WAVE OPTICS

1. Light as a kind of electromagnetic wave

- optics is one of the oldest parts of physics (defects of vision, ...)

- nature of light

i) corpuscular theory (Newton) – light is a beam of particles = corpuscules
(× diffraction, interference)

ii) wave theory (Huygens 1680) – light is a wave (× no medium?)

J.C.Maxwell 1864 – light is a kind of electromagnetic radiation, which can travel even in a vacuum

http://en.wikipedia.org/wiki/Maxwell's_equations

from which we could e.g. see the relation between c, μ_0 and ε_0: $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$

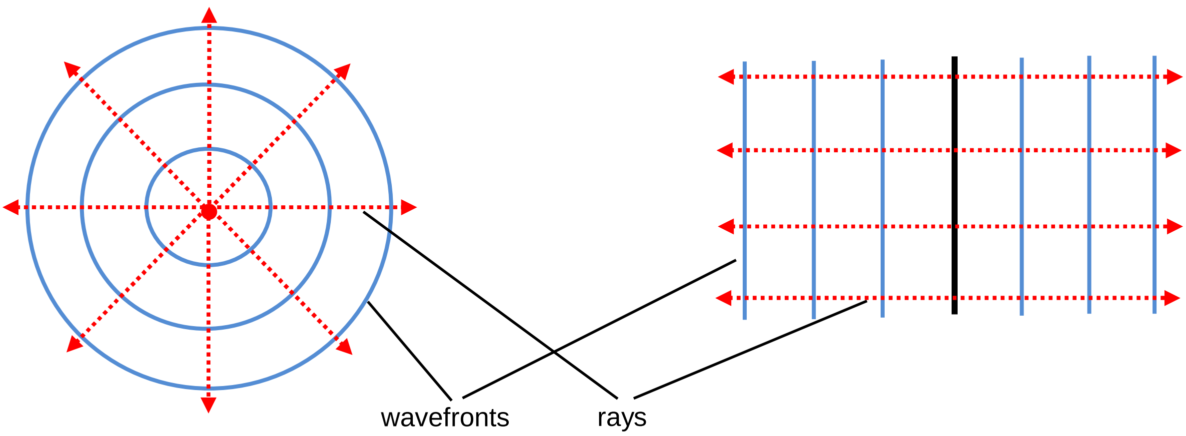
2. Speed of light, frequency, wavelength, absolute refractive index

- speed of electromagnetic radiation
  - in a vacuum $\boldsymbol{c = 3\times10^8\ m\cdot s^{-1}}$ and it does NOT depend on frequency
  - in other media $\mathbf{v} < \mathbf{c}$ and it depends on frequency (dispersion)

- light is electromagnetic radiation of frequencies 7.7×10^{14} Hz – 3.8×10^{14} Hz
(λ in vacuum 390 nm – 790 nm)

- wavefronts and rays

point source linear source



wavefront = the set of points with the same phase (where the wave appears at the same time), 3dim surface!
ray = the line representing the direction of propagation of the wave

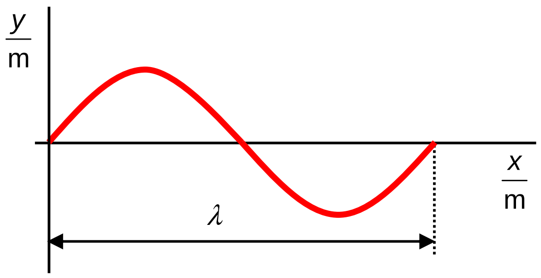
Wavefronts and rays are always perpendicular to each other.

- the law of propagation of light

In a uniform medium light rays travel in straight lines (in parallel, converging or diverging arrangement). If the rays cross, they do not affect each other.

