Crash Course on Photonics

by Manuel Ferrer

Outline of the course

1. What is light?
2. Ray optics
3. Vector nature of light
4. Gaussian Beams and friends ☺
5. Basic optics in the lab
6. How to make plot your Postdoc won’t hate

Who am I?

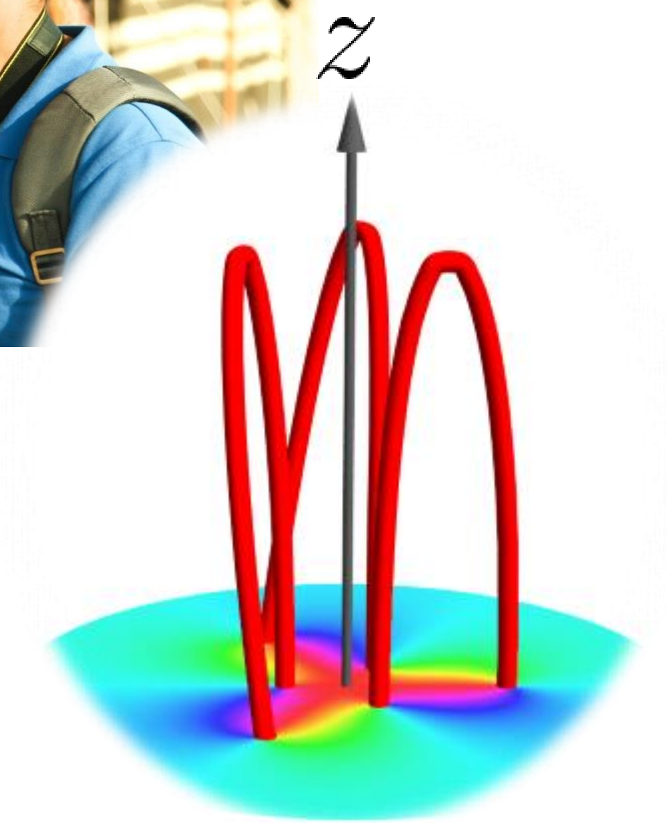
Manuel Ferrer

- ❖PhD in Physics - uOttawa
- ❖MSc in Nanotechnology
- ❖BS in Engineering Physics

❖Mexican

❖Used to work in structured light

❖Trying to master diffraction gratings

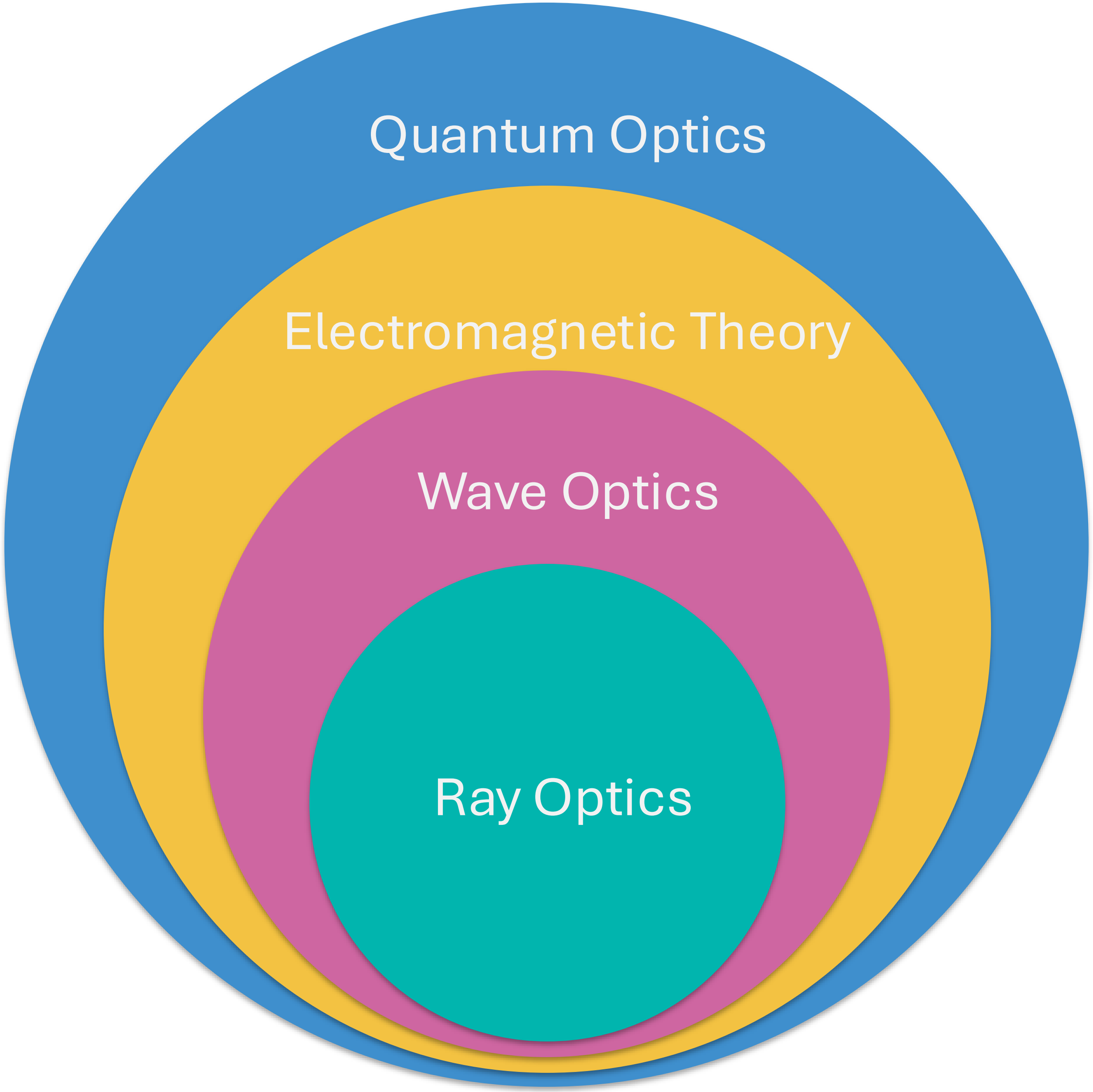


What is light?

Wave ?

Particle?

How do we master light?



Ray Optics!

1. Light travels in the form of rays; The rays are emitted by light sources and can be observed when they reach an optical detector.

Ray Optics!

2. An optical medium is characterized by a quantity n, called the refractive index. The refractive index is the ratio of the speed of light in free space c_0 to that in the medium c. Therefore, the time taken by light to travel a distance d equals to $d\,/\,c = d\,n/c_0$. It is thus proportional to the product nd known as the optical path length.

Ray Optics!

3. In an inhomogeneous medium, the refractive index $n(r)$ is a function of the position r=(x,y,z). The optical path length along a given path between two points A and B is therefore:

$$\text{Optical Path Length} = \int_{A}^{B} n(\boldsymbol{r})\, d\boldsymbol{s},$$

where ds is the differential element of length along the path. The time taken by light to travel from A to B is proportional to the optical path length.

Ray Optics!

4. **Fermat's Principle.** Optical rays traveling between two points, A and B, follow a path such that the time of travel (or the optical path length) between the two points is an extremum relative to neighboring paths. An extremum means that the rate of change is zero, i.e.,

$$\delta \int_{A}^{B} n(\boldsymbol{r})\, d\boldsymbol{s} = 0$$

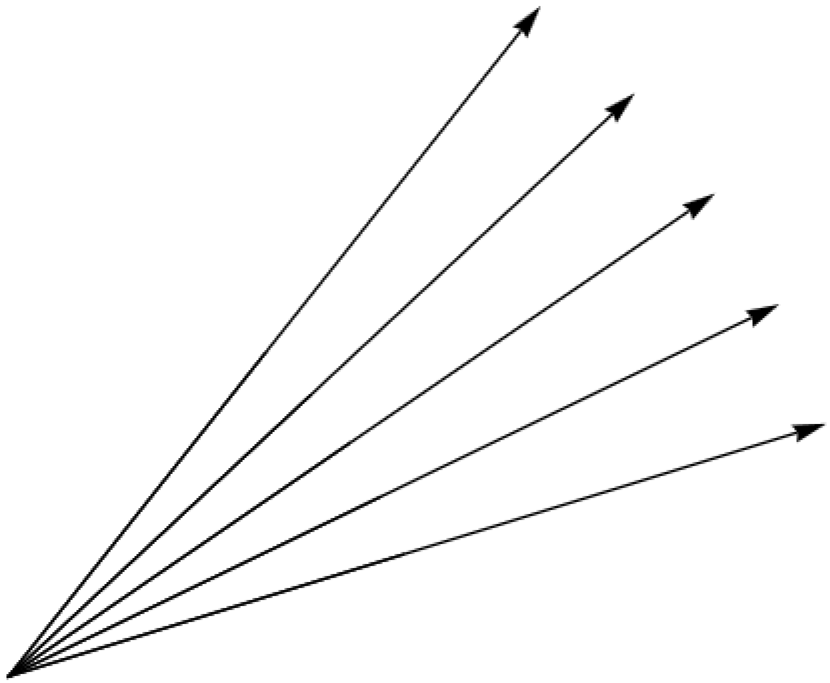
The extremum may be a minimum, a maximum, or a point of inflection. It is, however, usually a minimum, in which case:

Light rays travel along the path of least time.

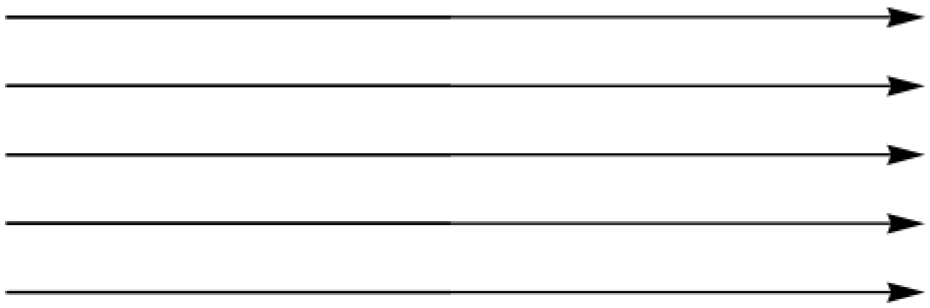
Summary of Ray Optics!

1. Describes light behavior with rays
2. Assumes light travels in straight lines
3. Ignores diffraction and interference
4. Used for mirrors, lenses, and instruments

