Interdisciplinary postgraduate program «Optics and Vision»

Foundations of Modern Optics

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Curriculum

Introduction-Basic Principles

Imaging

- Geometrical Optics
- Simple Optical systems
- The Matrix method
- Image Illumination
- Optical Aberrations

Detection and Sources of Radiation

Gaussian Beams

1 Introduction

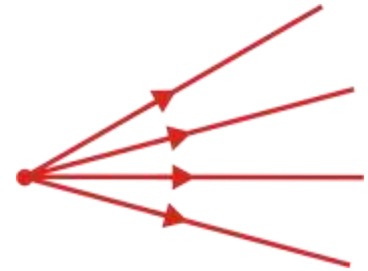
Historical introduction

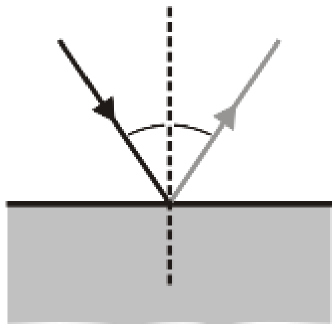
Ancient times

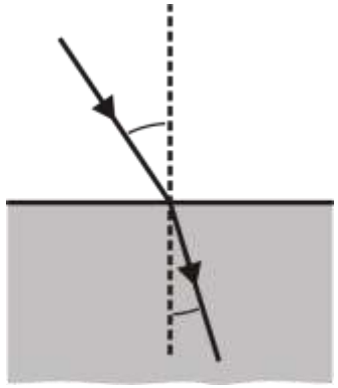
Rectilinear propagation of light
Pythagoras, Demokritos, Empedoklis, Platon, Aristotle

Law of reflection
300 BC Euclid *«Κατοπτρικά»*
~ 50 AD Heron:
"The path that light follows from one point to another is the smallest."

Refraction
50 BC Kleomedes,
130 AD Claudius Ptolemaeus
(refraction tables)