- wavelength

= the shortest distance between two points which vibrate with the same phase
= the distance travelled by the wave (in a certain medium) during the time of one period (T)



$(s = v \cdot t)$

$\lambda = v \cdot T$

- absolute refractive index n

= how much light in a vacuum is faster than in the given medium

$$n = \frac{c}{v}$$

medium	**n**
vacuum	1
air at s.t.p.	$1.002718 \cong 1$
ice	1.31
water	1.33
glass, Perspex	$\cong 1.5$
diamond	2.4

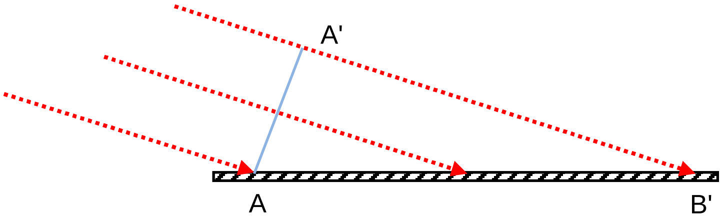
- light phenomena

a) reflection
b) refraction
c) dispersion
} geometrical optics

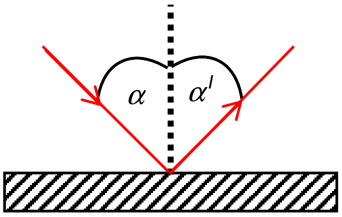
d) interference
e) diffraction
f) polarisation
} wave optics

3. Reflection

Reflection takes place when light is reflected back from some obstacle or at the end of the medium. It obeys the same ***law of reflection***, which was derived for mechanical waves in Y4 using the Huygens‘ construction.

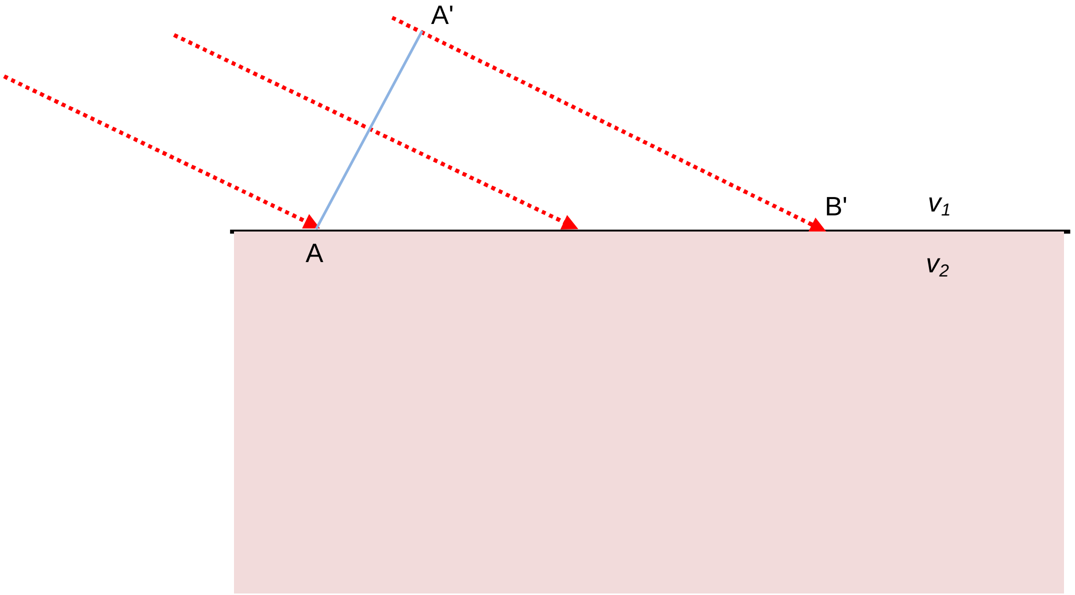


- the angle of incidence equals the angle of reflection; $\alpha = \alpha'$
- the incident and reflected rays and normal to the surface lie in the same plane

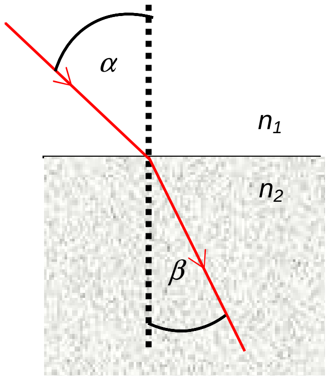


4. Refraction, total internal reflection

Refraction takes place when light enters another medium with different speed of propagation of light. ***The law of refraction*** is valid for mechanical waves and it was derived in Y4.