Sources of light



Point source



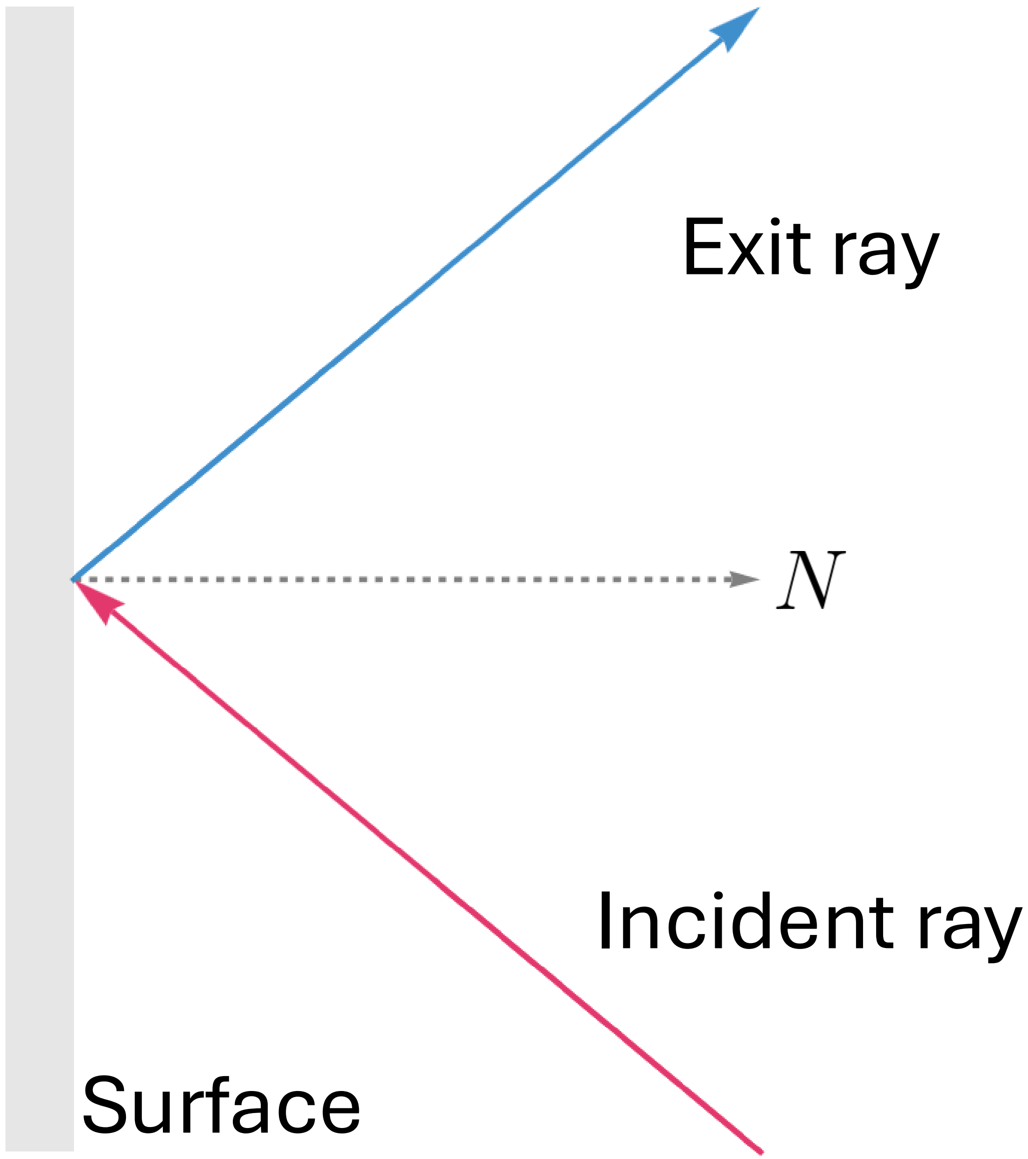
Collimated source

Phenomena in Optics

1. Reflection
2. Refraction
3. Polarization
4. Diffraction
5. Interference

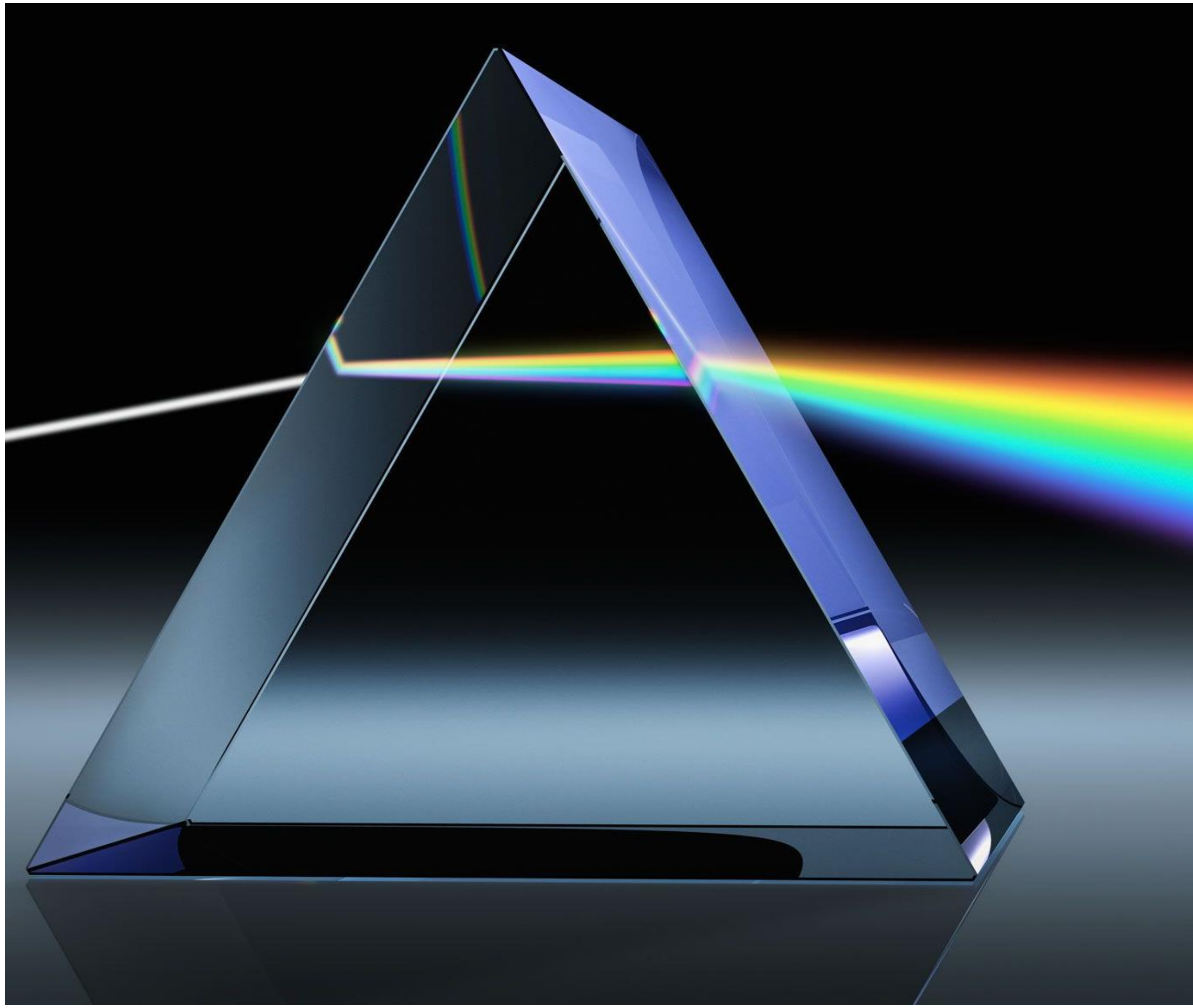
Reflection

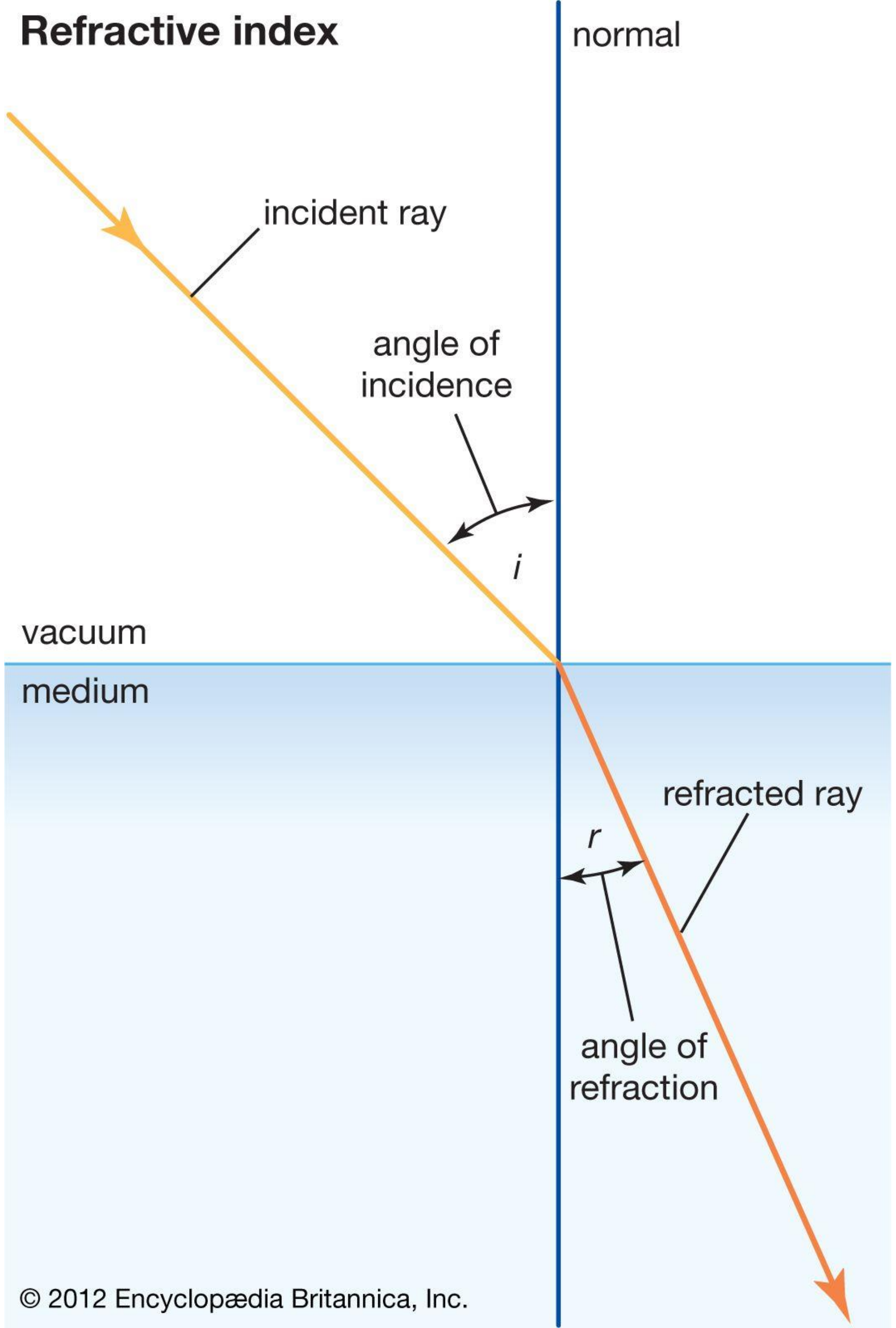
change in direction of a wavefront at an interface between two different media so that the wavefront returns into the medium from which it originated.



Refraction

redirection of a wave as it passes from one medium to another

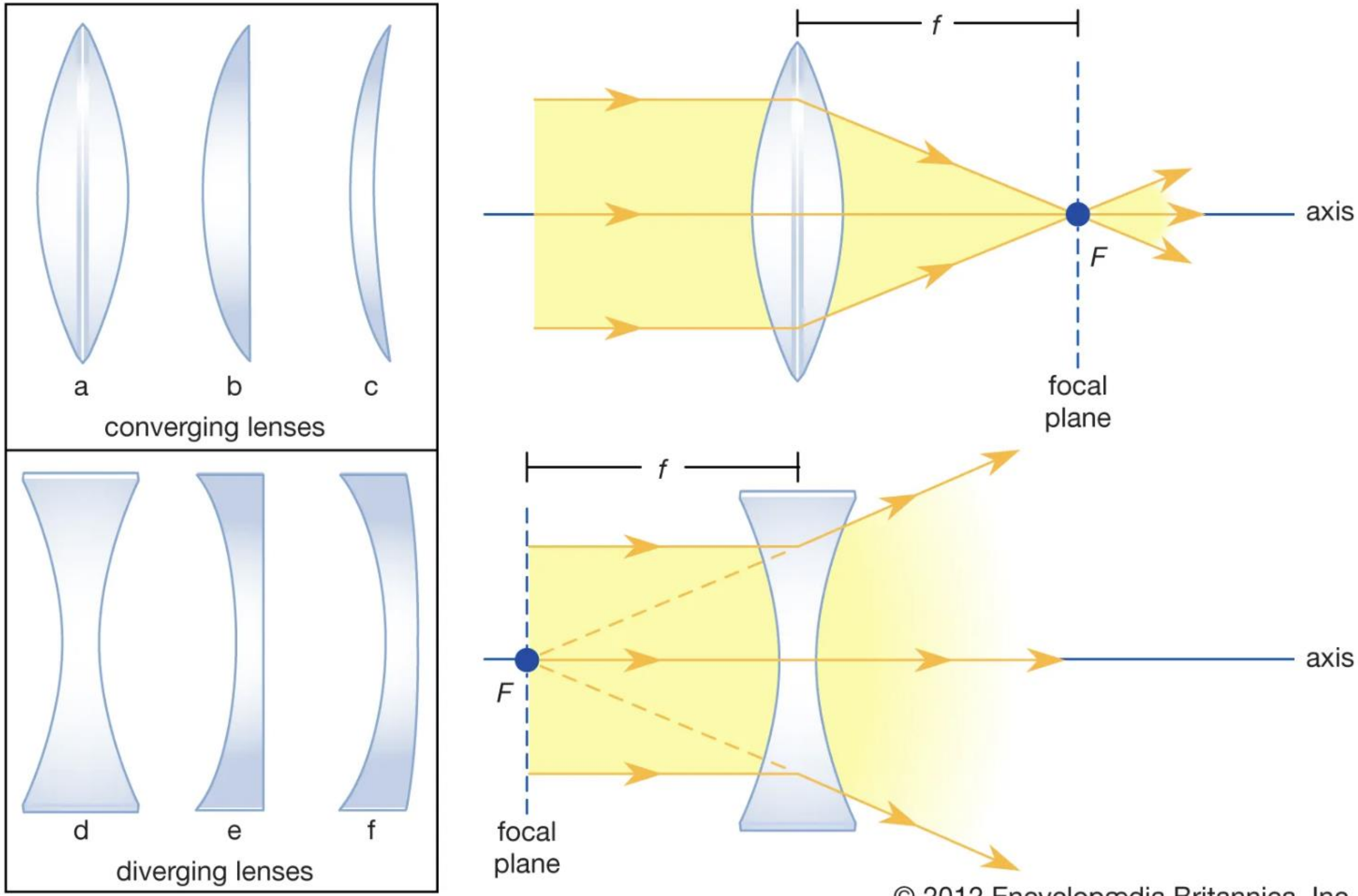




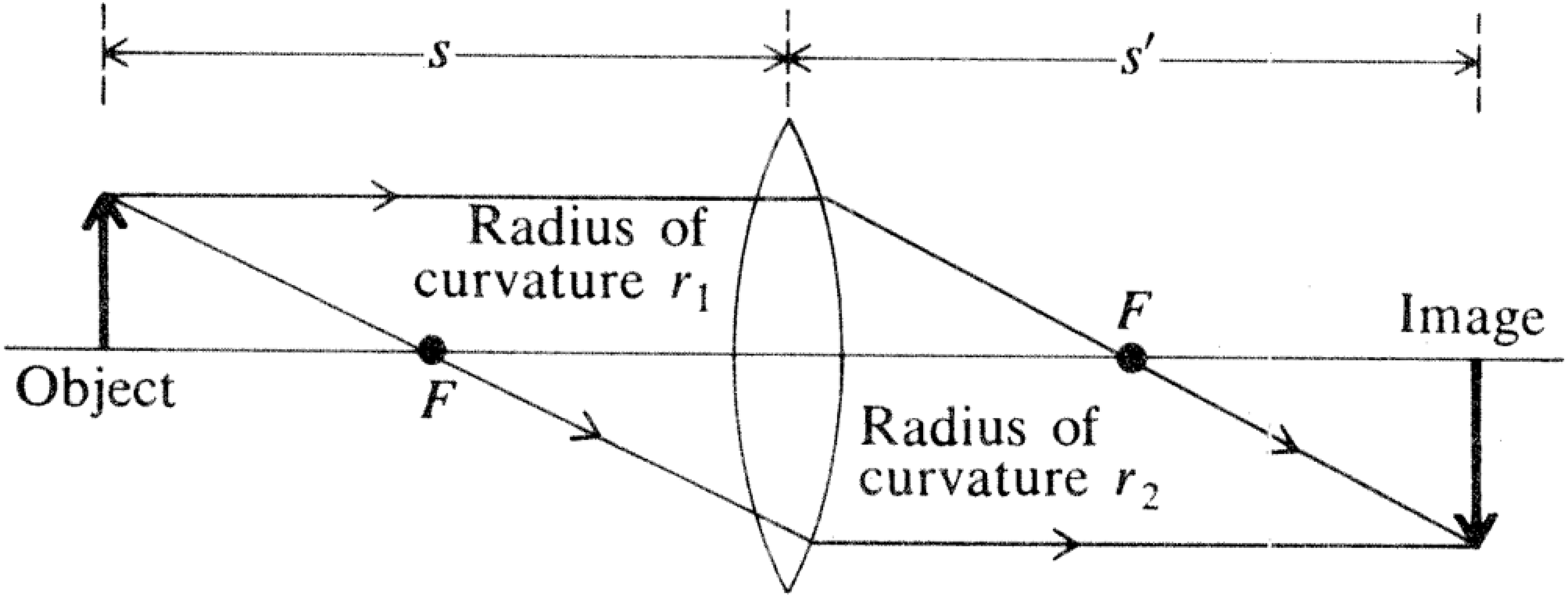
Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Lenses


a
b
c
converging lenses
d
e
f
diverging lenses
f
axis
F
focal plane
f
axis
F
focal plane