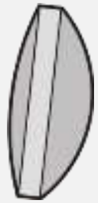






Mirrors
1900 BC Egypt

Converging lenses
424 BC (Aristophanes *"Νεφέλες"*)
~ 30 A.C. Seneka

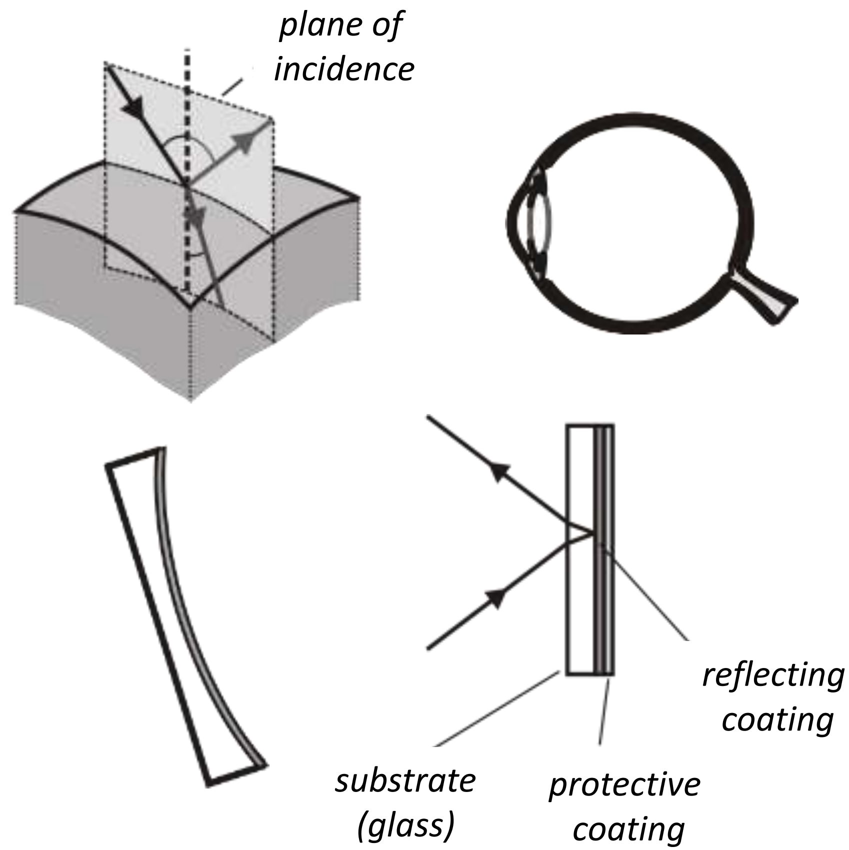


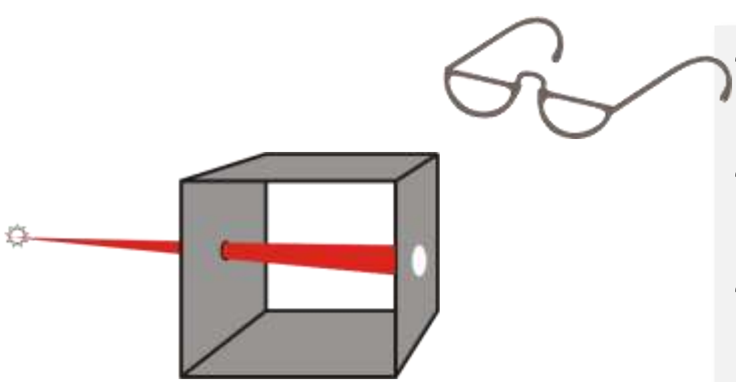
Middle ages

1000 AC. Alhazen
(Plane of Incidence,
spherical and parabolic mirrors,
detailed description of the human eye)

~1230 AC. Bacon
Correction of vision with lenses.
We can build a telescope by combining lenses!

~ 1500 AC. Lenardo Da Vinci
Camera Obscura





~ 1250 AC. eyeglasses

~1300 AC. Coated Mirrors

~1500 AC. Camera Obsura
(The first photographic camera!)

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17^{th} -18^{th} Century

1611 Kepler Dioptrice Total reflection

1621 Snell Refraction Law

1637 Descartes La Dioptrique,

«Light is a disturbance that propagates through an elastic medium!»

~ 1657 Fermat

Principle of Least Time

~1650 Grimaldi & Hooke Diffraction,

«Light is a rapid vibration of the medium that travels at a great speed»

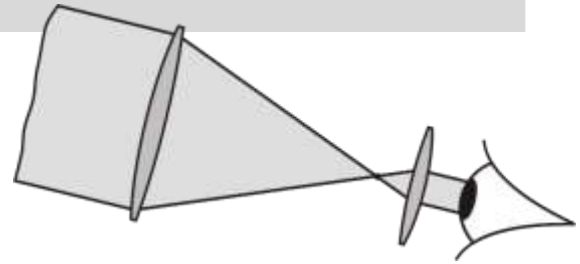
~1665 Newton Spectral analysis, Mirror Telescopes, corpuscular nature of Light

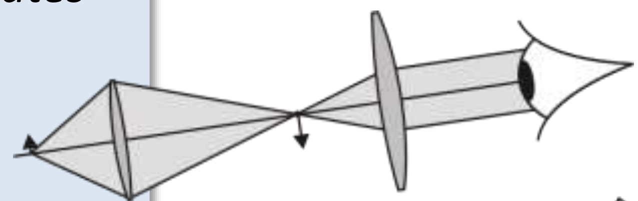
~ 1665 Huygens Polarization,

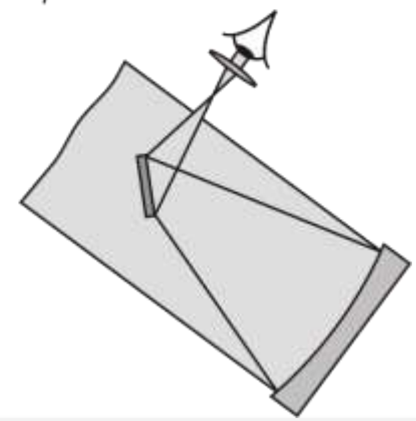
"Light is a wave"