For light it was discovered by the Dutch scientist Snell (1591-1626) and therefore it is called ***Snell's law***:



- $\dfrac{\sin\alpha}{\sin\beta} = \dfrac{v_1}{v_2} = \dfrac{n_2}{n_1}$

- the incident and refracted rays and normal to the surface lie in the same plane

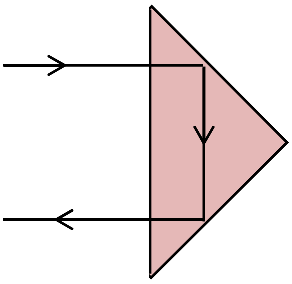
http://www.walter-fendt.de/ph14e/huygenspr.htm
http://www.worsleyschool.net/science/files/refraction/refraction2.html

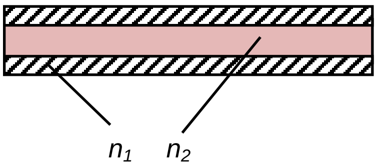
We can say that some medium is optically denser (rarer) when a light beam in it is slower (faster) than in another medium. The ray is then bent towards (away from) the normal.

- **total internal reflection** takes place when light comes from an optically denser to an optically rarer medium (it is bent away from the normal) and the angle of incidence exceeds a certain value called ***critical angle*** α_C**,** for which the angle of refraction is 90°. Then there is no refraction, only reflection.

$$\frac{\sin\alpha_C}{\sin 90^o} = \frac{n_2}{n_1}$$

use: measurement of absolute refractive index, reflectors, fibre optics





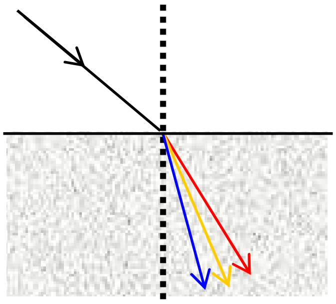
Questions:

1. Explain the difference between the corpuscular and wave theory of light.
2. Could particles be faster than light?
3. Does the speed of light depend on its frequency?
4. What is the relation between rays and wavefronts?
5. Show the situation when the angles of incidence and reflection equal each other but the rays do not lie in the same plane with the normal to the plane.
6. In the figure for reflection label the following lines: incident ray, reflected ray, normal to the surface.

7. In the figure for refraction label the following lines: incident ray, refracted ray, normal to the surface.
8. What would be different in Snell's law (the law of refraction) if it described mechanical waves? Derive the equation.
9. Sketch a figure for refraction where ray no.1 is refracted, ray no.2 is incident at critical angle and ray no.3 is totally reflected.
10. Think about the uses of total internal reflection, explain them, and finish the sketches.
11. Calculate critical angles for the following interfaces: glass ⟶ air, air ⟶ glass, glass ⟶ water.
12. Light goes from water to glass. When it is bent at 30°, calculate the angle of incidence.
13. Suggest a method that could be used to measure the absolute refractive index of some medium. Make this experiment, discuss results.

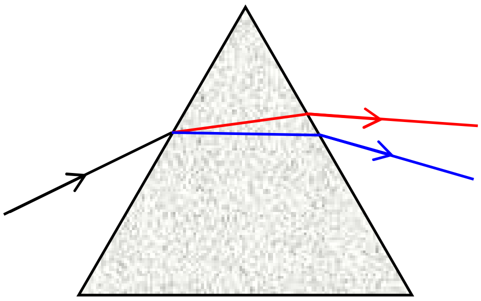
L6/1-3, 9-11, 14-20, 23, 26, 39-40

5. Dispersion, spectroscopy



n is different for each frequency!!!

optical prism



Prism spectrum – "NORMAL" – minimum deviation for RED

http://en.wikipedia.org/wiki/Spectroscopy

Spectroscopy is used in .... to identify substances through the typical spectrum emitted or absorbed by them. It is also used in ....to state the chemical composition of astronomical objects and their velocities from the Doppler shift of their ....

