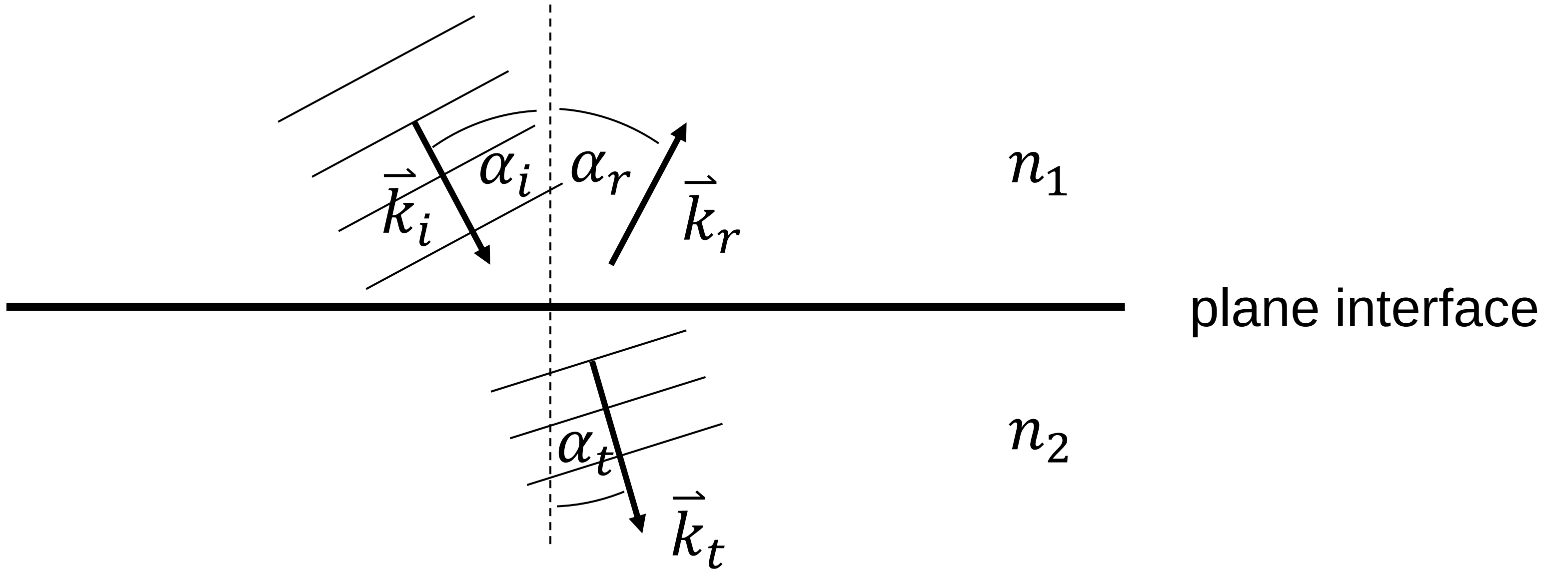


➡ **representation of rays !**

wave-front → surface of equal phase

1.2 Interaction of light with plane interfaces

consider a plane wave with propagation direction $\vec{k}$



Symmetry: only 3 waves present

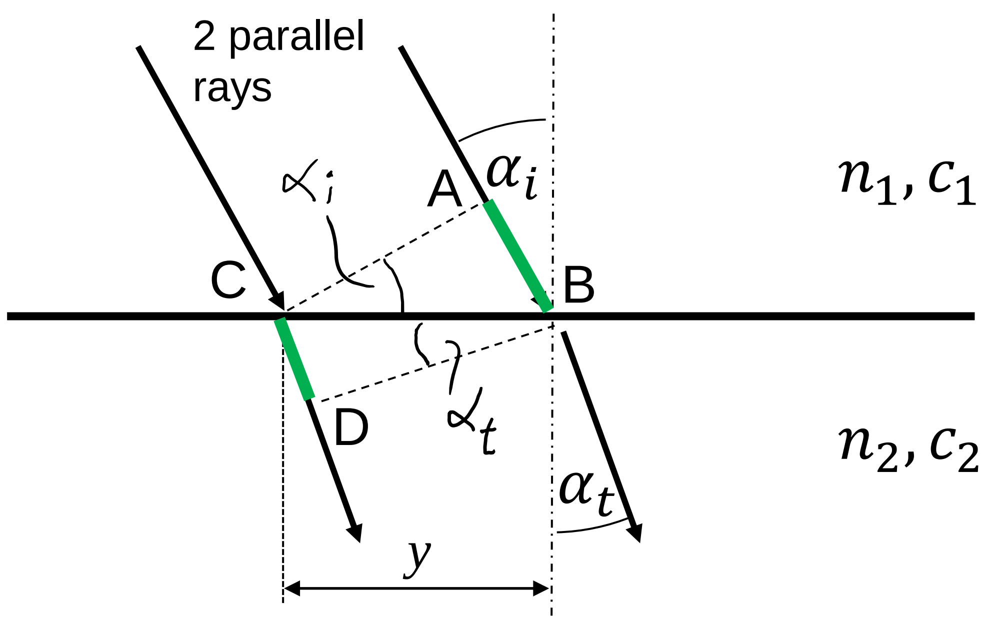
- incident field, direction $\vec{k}_i$, α_i to surface normal
- transmitted field, direction $\vec{k}_t$, α_t to surface normal
- reflected field, direction $\vec{k}_r$, α_r to surface normal

$\Big\}$ **all plane waves**

Relation between the α and distribution of energy among the waves ➡ **Fresnel's formulas**

The Transmitted Wave

using a different model, based on a **consideration of travelling speeds** of rays in the different media



$$c_1 = \frac{c_0}{n_1} \quad ; \quad c_2 = \frac{c_0}{n_2}$$

incident plane wave → transmitted plane wave

➡ same travelling time A → B
C → D

$$t = \frac{y \cdot \sin \alpha_i}{c_1} \overset{!}{=} \frac{y \cdot \sin \alpha_t}{c_2}$$

$$\boxed{n_1 \cdot \sin \alpha_i = n_2 \cdot \sin \alpha_t} \tag{1.6}$$

law of refraction, Snell's law

Similar consideration for reflected wave: $\boxed{\alpha_i = \alpha_r}$ **law of reflection** (1.7)