~1676 Romer

Measurement of the speed of light







1608 Lippershey Refractive telescope

1610 Janssen Microscope

1668 Newton Reflective telescope

1758 Dollond Achromatic Lens

19^{th} century

1801 Young, interference principle

~1820 Fresnel, wave propagation (longitudinal waves), diffraction, interference

1825 Young , Light is a transverse wave

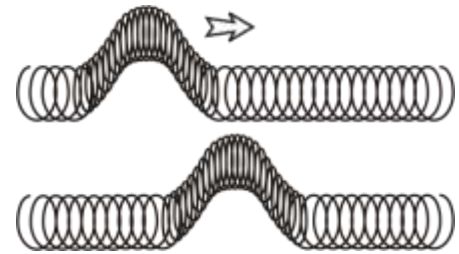
1845 Faraday, Magneto-Optical effect

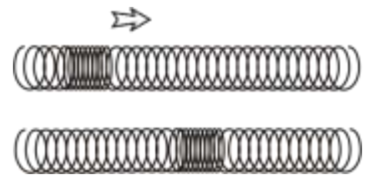
~ 1849 Fizeau, terrestrial measurement of the speed of light

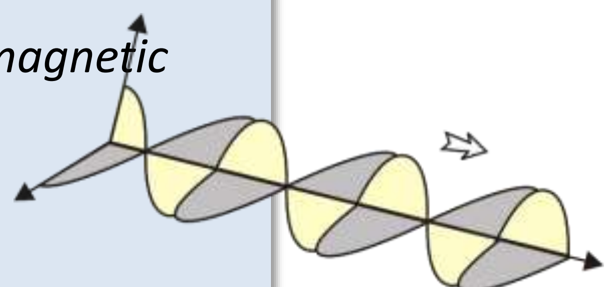
1870 Maxwell, *«Light is an electromagnetic wave!»*

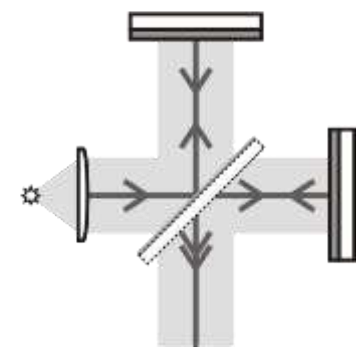
1881,1887 Michelson, Morely

«Ether is stationary in relation to the earth»









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20th century

1900 Poincare, *«Ether does not exist!»*

1900 Planck, Beginning of Quantum Mechanics

1905 Einstein, *"Light propagates in vacuum at a constant speed independent of the movement of the source"*
Light behaves as a particle when interacts with matter

1913 Bohr, Quantum mechanical description of Hydrogen atom

1948 Gabor, Holography

1950 Fourier Optics, Optics & telecommunication theory

1958 Townes, Laser
(1917 Einstein Theoretical Prediction)

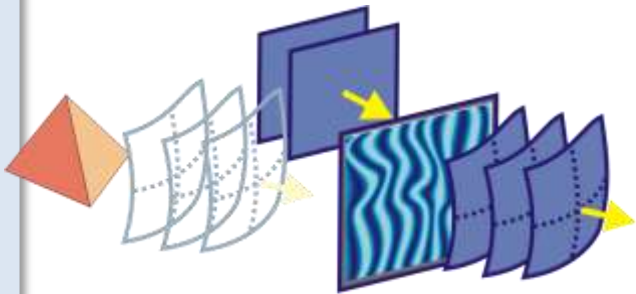
1966 Kao, Optical Fibers

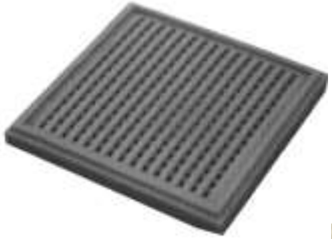
1966 Ashkin, Photorefractive materials

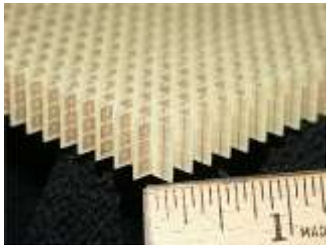
1969 Boyle, Smith, CCD camera

1987 Yablonovitch, Sajeev, Photonic materials

1999 Pedry, Meta-materials
(1967 Veselago Theoretical prediction)







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Πηγές: wikipedia, http://www.warnlaser.com