Choose: (1) spectral lines (2) chemistry (3)astronomy

6. Interference, coherent light

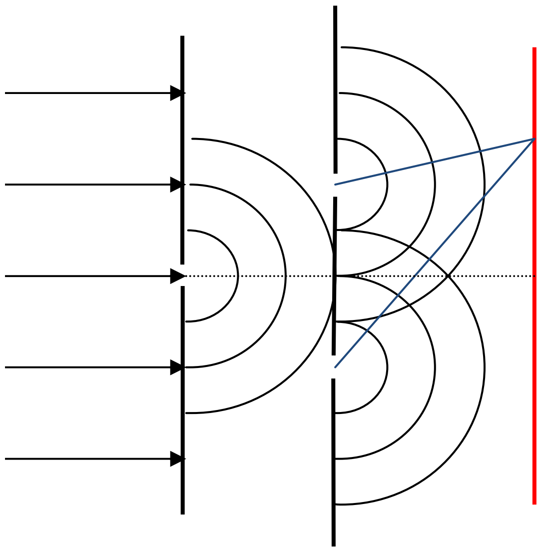
⊂ superposition

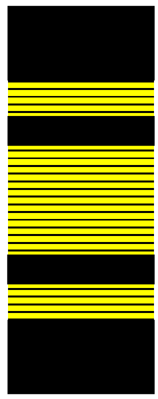
when waves coming from 2 COHERENT (freq., amplitude, phase) sources meet

white monochromatic coherent

- **Young's double slit experiment (1801/7?)**

http://www.walter-fendt.de/ph14e/doubleslit.htm
http://phet.colorado.edu/simulations/sims.php?sim=Wave_Interference



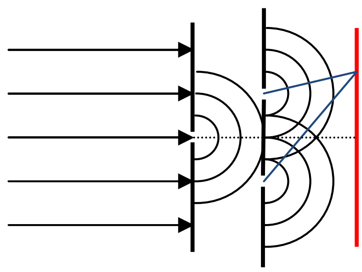


label Δl on the figure above

maximum for $\Delta l = k\lambda$ *k = 0, 1, 2, ...*

minimum for $\Delta l = (2k+1)\dfrac{\lambda}{2}$

$$X\lambda = \frac{ay}{d} = \frac{dist.btw\ the\ slits\ x\ fringe\ spacing}{slit - screen\ dist.}$$



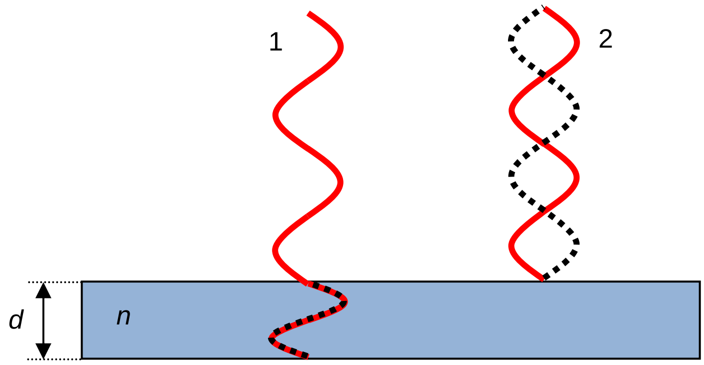
- **wedge fringes**

<u>optical path length</u> *l* = the distance in a vacuum which corresponds with the distance travelled in a denser medium

$$l = ns$$

<u>reflection:</u>

denser $\rightarrow$ rarer 1) no phase change as on the free end in mech. waves, Δl only rarer $\longrightarrow$ denser 2) $\Delta\varphi$ by π as on the fixed end in mech. waves $\Rightarrow \Delta l$ changed by $\frac{\lambda}{2}$ as well ($\Delta l + \frac{\lambda}{2}$)



bright fringe: $\Delta l + \frac{\lambda}{2} = k\lambda$ ... in phase $\qquad \Delta l = 2nd$

to-and-fro $\qquad$ because of 2)