Thin Lenses



s
s′
Radius of
curvature r_1
F
Image
Object
F
Radius of
curvature r_2

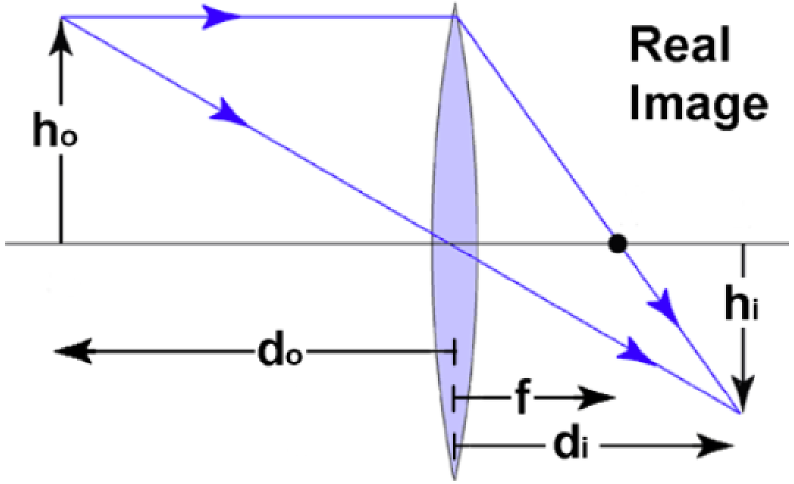
Magnification

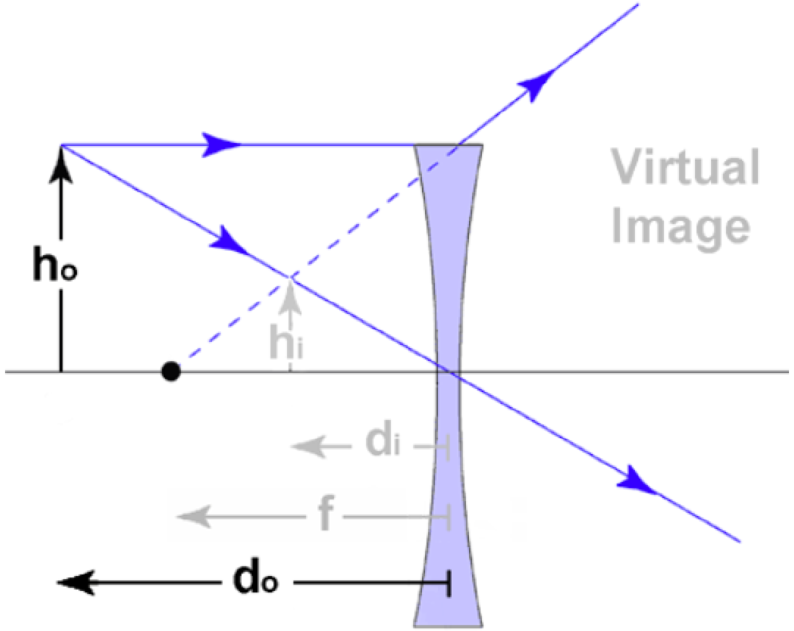
A single lens

$$M = \frac{f}{f - d_o} = -\frac{d_o}{d_i} = \frac{h_o}{h_i}$$

Real image ⇨ Negative ⇨ Inverted

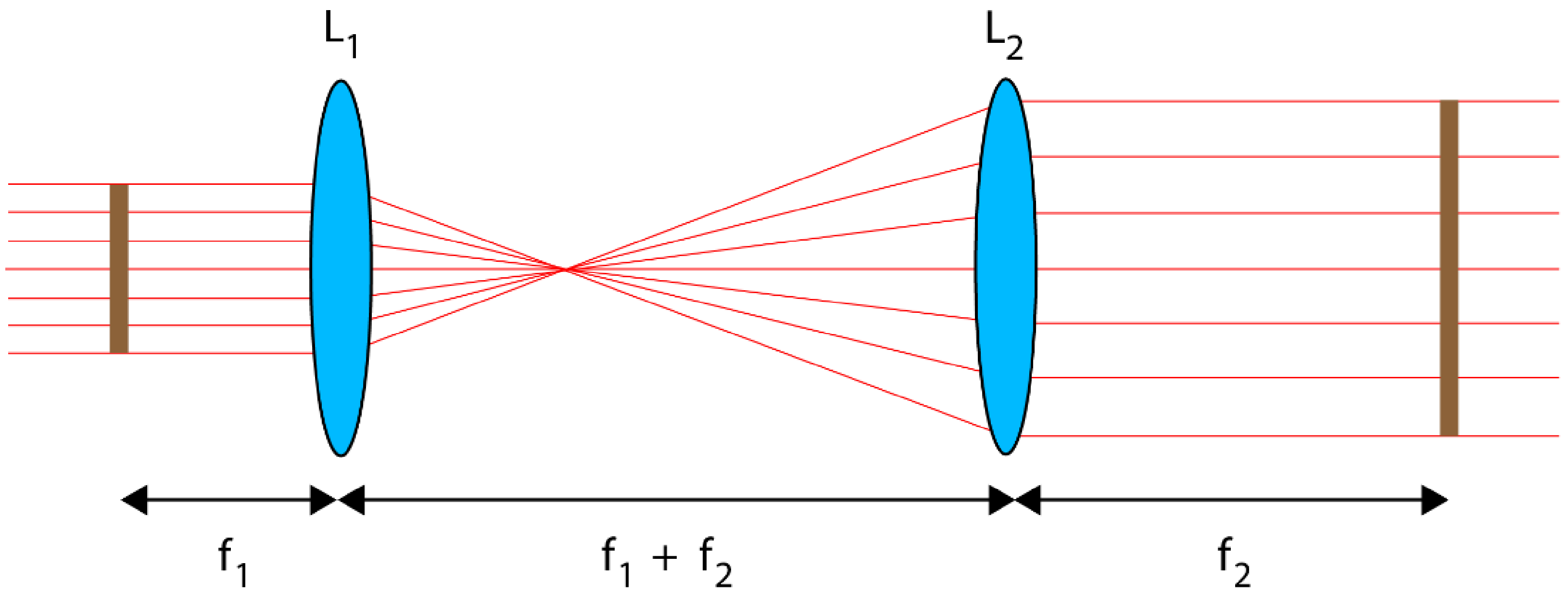
Virtual image ⇨ Positive ⇨ Upright





Magnification

4f system



M = 2

$$M = \frac{f_2}{f_1}$$

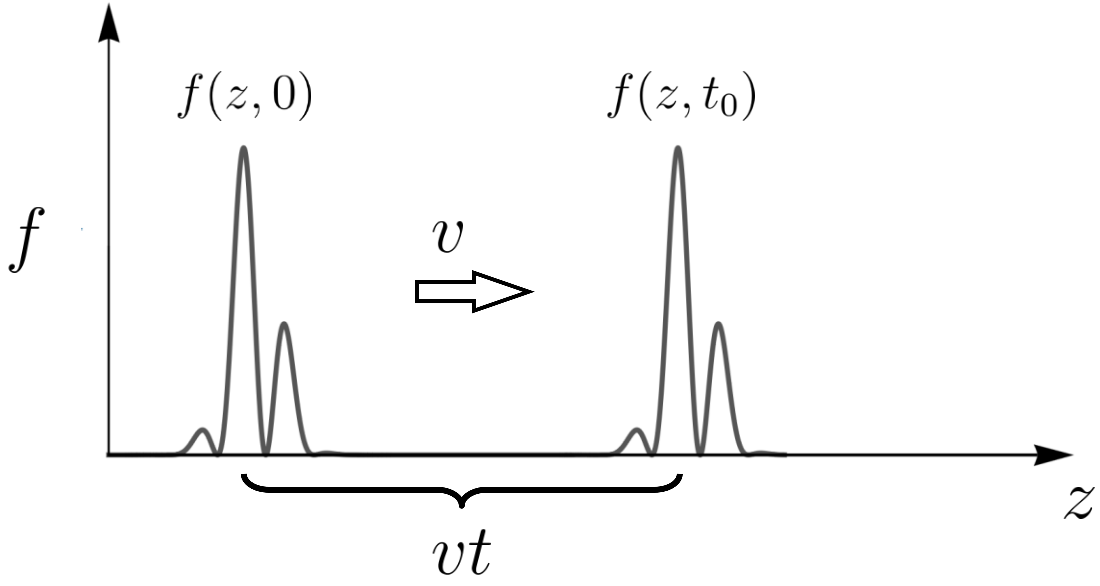
- Big to small ?
- Small to big?

Light as a wave

Wave:

disturbance of a continuous medium that propagates with a fixed shape at constant velocity

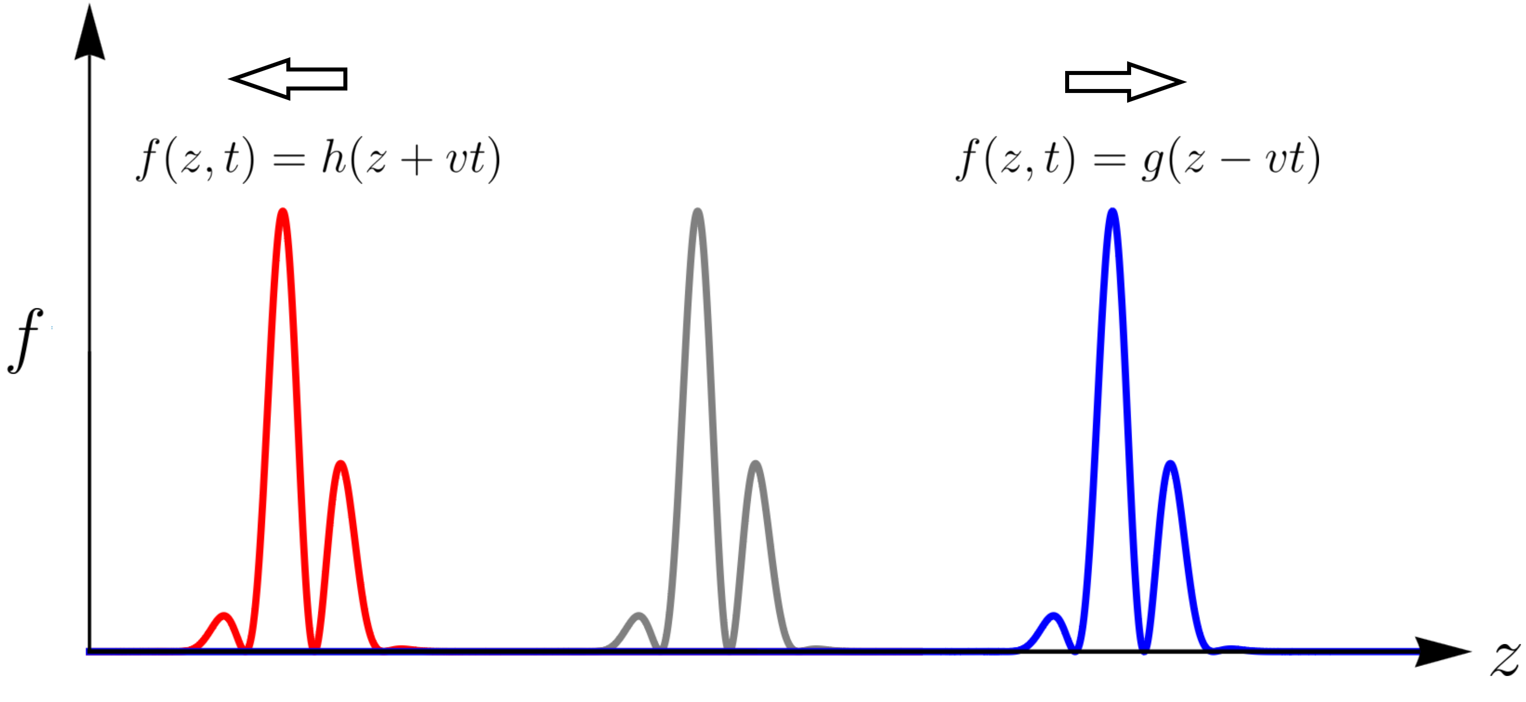
$$f(z,t)$$



$$\frac{\partial^2 f}{\partial z^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2},$$

$$f(z,t)$$

Light as a wave



$$f(z,t) = g(z-vt) + h(z+vt)$$

$$f_3(z,t) = \frac{A}{b(z-vt)^2+1} \qquad f_2(z,t) = A\sin[b(z-vt)] \qquad f_1(z,t) = Ae^{-b(z-vt)^2}$$