Waves

Wave equation

$$\nabla^2\Psi - \frac{1}{\upsilon^2}\frac{\partial^2\Psi}{\partial t^2} = 0$$

disturbance

$\Psi(\mathbf{r},t)$

propagation speed

✓ **Linear** $\Rightarrow$ ***the sum of solutions is a solution***

Linearity and superposition principle

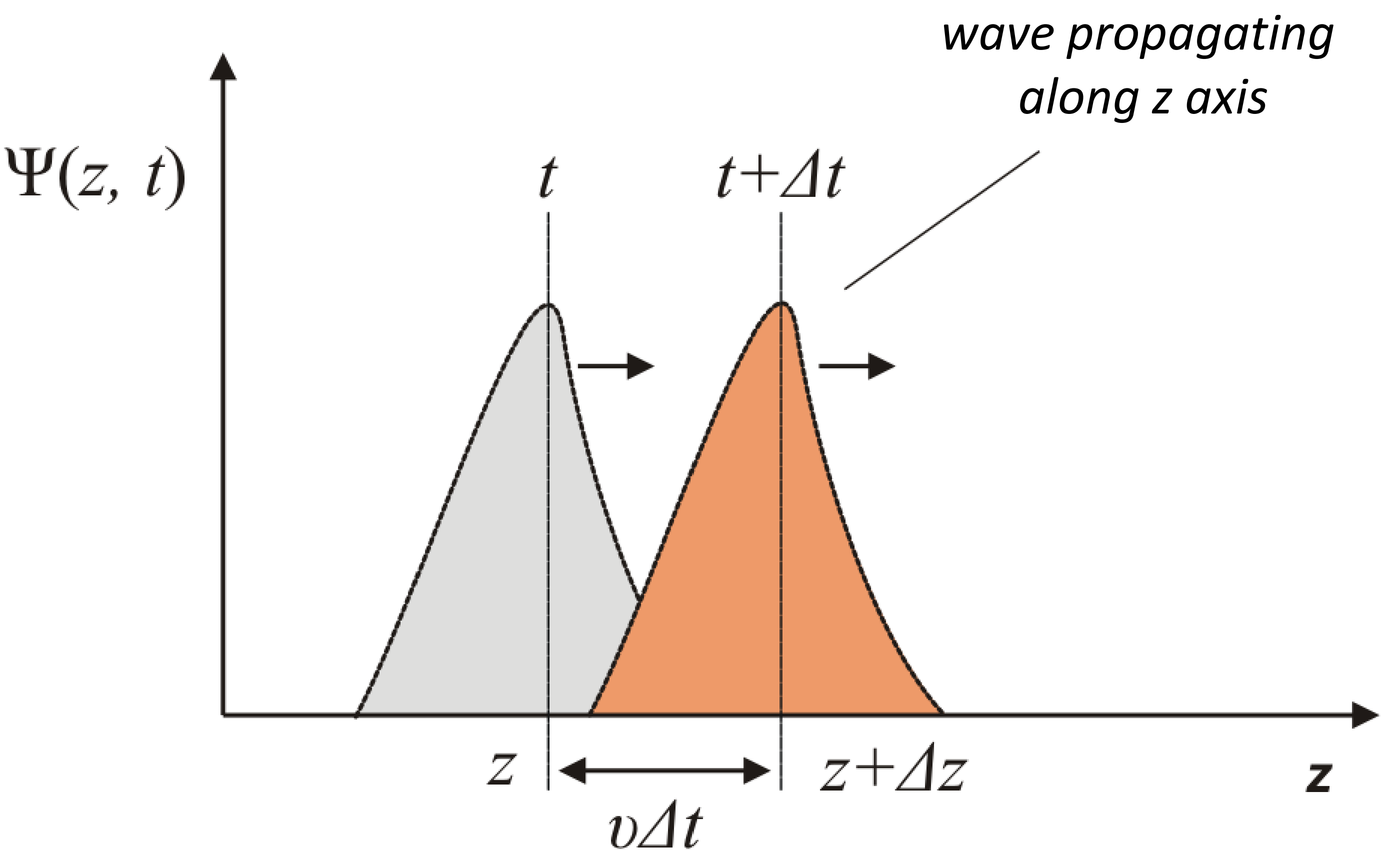
$$\left.\begin{aligned}
&\nabla^2\Psi_1 - \frac{1}{\upsilon^2}\frac{\partial^2\Psi_1}{\partial t^2} = 0 \\
&\nabla^2\Psi_2 - \frac{1}{\upsilon^2}\frac{\partial^2\Psi_2}{\partial t^2} = 0 \\
&\qquad\vdots \\
&\nabla^2\Psi_N - \frac{1}{\upsilon^2}\frac{\partial^2\Psi_N}{\partial t^2} = 0
\end{aligned}\right\} \Rightarrow \nabla^2\left(\sum_{i=1}^{N}\Psi_i\right) - \frac{1}{\upsilon_1^2}\frac{\partial^2}{\partial t^2}\left(\sum_{i=1}^{N}\Psi_i\right) = 0$$