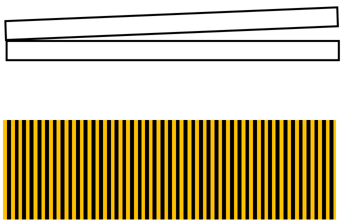
$$2nd = (2k+1)\frac{\lambda}{2} \qquad k=0,1,2,\ ...$$

dark fringe: $\Delta l + \frac{\lambda}{2} = (2k+1)\frac{\lambda}{2}$ ... out of phase $\qquad \Delta l = 2nd$

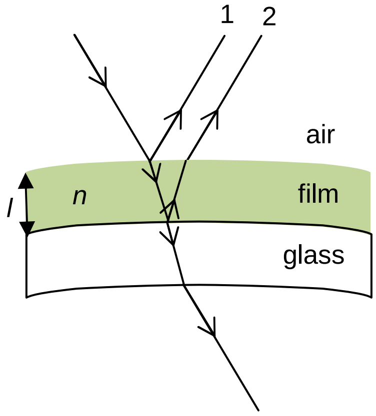
$$2nd = k\lambda \qquad k=0,1,2,\ ...$$

- **uses of interference:**

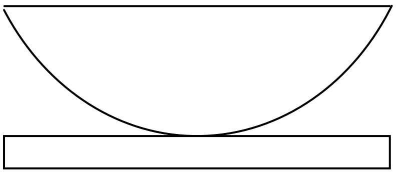
a) testing optical surfaces

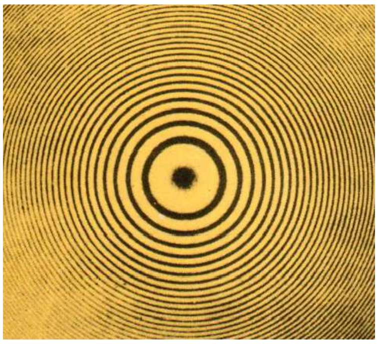


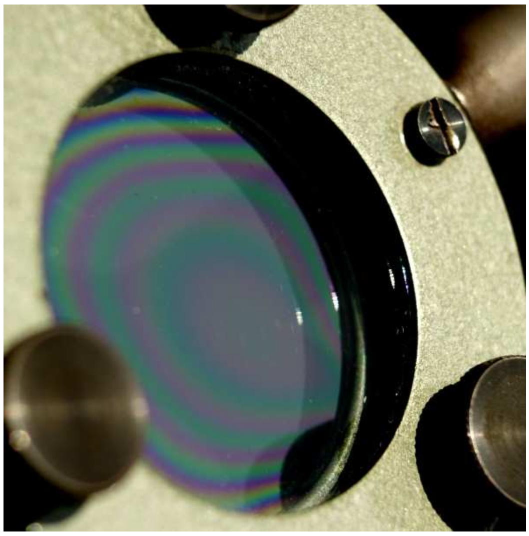
b) non-reflecting glass
film – destructive interference of 1 and 2



c) measurement of λ (Newton's rings)



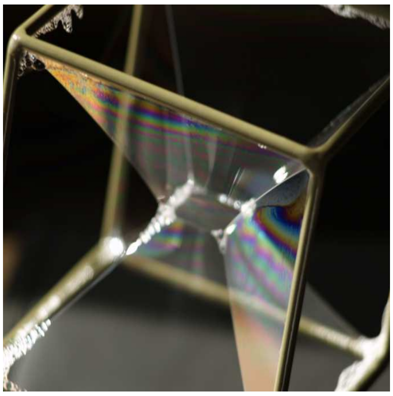


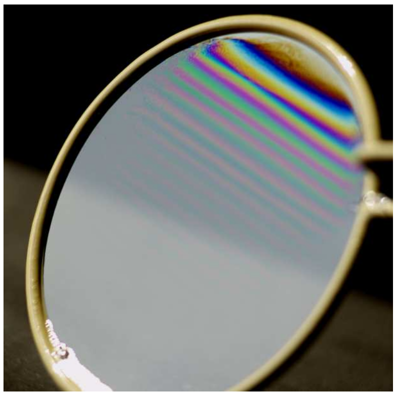


d) measurement of 1m – certain huge multiple of wavelengths of radiation produced by excited krypton