Light as a wave

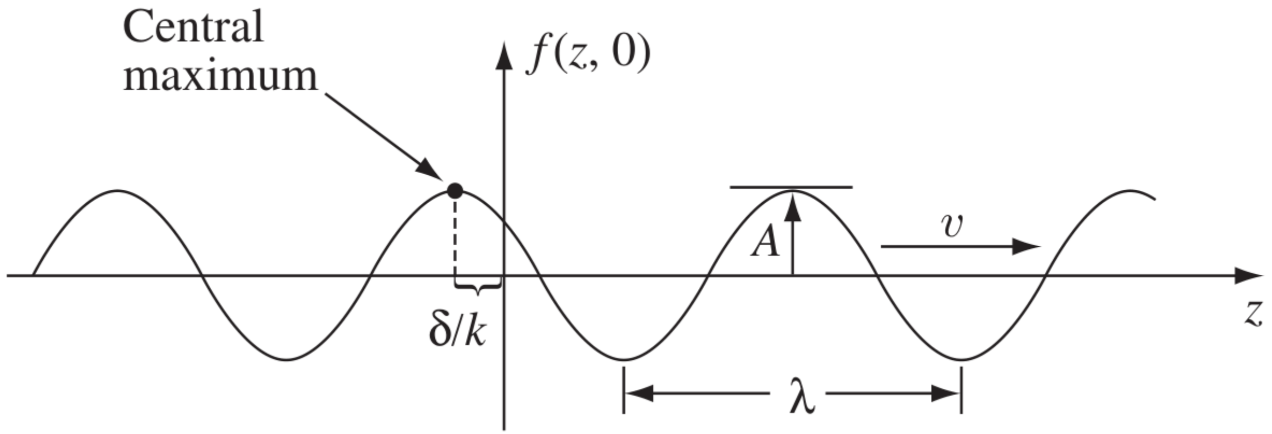
Amplitude

$$f(z,t) = A\cos[\overbrace{k(z - vt) + \delta}^{\text{Phase}}]$$

Wavenumber

$$\lambda = \frac{2\pi}{k}$$

Constant phase



Complex fields for babies

Recalling **Euler's formula**

$$e^{i\theta} = \cos\theta + i\sin\theta \qquad\qquad i^2 = -1$$

We can rewrite the cosine function as

$$f(z,t) = \mathrm{Re}\left[Ae^{i(kz-\omega t+\delta)}\right]$$

Light as a complex field

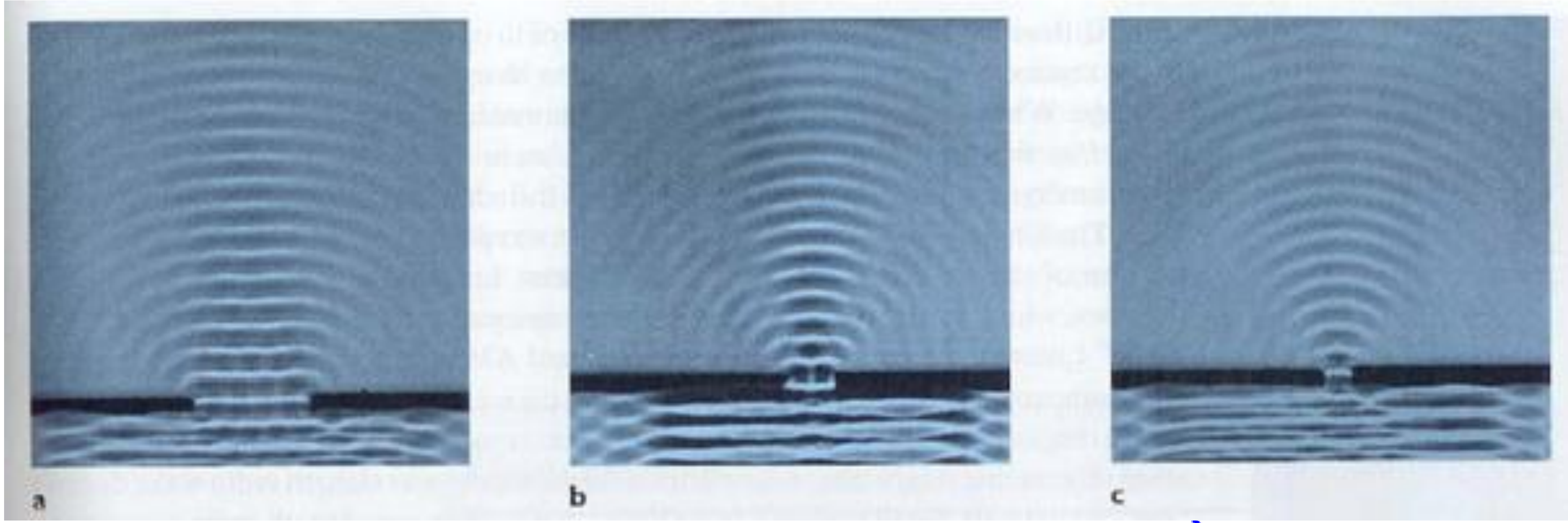
The physical electric field

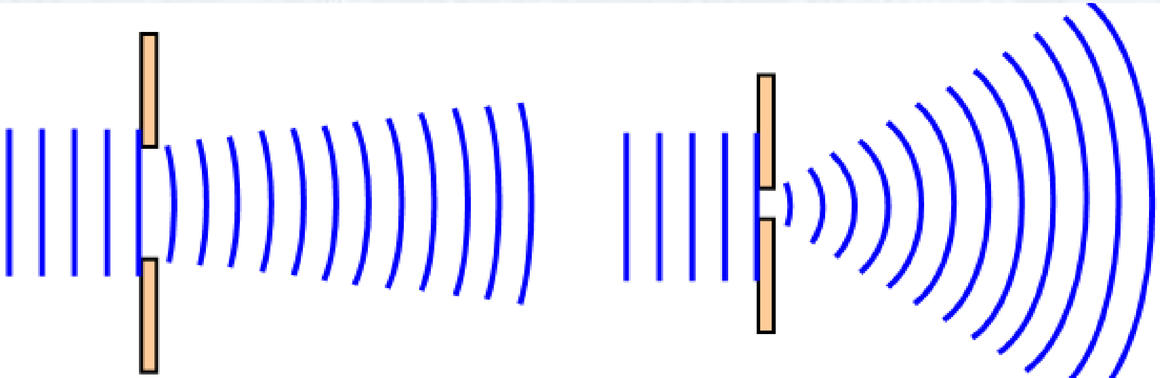
$$\mathbf{E}(\mathbf{r},t) = \mathrm{Re}\left[Ae^{i(kz-wt+\delta)}\right]$$

But complex field, makes it practical

$$\mathbf{E}(\mathbf{r},t) = Ae^{i(kz-wt+\delta)}$$

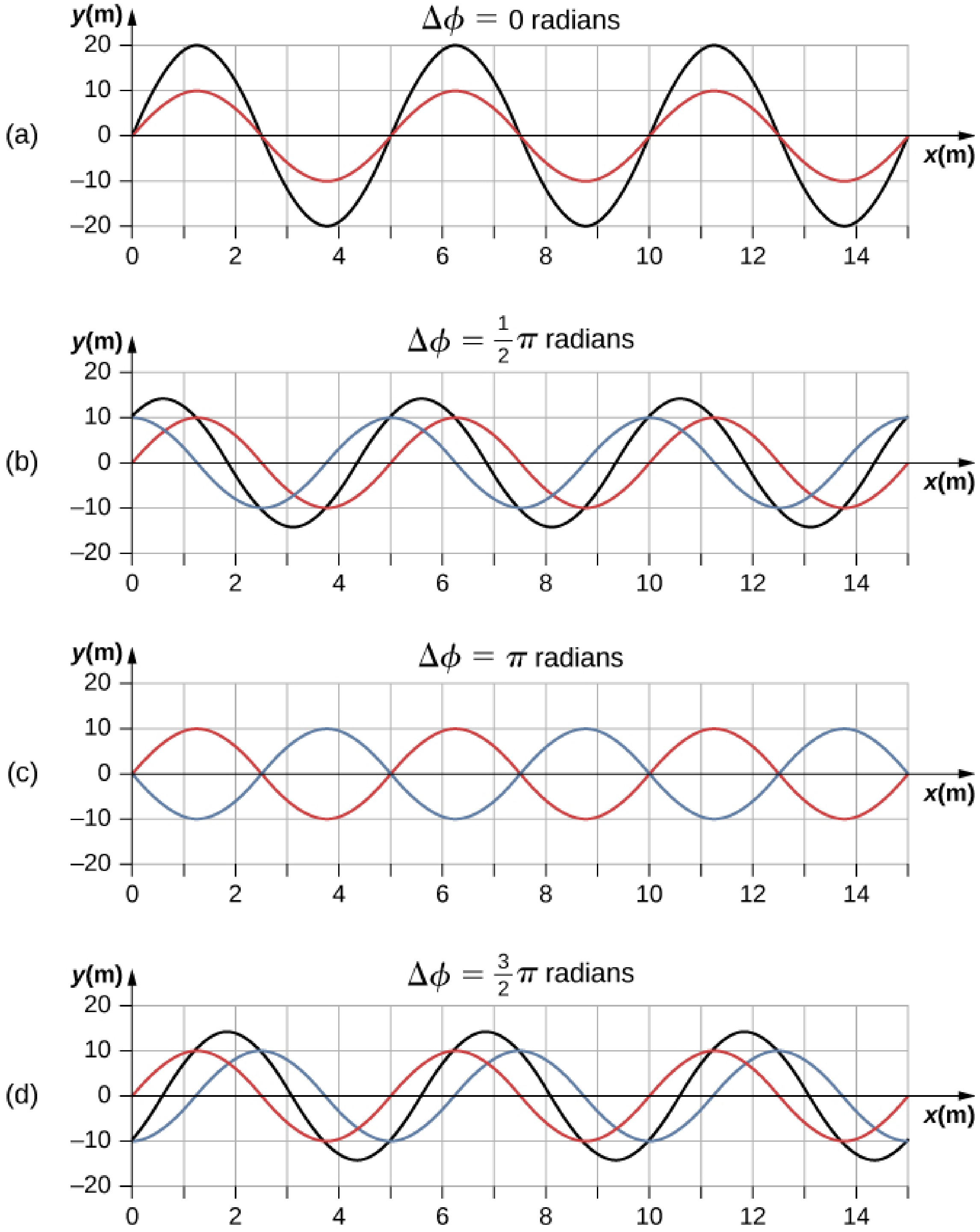
Diffraction





Wide gap – small diffraction effect

Narrow gap – large diffraction effect



Interference

INTERFERENCE OF TWO WAVES

- **Constructive interference**:

  Phase: $\boxed{\Delta\varphi = m2\pi}$ $\boxed{m \in \mathbb{Z}}$

  Optical path: $\boxed{\Delta\delta = m\lambda}$

- **Destructive interference**:

  Phase: $\boxed{\Delta\varphi = \left(m + \frac{1}{2}\right)2\pi}$ $\boxed{m \in \mathbb{Z}}$

  Optical path: $\boxed{\Delta\delta = \left(m + \frac{1}{2}\right)\lambda}$

Wave Equation

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

Wave Equation

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\mathbf{E}(\mathbf{r}, t) = A(\mathbf{r}) e^{i\omega t}\, \hat{\mathbf{e}}$$