N waves

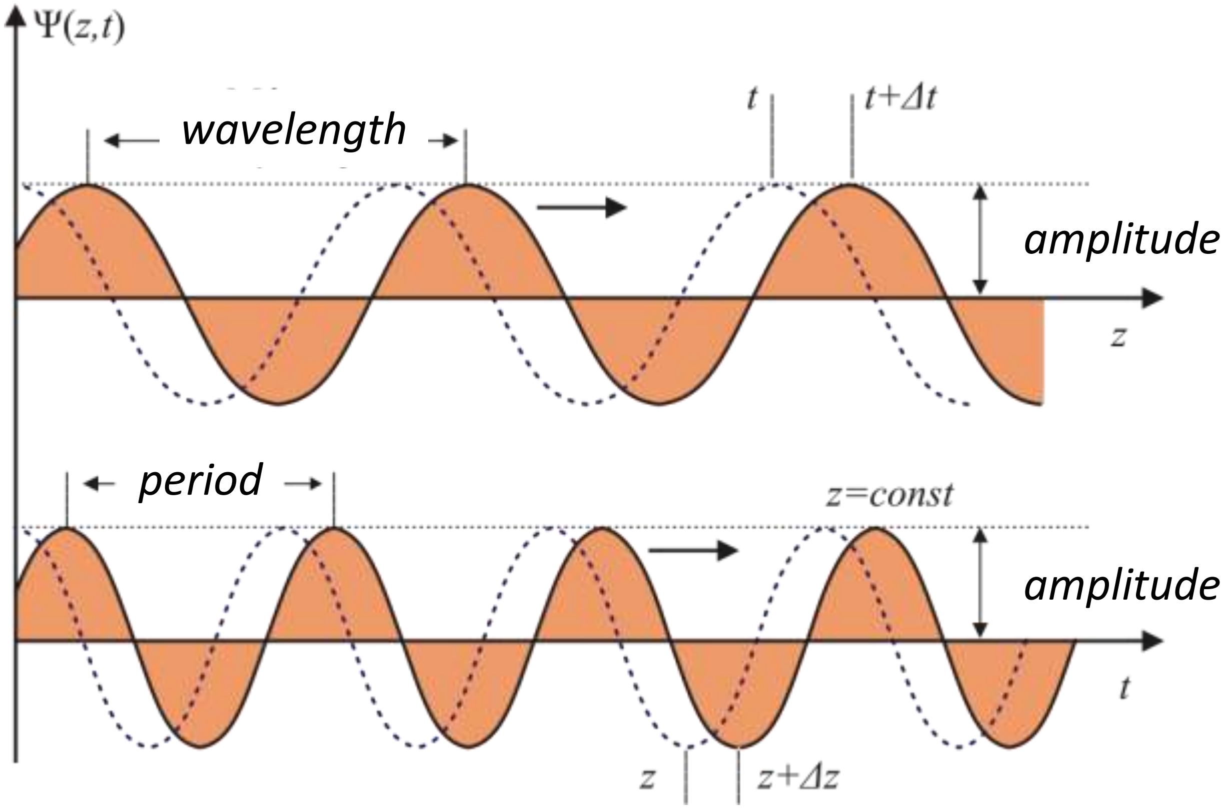
Their superposition is a wave

Wave equation in one dimension

$$\frac{\partial^2 \Psi}{\partial z^2} - \frac{1}{\upsilon^2}\frac{\partial^2 \Psi}{\partial t^2} = 0$$