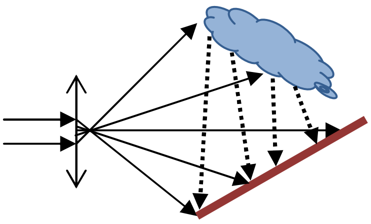
e) everyday examples

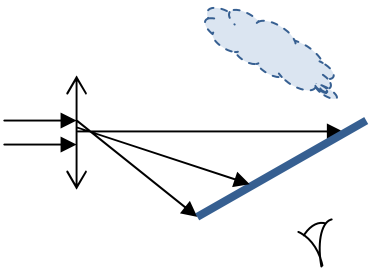
- colour of oil films on water
- colours on bubbles





f) holograms = records of interference pattern, which is then exposed to light – reconstruction





Questions:

14. Which spectrum is defined as a „normal“ one? Where can we observe it?
15. What is the basic condition for dispersion?
16. Why can you see colours on oil films on water? Explain for the point where e.g. yellow appears.
17. The absolute refractive index of red light is 1.328 in some medium. If the wavelength of the light in vacuum is 700 nm and frequency 4.286×10^{14} Hz, what is its speed and frequency in this medium?
18. Light of wavelength 550 nm is used in the Young's double slit experiment. When one of the rays has travelled a) 6.05 µm b) 6.875 µm more than the other one to certain point P, is there a dark fringe at P?
19. Light goes from water to the air and the angle of incidence is 60^{o}. Calculate the angle of refraction.
20. The width of an oil film (n=1.5) on water is 2.5 µm. When a beam of red light (600 nm) is incident, is there a dark or bright fringe?
21. Green light (500 nm) is used in Young's double slit experiment. The ray from the first source has travelled 562 µm to a certain point P, the ray from the second source has travelled 572.25 µm to the same point. Is there a dark or a bright fringe?
22. The width of an air wedge is 12.6 µm. When a beam of violet light (420 nm) is incident, is there a dark fringe?

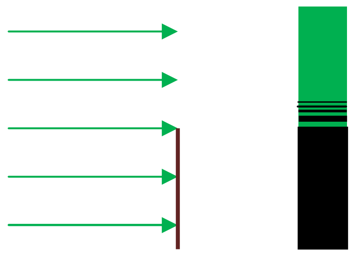
L6/46-52, X54-5, 55, X57, 58

7. Diffraction

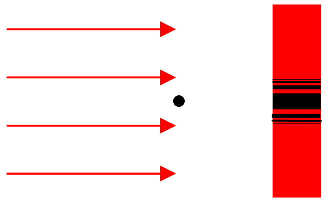
http://www.walter-fendt.de/ph14e/singleslit.htm
http://www.worsleyschool.net/science/files/singleslit/diffraction.html

Diffraction takes place when the wavefront has been limited (obstacle, gap), which works as superposition from many point sources (but not from the whole space) – diffraction pattern is formed

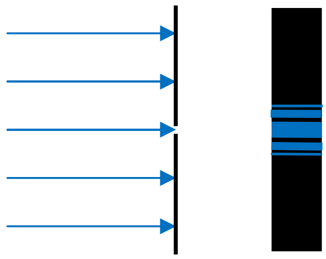
a) straight edge



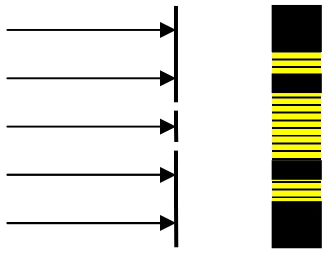
b) wire



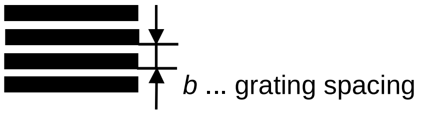
c) single slit

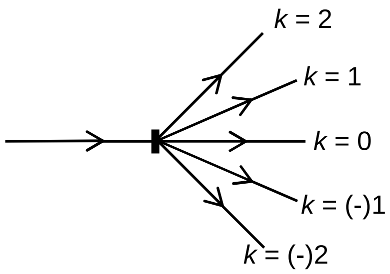


d) double slit



e) grating





$$b \sin \alpha_k = k\lambda$$

order of maximum

when white light used: *k* = 0 ... white; *k* = 1,2,... coloured spectrum
minimum deviation for BLUE – INVERTED SPECTRUM