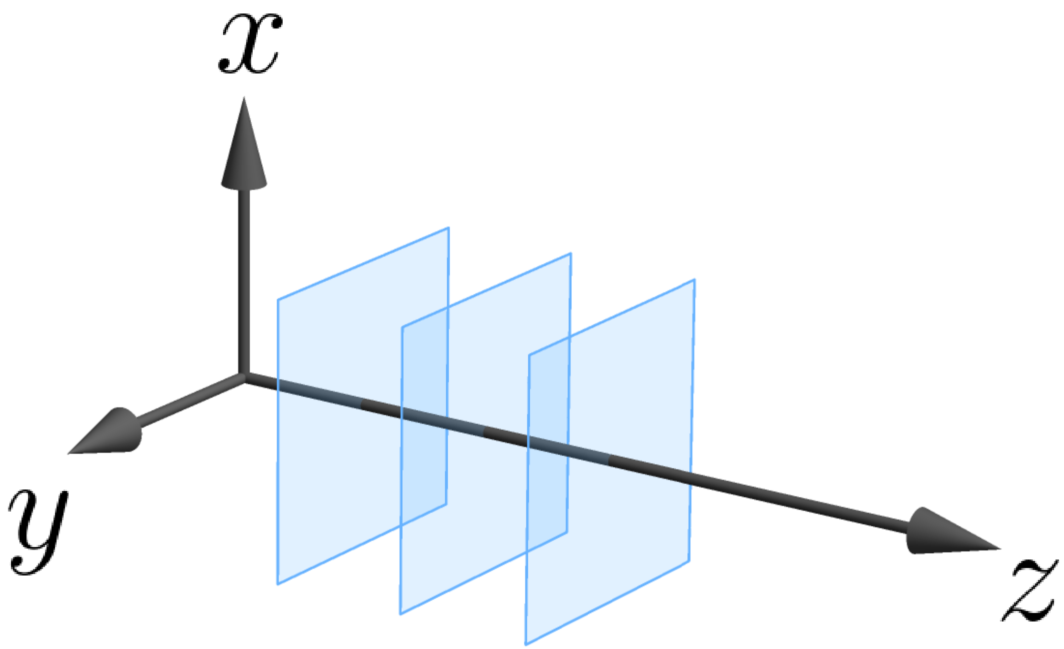
Spatial distribution

Frequency

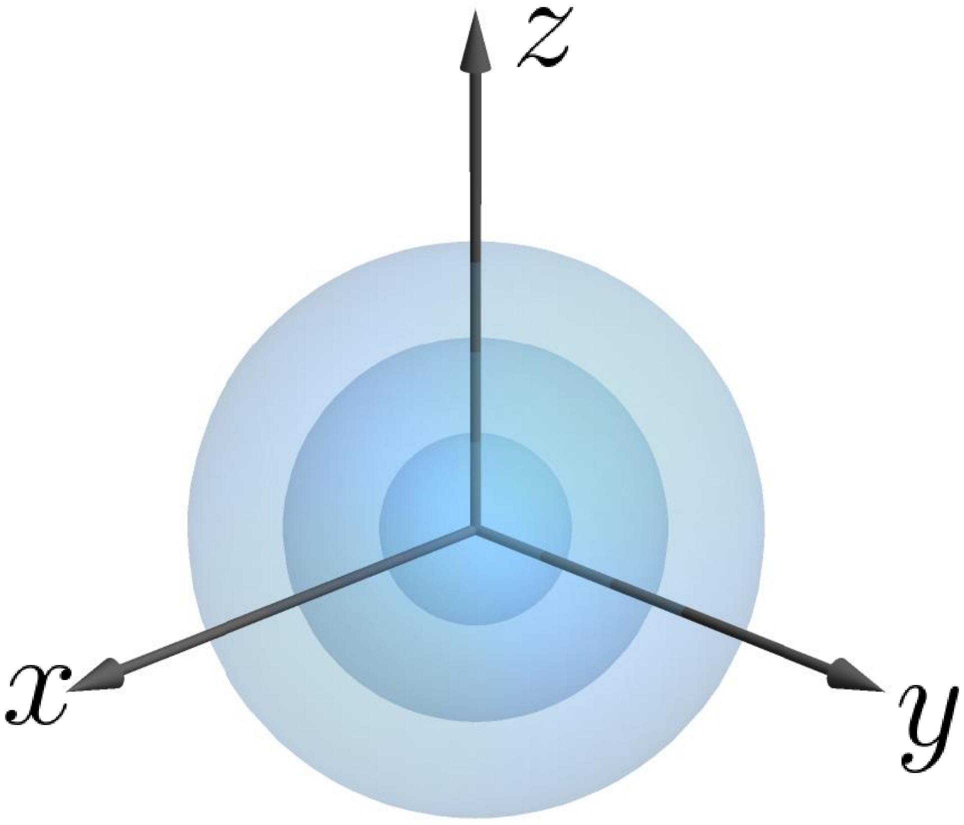
Polarization

Wave Equation

Plane wave

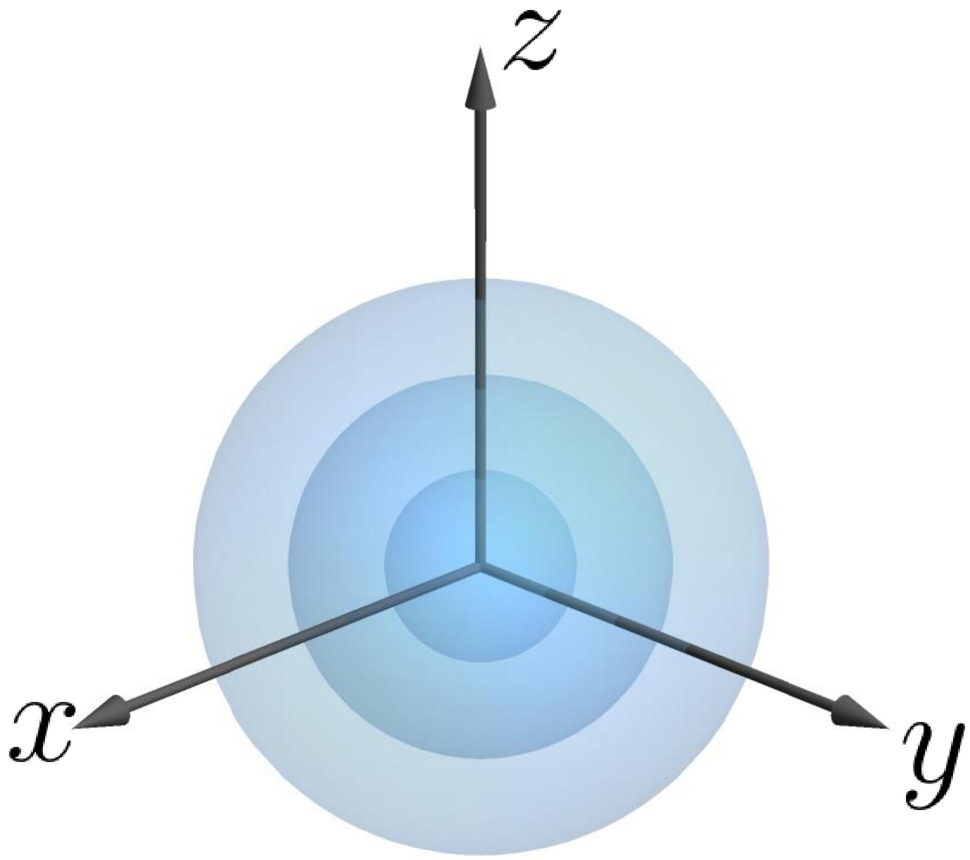


Spherical wave



Are they real tho?

Spherical wave



Gaussian Beams and friends ☺

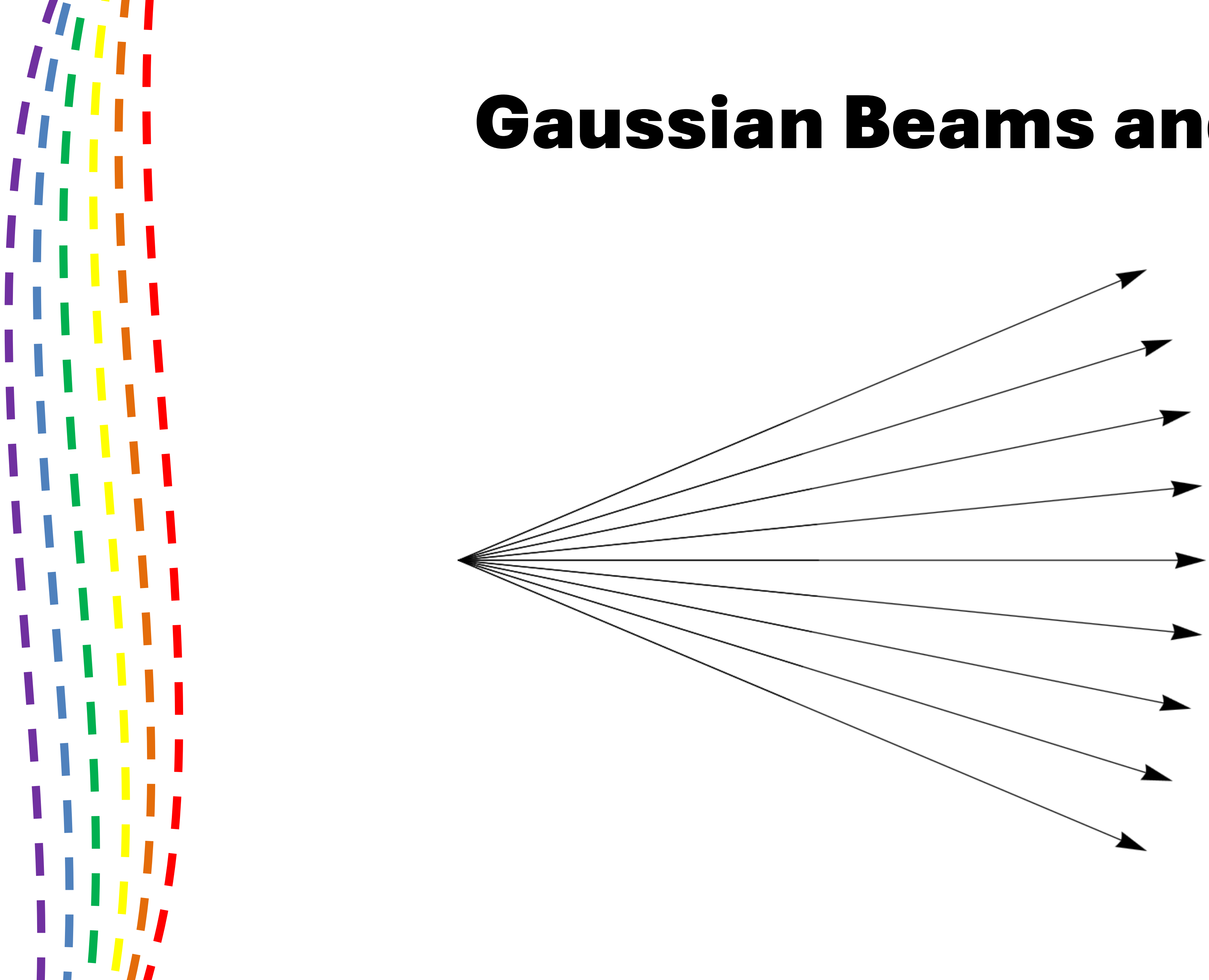
$$\mathbf{E}(\mathbf{r}, t) = A(\mathbf{r})e^{i\omega t}\,\hat{\mathbf{e}}$$

Gaussian Beams and friends ☺

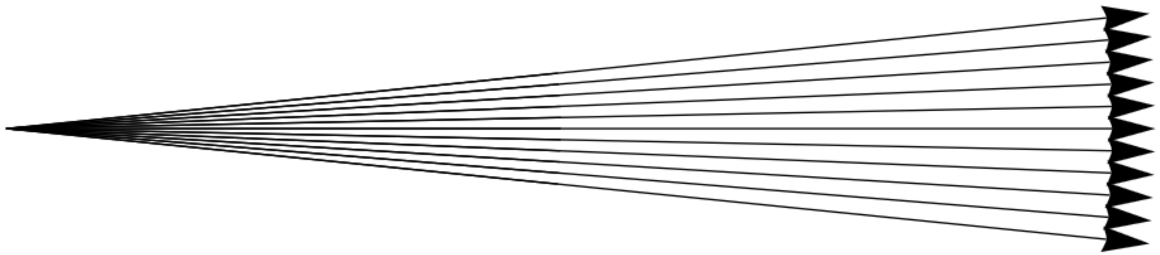
Let's impose more rules on the amplitude $A(\mathbf{r})$

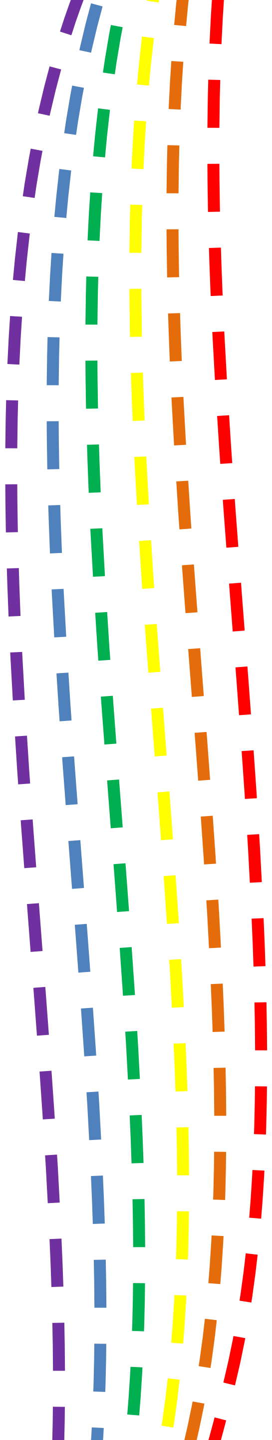
1. Most of the light goes in one direction $\Rightarrow$ z

Gaussian Beams and friends ☺



Gaussian Beams and friends ☺





Gaussian Beams and friends ☺

Gaussian Beams and friends ☺

Let's impose more rules on the amplitude $A(\mathbf{r})$

1. Most of the light goes in one direction $\Rightarrow$ z

$$A(\mathbf{r}) \approx A(\mathbf{r})e^{ikz}$$

Gaussian Beams and friends ☺

Let's impose more rules on the amplitude $A(\mathbf{r})$

1. Most of the light goes in one direction $\Rightarrow$ z

$$A(\mathbf{r}) \approx A(\mathbf{r})e^{ikz}$$

$$\nabla^2 A(\mathbf{r}) + 2ik\frac{\partial A(\mathbf{r})}{\partial z} = 0$$

Gaussian Beams and friends ☺

Let's impose more rules on the amplitude $A(\mathbf{r})$

1. Most of the light goes in one direction $\Rightarrow$ z

2. The complex amplitude varies very slowly

Gaussian Beams and friends ☺

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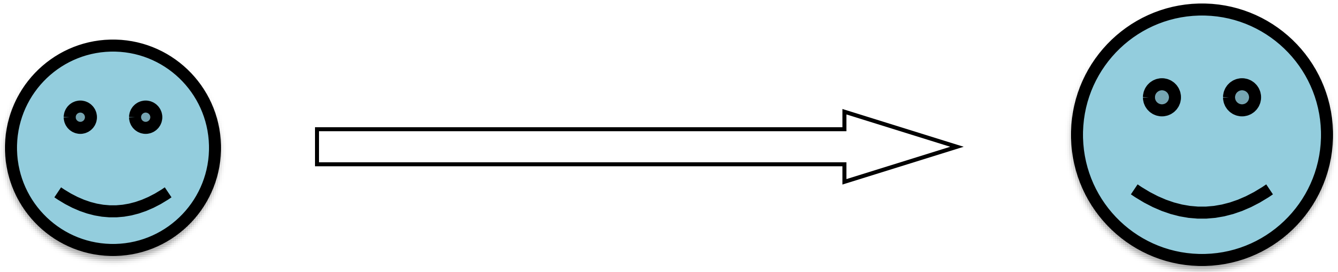


Gaussian Beams and friends ☺

Let's impose more rules on the amplitude

$$A(\mathbf{r})$$

1. Most of the light goes in one direction $\Rightarrow$ z

2. The complex amplitude varies very slowly

$$\nabla_{\perp}^{2} A(\mathbf{r}) + 2ik\frac{\partial A(\mathbf{r})}{\partial z} = 0$$

Gaussian Beams and friends ☺

$$\nabla_\perp^2 A(\mathbf{r}) + 2ik\frac{\partial A(\mathbf{r})}{\partial z} = 0$$

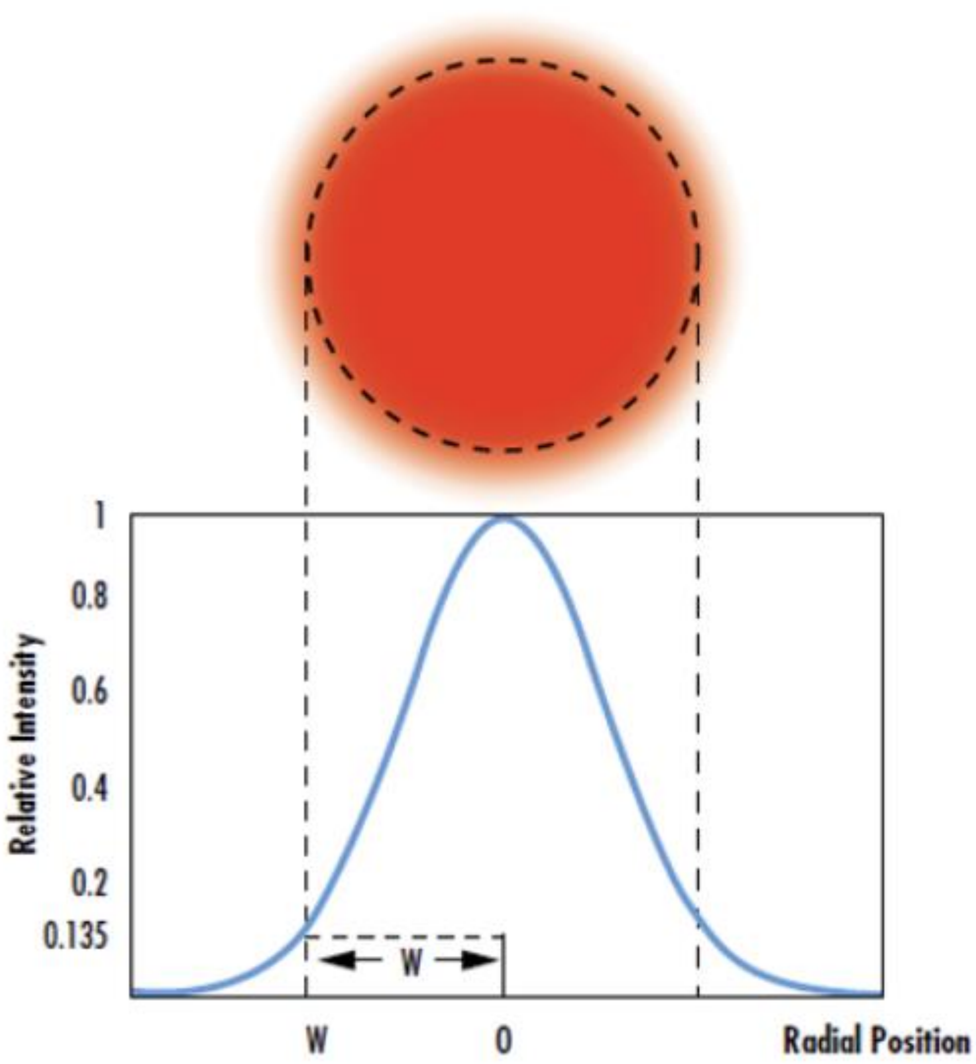
Paraxial wave equation

$$\mathbf{A}(r,z) = A_0 \frac{w_0}{w(z)} \underbrace{\exp\left(\frac{-r^2}{w(z)^2}\right)}_{\text{Envelope}} \exp\left[-i\left(kz + \underbrace{k\frac{r^2}{2R(z)}}_{\text{Deformation}} - \overbrace{\psi(z)}^{\text{Gouy Phase}}\right)\right]$$