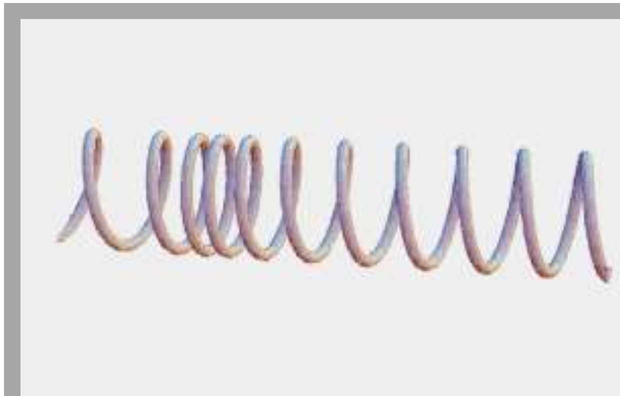
wave attributes



- **Wavelength** *(periodicity in space)*
- **Period** *(periodicity in time)*
- **Amplitude**
- **velocity**
- **phase**

Wave types

Longitudinal



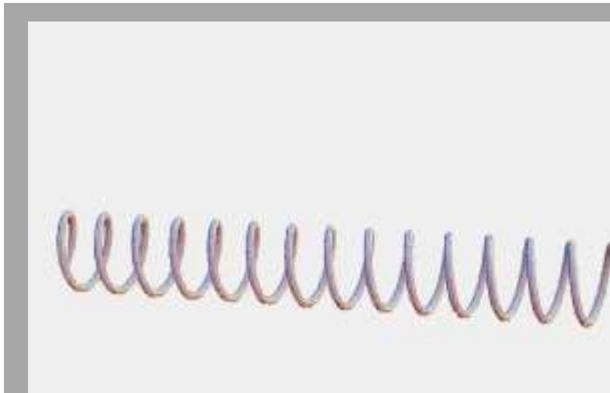
Propagation

Disturbance

scalar $\Psi(\mathbf{r},t)$

Typical example: sound waves

Transverse



Propagation

Disturbance

vector $\mathbf{A}(\mathbf{r},t)$

Typical example: vibrations of a string

Harmonic waves

The disturbance $\Psi(\mathbf{r}, t)$ is a harmonic function of time

amplitude >0

$$\Psi(\mathbf{r},t) = a(\mathbf{r})\cos[\underbrace{g(\mathbf{r}) - \omega t}_{\textit{phase}}]$$

phase

Iso-phase surface

$$g(\mathbf{r}) - \omega t = const$$

Surface of constant amplitude

$$\alpha(\mathbf{r}) = const$$

Phase velocity

Phase velocity υ_p refers to the propagation velocity of the isophase surfaces

$$\varphi(\mathbf{r},t) \equiv g(\mathbf{r}) - \omega t = const \Rightarrow d\varphi(\mathbf{r},t) = 0 \Rightarrow$$

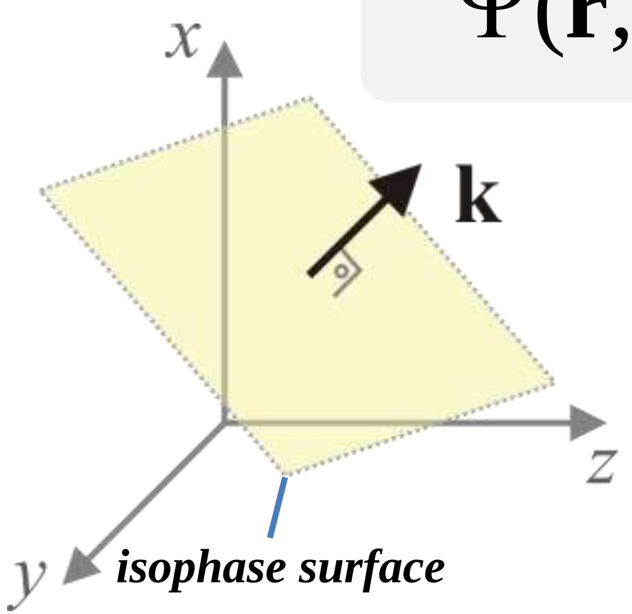
$$\left.\begin{array}{c} \nabla g(\mathbf{r}) \cdot d\mathbf{r} - \omega\, dt = 0 \\ d\mathbf{r} = dr\,\hat{\mathbf{q}} \end{array}\right\} \Rightarrow (\nabla g(\mathbf{r}) \cdot \hat{\mathbf{q}})dr = \omega dt \Rightarrow \frac{dr}{dt} = \frac{\omega}{\nabla g(\mathbf{r}) \cdot \hat{\mathbf{q}}}$$