use: measurement of wavelength

Questions:
23. Light of wavelength 600 nm is incident on a grating containing 500 lines per mm. What will be the distance between zero and first order maximum on the screen placed 1 m from the grating?

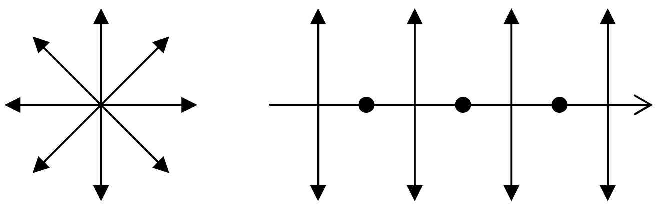
L6/59-62, 64, X65-6

8. Polarisation

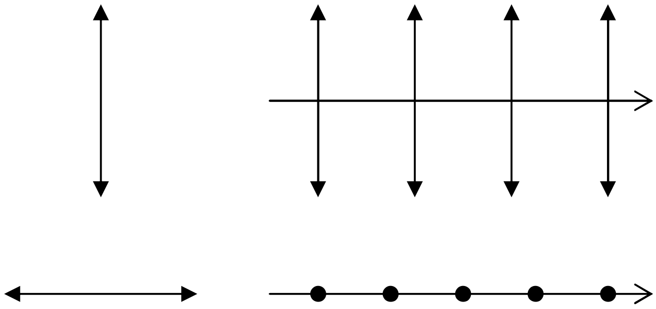
„Ordinary“ unpolarized light - $\vec{E}$ vibrates in all directions × polarised – in one direction only

http://www.walter-fendt.de/ph14e/emwave.htm
http://kabinet.fyzika.net/aplety/CircPol/CircPol.html

unpolarized light



plane polarized light



- **producing polarised light**

a) polaroid – selective absorption

b) reflection – light incident at any angle is partly polarised when both reflected and refracted (fig.1)
- when incident at Brewster's angle the reflected ray is TOTALLY plane polarised ($n = \tan \alpha_B$) as in fig.2