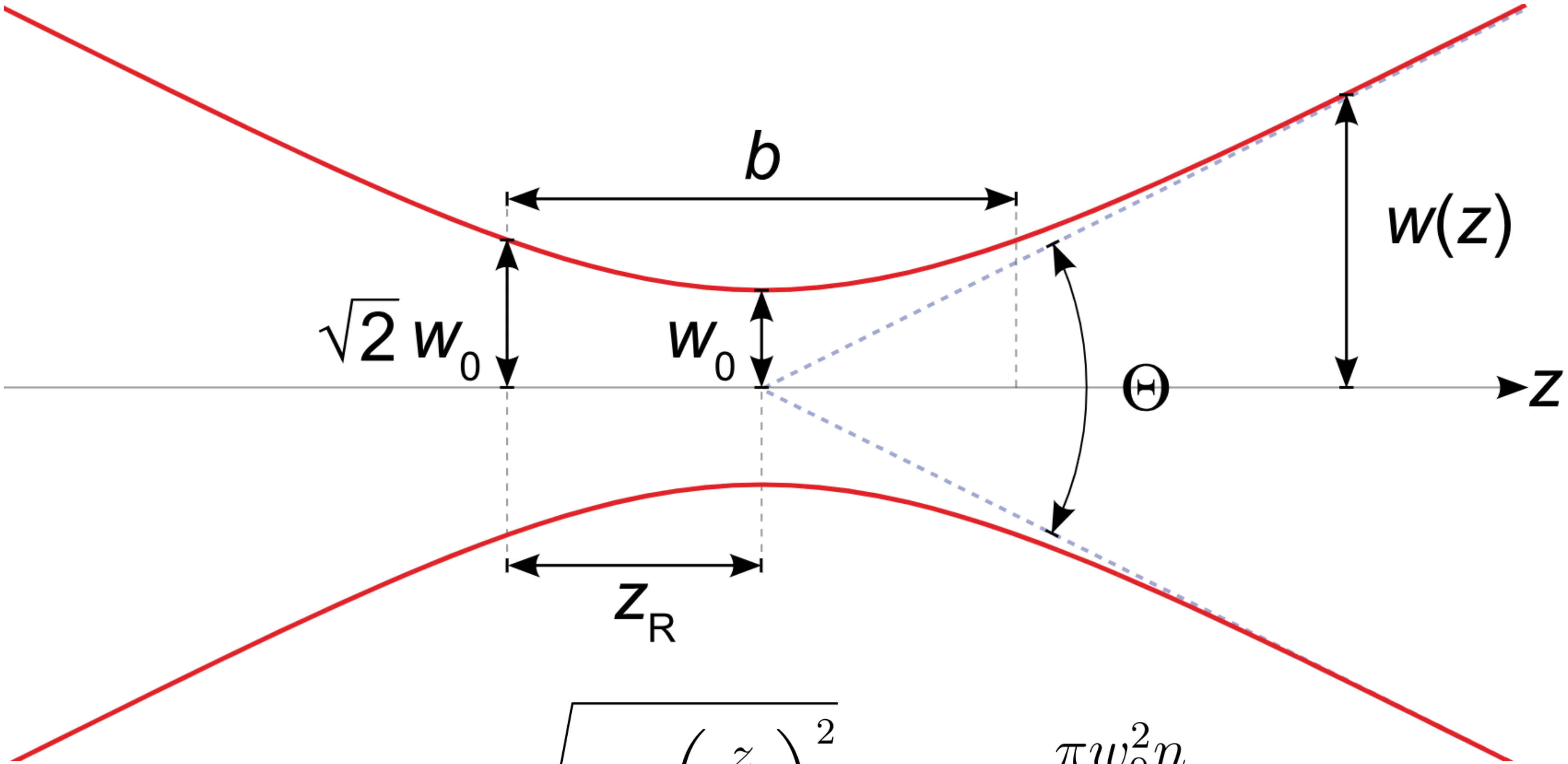
Fundamental Gaussian Beam

$$\overbrace{\exp\left(\frac{-r^2}{w(z)^2}\right)}^{\text{Gaussian envelope}}$$

$$w(z) = w_0\sqrt{1 + \left(\frac{z}{z_\mathrm{R}}\right)^2}$$

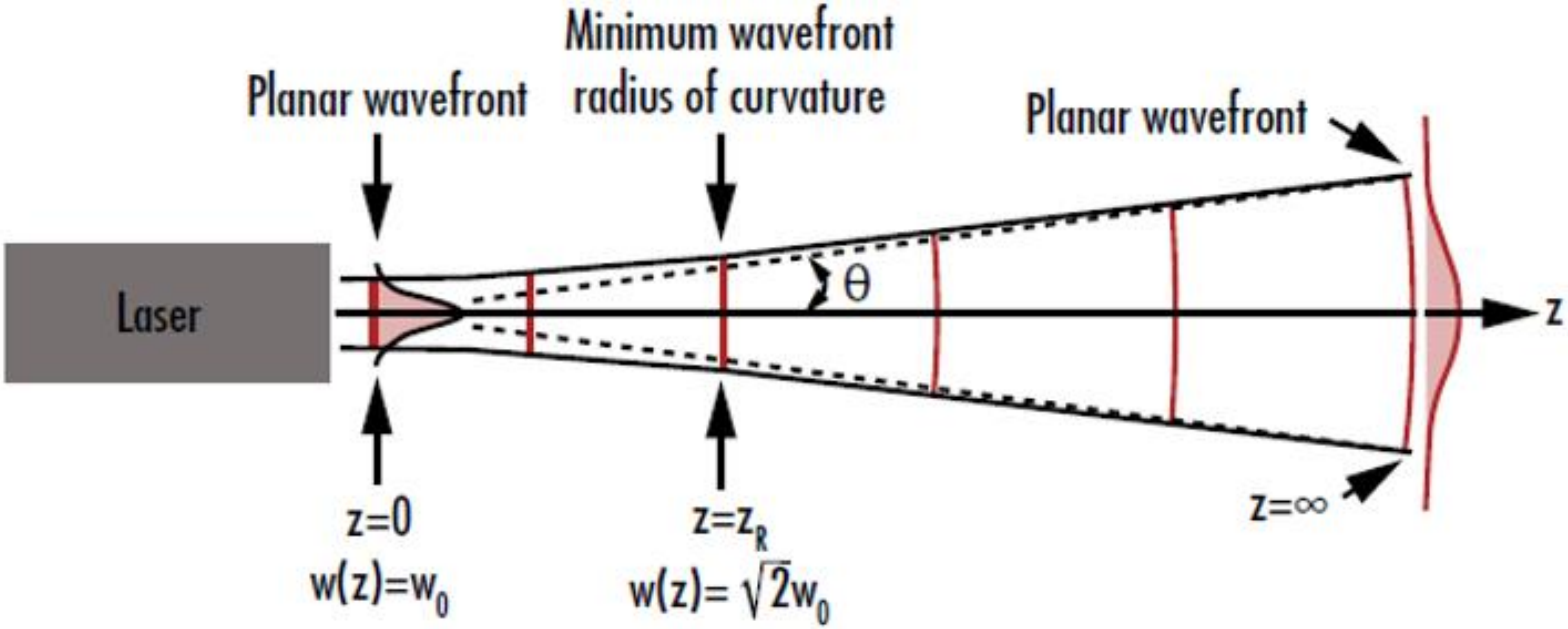


Fundamental Gaussian Beam



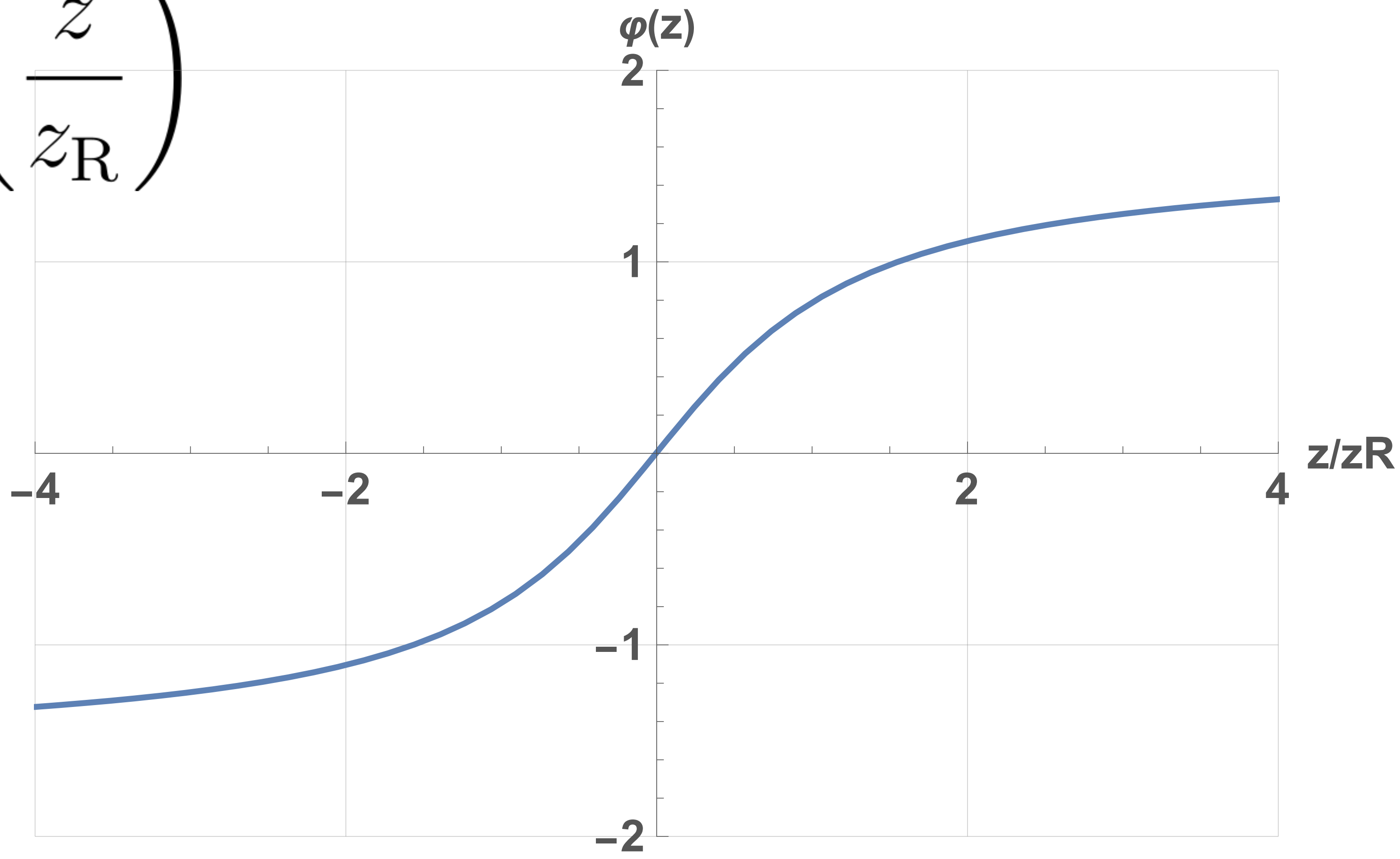
$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_\mathrm{R}}\right)^2} \qquad z_\mathrm{R} = \frac{\pi w_0^2 n}{\lambda}$$