$$\hat{\mathbf{q}} \perp isosurface \Rightarrow \hat{\mathbf{q}} = \frac{\nabla g(\mathbf{r})}{\left|\nabla g(\mathbf{r})\right|} \Rightarrow \nabla g(\mathbf{r}) \cdot \hat{\mathbf{q}} = \left|\nabla g(\mathbf{r})\right| \Rightarrow$$

$$\upsilon_p \equiv \frac{\omega}{\left|\nabla g(\mathbf{r})\right|}$$

Harmonic plane waves

The disturbance $\Psi(\mathbf{r}, t)$ is harmonic both in **Time** and in **Space**. The amplitude is constant.



isophase surface

$$\mathbf{k}\cdot\mathbf{r} = const$$

$$\Psi(\mathbf{r},t) = \Psi_o \cos[\mathbf{k}\cdot\mathbf{r} - \omega t]$$

wavevector

wavenumber

$$|\mathbf{k}| = k \equiv \frac{2\pi}{\lambda}$$

wavelength

Phase velocity of a harmonic wave

frequency

$$\upsilon_p \equiv \frac{\omega}{\left|\nabla g(\mathbf{r})\right|} = \frac{\omega}{\left|\nabla(\mathbf{k}\cdot\mathbf{r})\right|} = \frac{\omega}{k} = \frac{2\pi\nu}{2\pi/\lambda} \Rightarrow$$

$$\boxed{\upsilon_p = \frac{\omega}{k} = \nu\cdot\lambda}$$

* $\nabla(\mathbf{k}\cdot\mathbf{r}) = \nabla(k_x\,x + k_y\,y + k_z\,z) = k_x\hat{\mathbf{x}} + k_y\hat{\mathbf{y}} + k_z\hat{\mathbf{z}} = \mathbf{k}$

Complex description of a harmonic wave

$$\Psi(\mathbf{r},t)=a(\mathbf{r})\cos[g(\mathbf{r})-\omega t]$$

complex amplitude

$$=\mathrm{Re}\{\overbrace{a(\mathbf{r})e^{ig(\mathbf{r})}}^{A(\mathbf{r})}e^{-i\omega t}\}=\boxed{\mathrm{Re}\{A(\mathbf{r})e^{-i\omega t}\}}\,^{*}$$

$$=\frac{1}{2}[A(\mathbf{r})e^{-i\omega t}+\overbrace{A^{*}(\mathbf{r})e^{+i\omega t}}^{c.c.}]=\boxed{\frac{1}{2}A(\mathbf{r})e^{-i\omega t}+c.c.}$$

* **Re{..} can be omitted in linear calculations!**

Complex description and wave equation

$$\nabla^2\Psi - \frac{1}{\upsilon^2}\frac{\partial^2\Psi}{\partial t^2} = 0 \Rightarrow e^{-i\omega t}\nabla^2 A(\mathbf{r}) - \frac{1}{\upsilon^2}(-\omega^2)e^{-i\omega t}A(\mathbf{r}) \Rightarrow$$

$$\nabla^2 A(\mathbf{r}) + \frac{\omega^2}{\upsilon^2}A(\mathbf{r}) = 0$$

If the wave is plane and harmonic:

$$\nabla^2 A(\mathbf{r}) + k^2 A(\mathbf{r}) = 0$$

Helmholtz equation