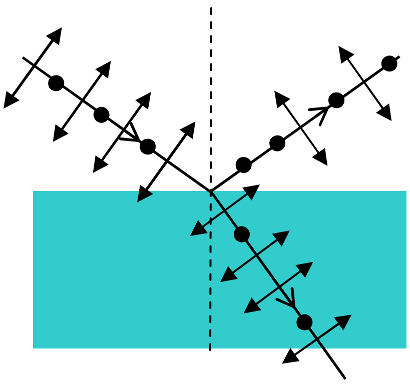


Fig. 1

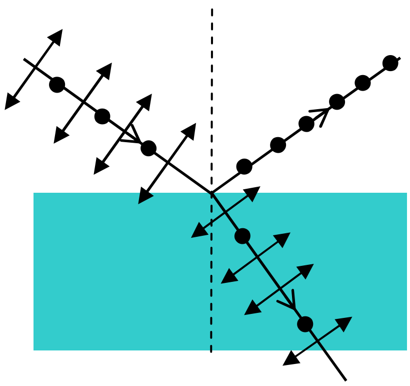


Fig. 2

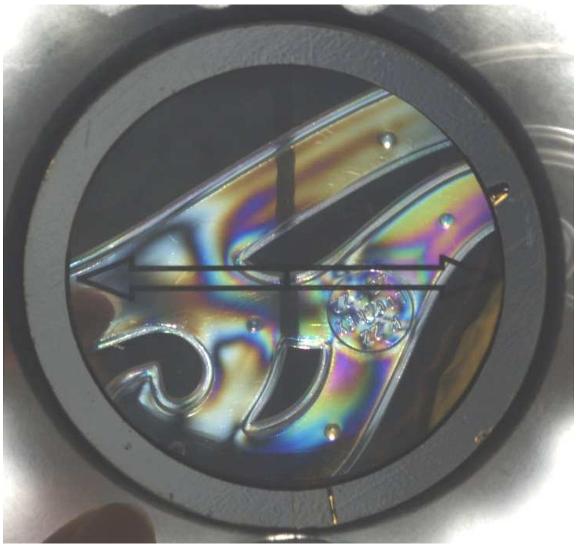
c) double refraction – some materials e.g. Iceland spar exhibit double refraction – incident unpolarized light is split into two rays polarised at right angle to each other (× special arrangement of the two bits to get bigger angle between is called Nicol prism)

- **uses**

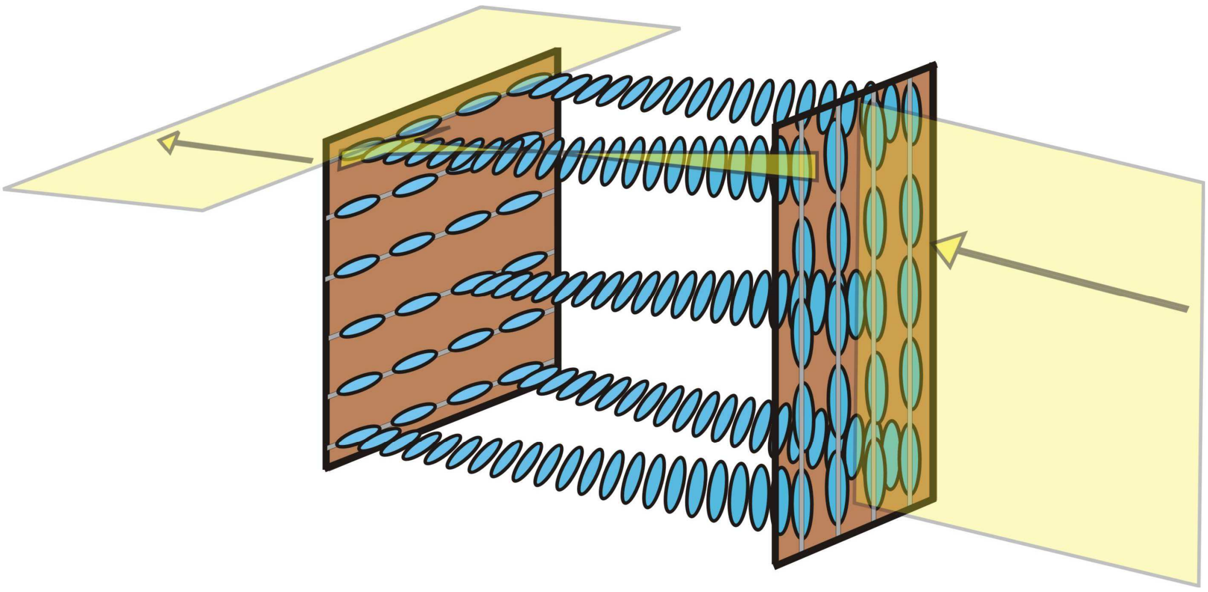
a) reducing glare – polarising materials as e.g. coatings on sunglasses

b) optical activity – some crystals (quartz) or liquids (sugar solution) turn the plane of polarised light. E.g. bigger concentration of sugar $\Rightarrow$ bigger angle: polarimeter (device)

c) stress analysis – glass, Perspex, become double refracting when under stress = photo elasticity, models of bridges etc



d) liquid crystal displays (LCD)



Questions:

24. Explain the difference between unpolarised and plane polarised light.

25. How can we make polarised light?

26. What is polarised light used for?

Answers:

11. 41.8°, not possible, 62.5°
12. 34.3°
17. 225 900 km·s^{-1}, 4.286×10^{14} Hz
18. a) bright, k=11 b) dark, k=12.5
19. TIR
20. bright, k=12.5
21. dark, k=20.5
22. dark, k=60
23. 31 cm