Fundamental Gaussian Beam



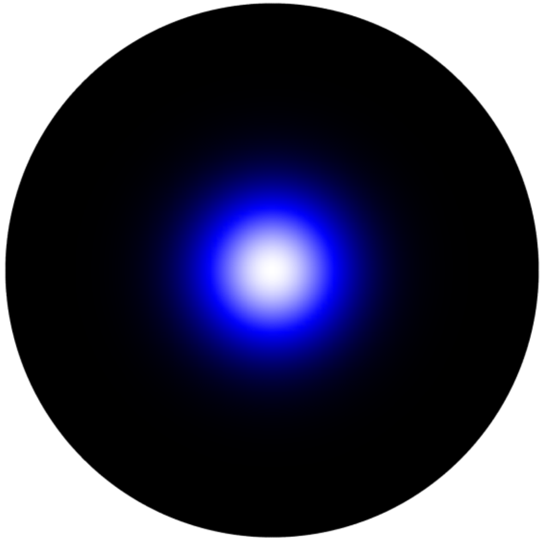
Fundamental Gaussian Beam

$$\psi(z) = \arctan\left(\frac{z}{z_{\mathrm{R}}}\right)$$



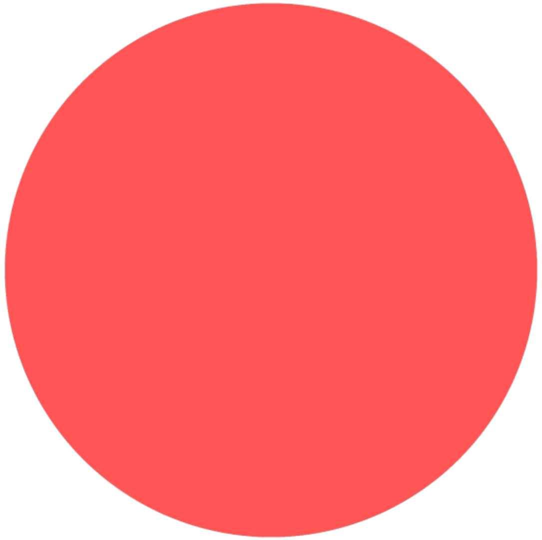
Fundamental Gaussian Beam

Intensity



$$|A(\mathbf{r})|^2$$

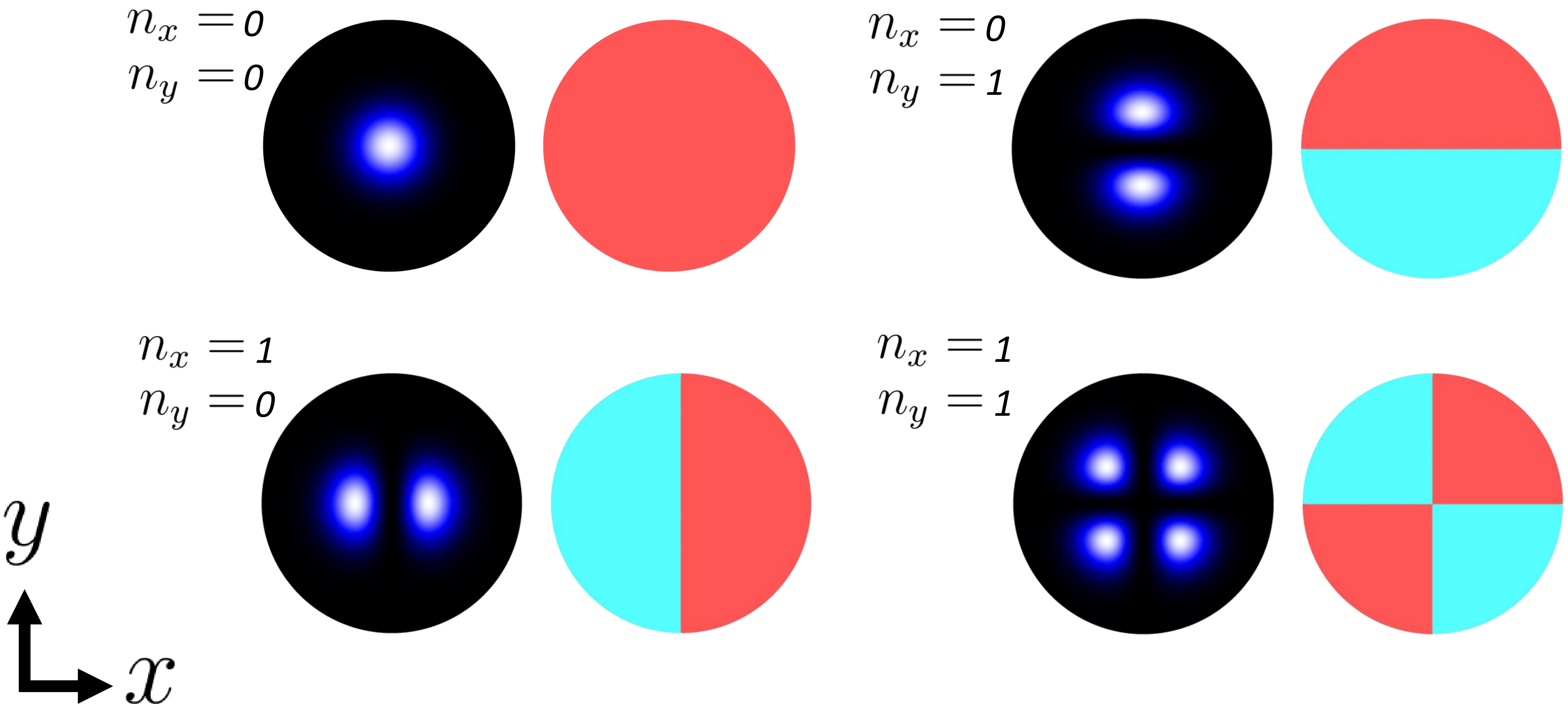
Phase



$$\mathrm{Arg}\left[A(\mathbf{r})\right]$$

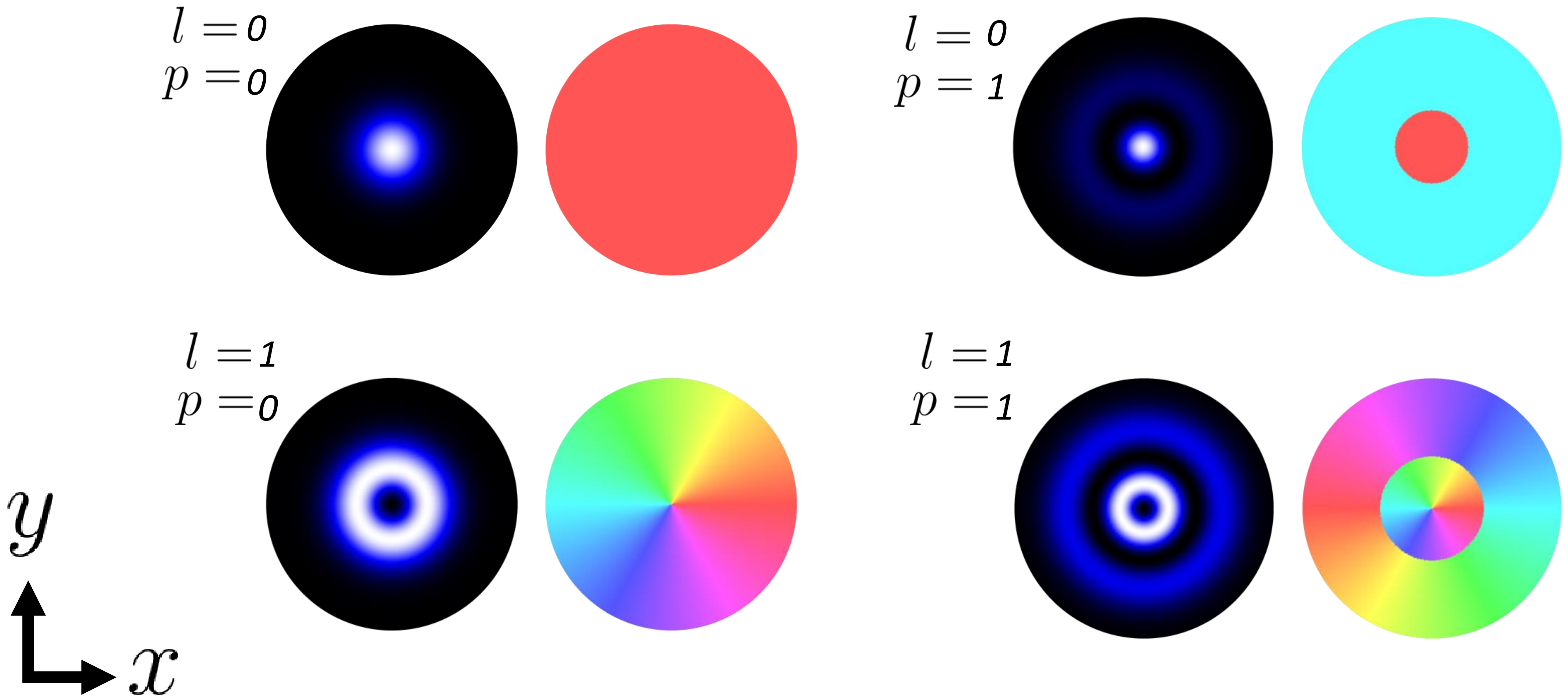
Can you take me HIGHER!!!!

Cartesian Coordinates – Hermite Gaussian beams



Can you take me HIGHER!!!!

Cylindrical Coordinates – Laguerre Gaussian beams



Vector nature of light - Polarization

$$\mathbf{E}(\mathbf{r}, t) = A(\mathbf{r})e^{i\omega t}\,\hat{\mathbf{e}}$$

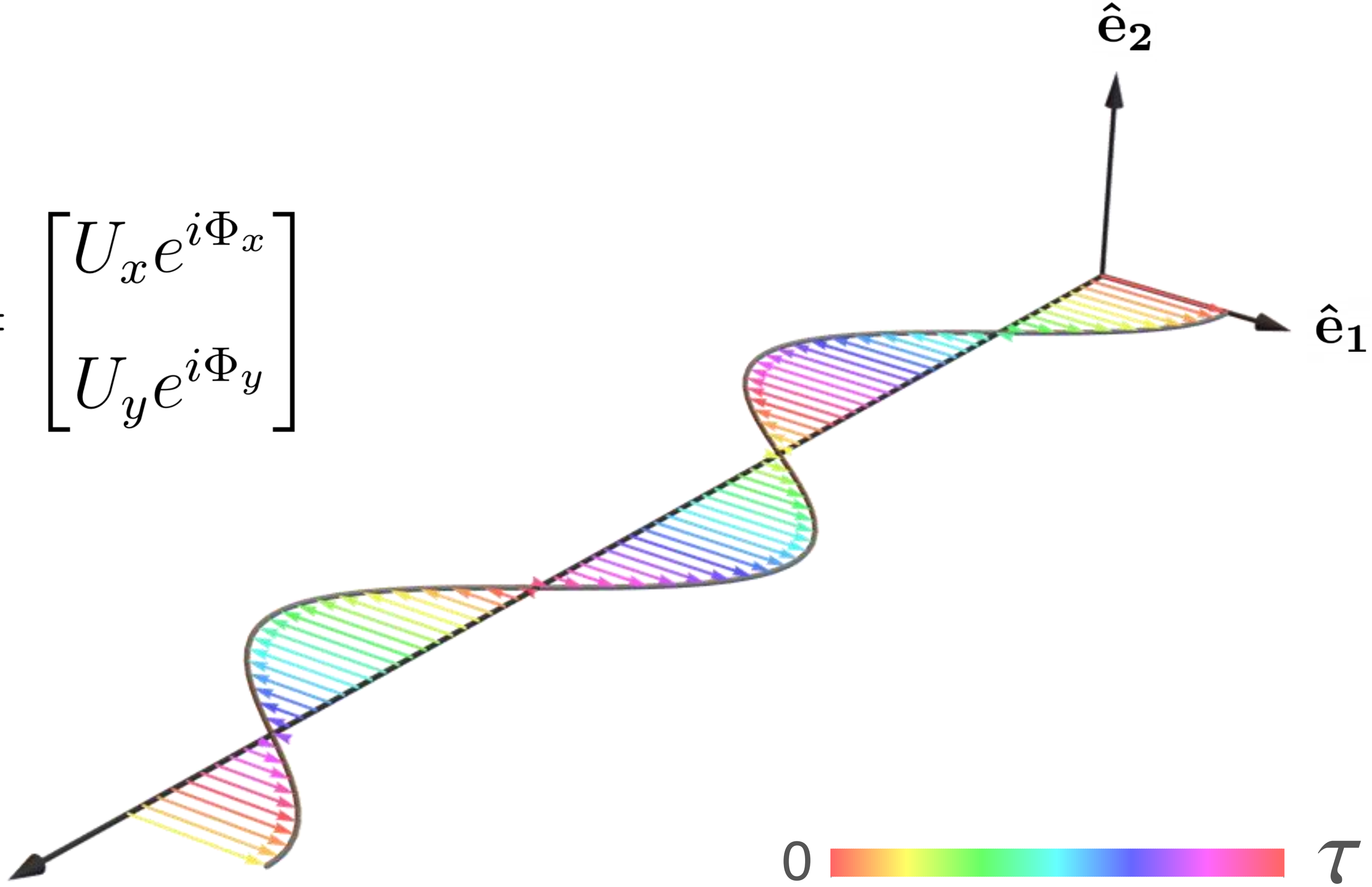
Spatial distribution

Frequency

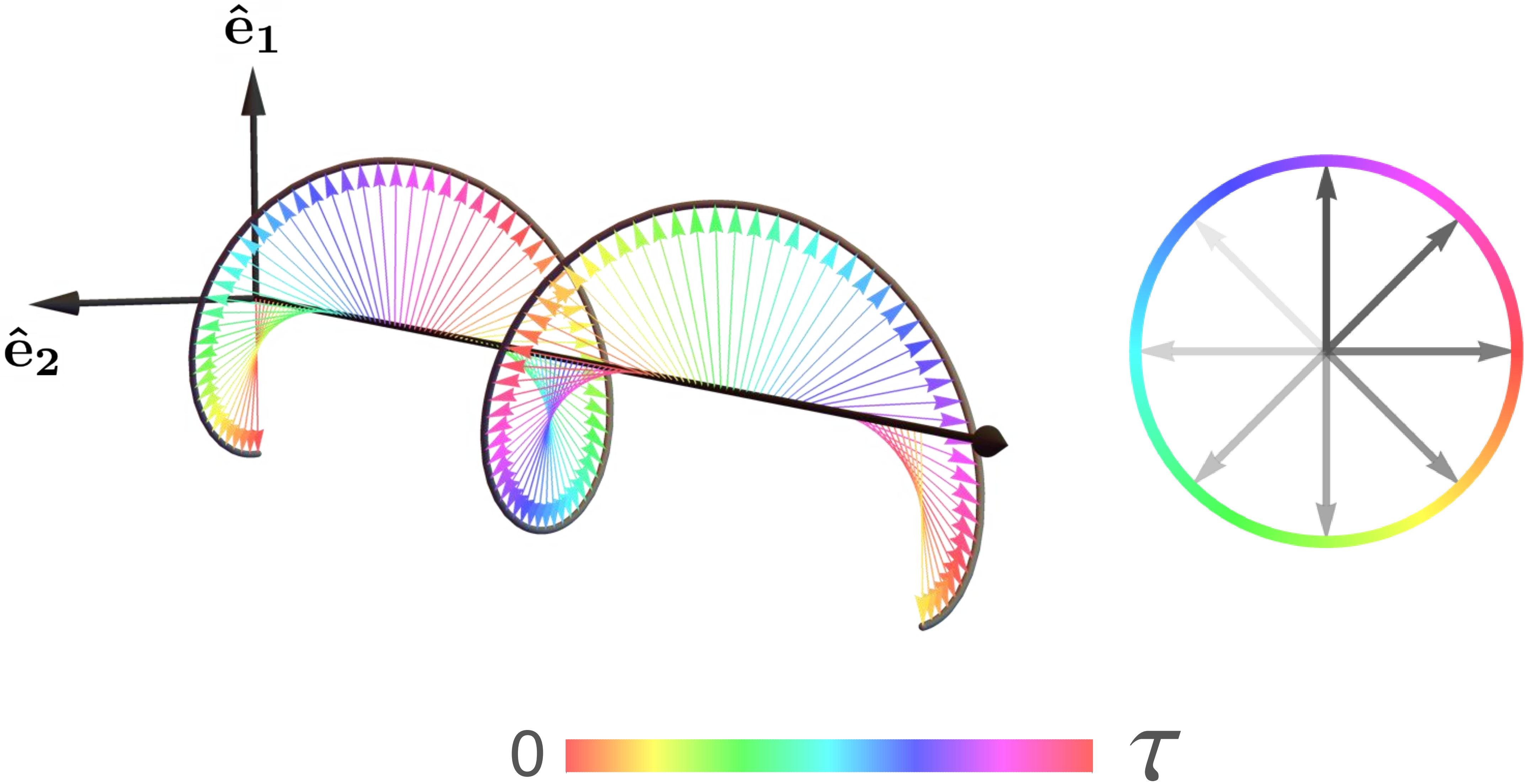
Polarization

Vector nature of light - Polarization

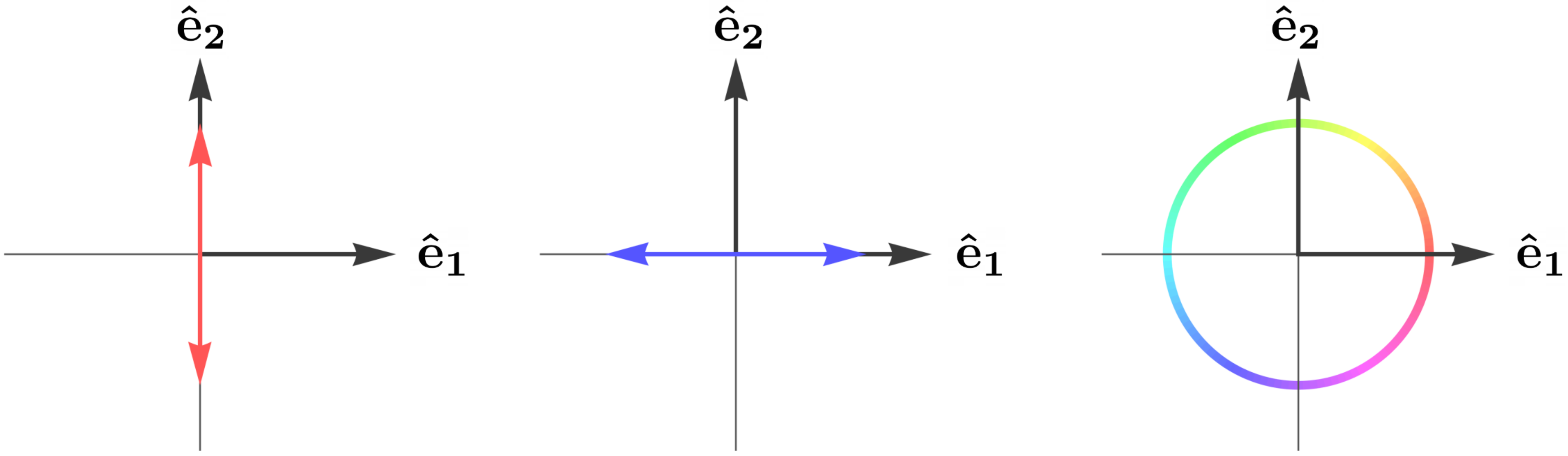
$$\mathbf{E}(\mathbf{r}) = \begin{bmatrix} U_x e^{i\Phi_x} \\ U_y e^{i\Phi_y} \end{bmatrix}$$



Vector nature of light - Polarization



Polarization ellipse



Linear

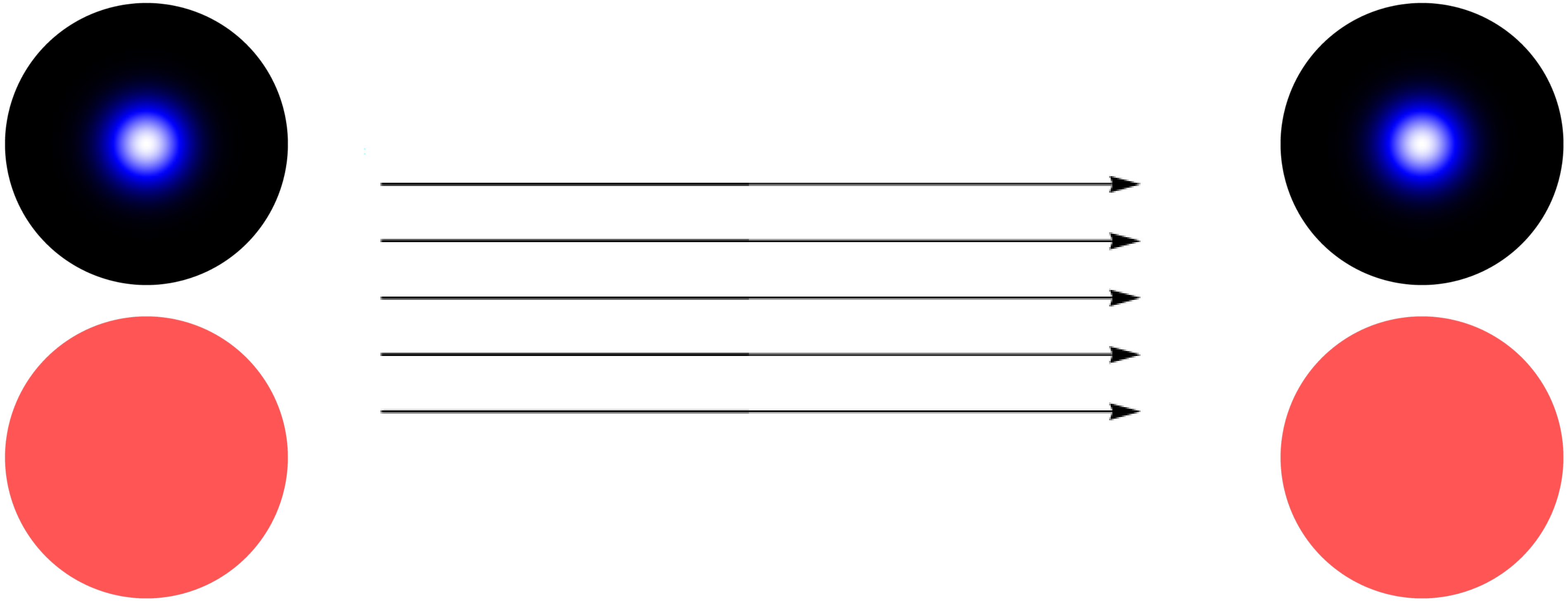
Circular

Tips for the Laboratory

by Manuel Ferrer

Glossary

Collimated light



Collimated light consists of light rays that are nearly parallel to each other, resulting in minimal divergence or convergence as the light propagates. Essentially, collimated light maintains a constant beam diameter over a long distance.

Beam divergence angle

$$\theta = \frac{\lambda}{\pi w_0}$$

Glossary

Aperture

Refers to an opening or hole through which light can pass in an optical system.

Glossary

Optical fiber

Modes?

Multi Mode

Single Mode

Polarization – maintaining

Conectors?

SMA

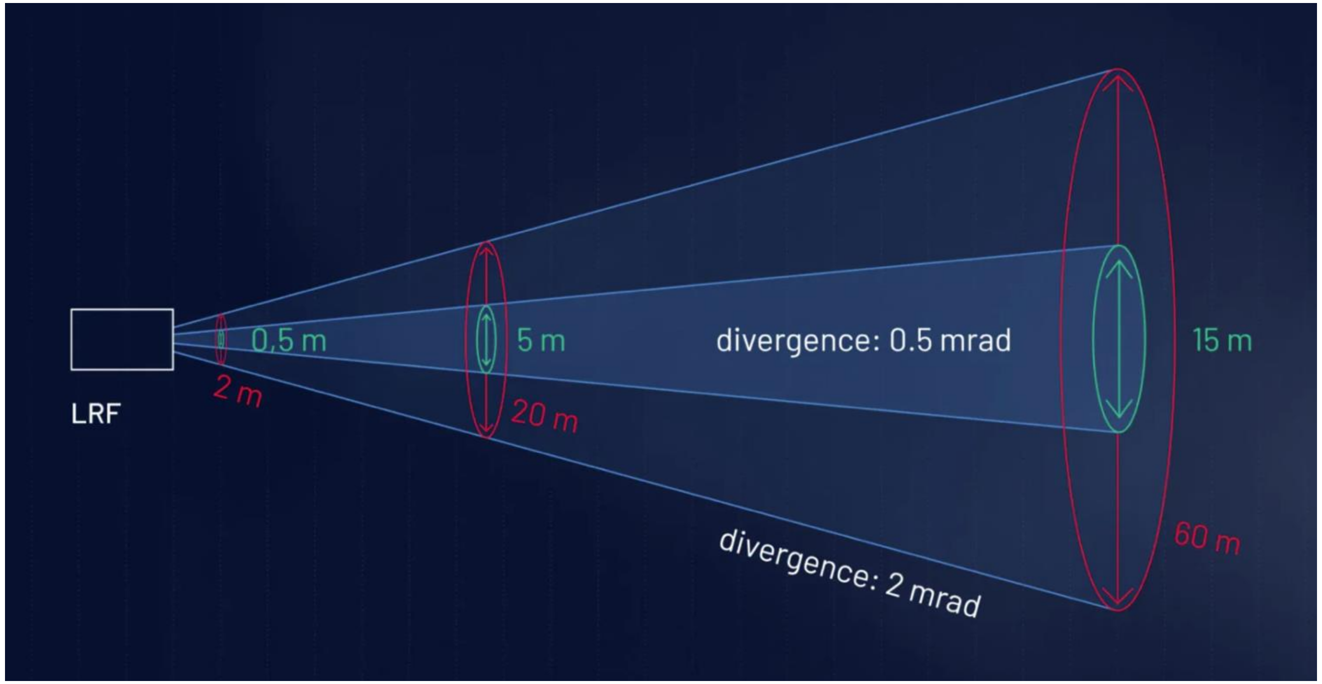
FC/PC

FC/APC

Glossary

Beam Divergence

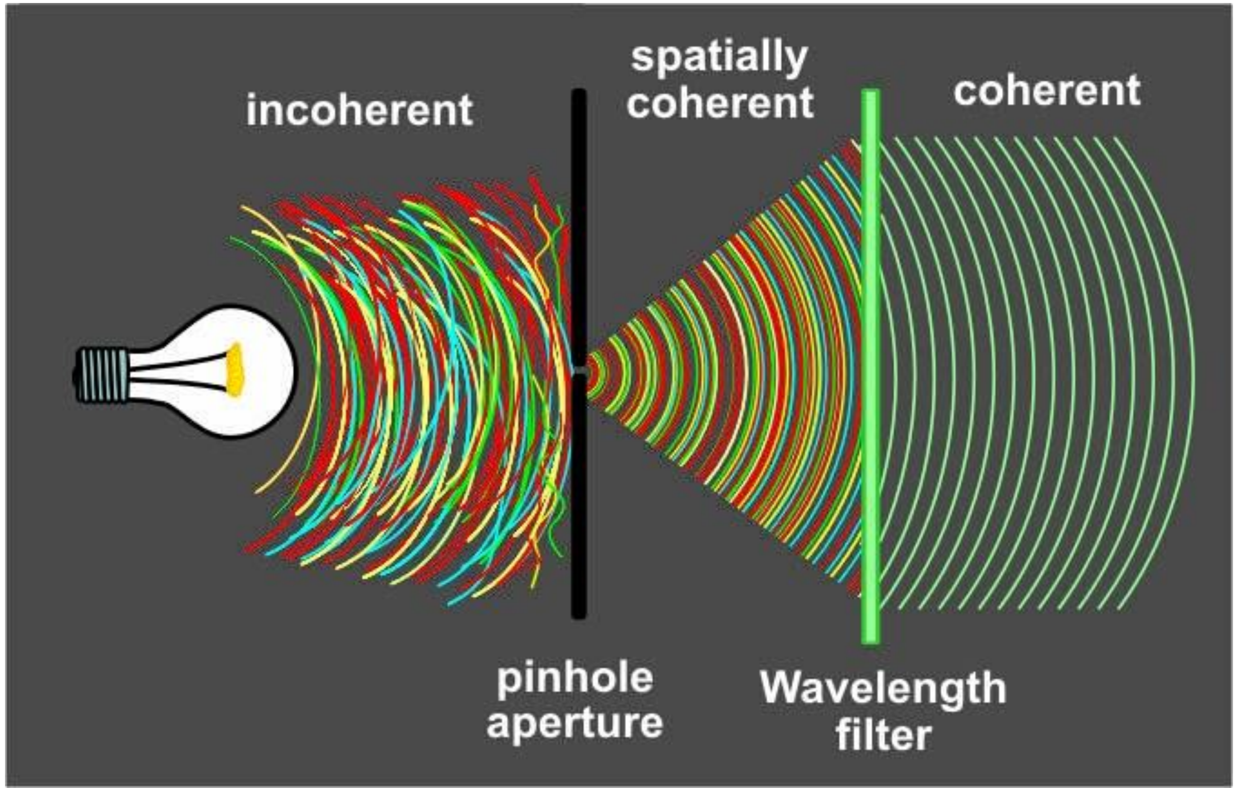
The gradual spreading of a light beam over a distance.
It is usually measured in degrees or milliradians.



Glossary

Coherent light

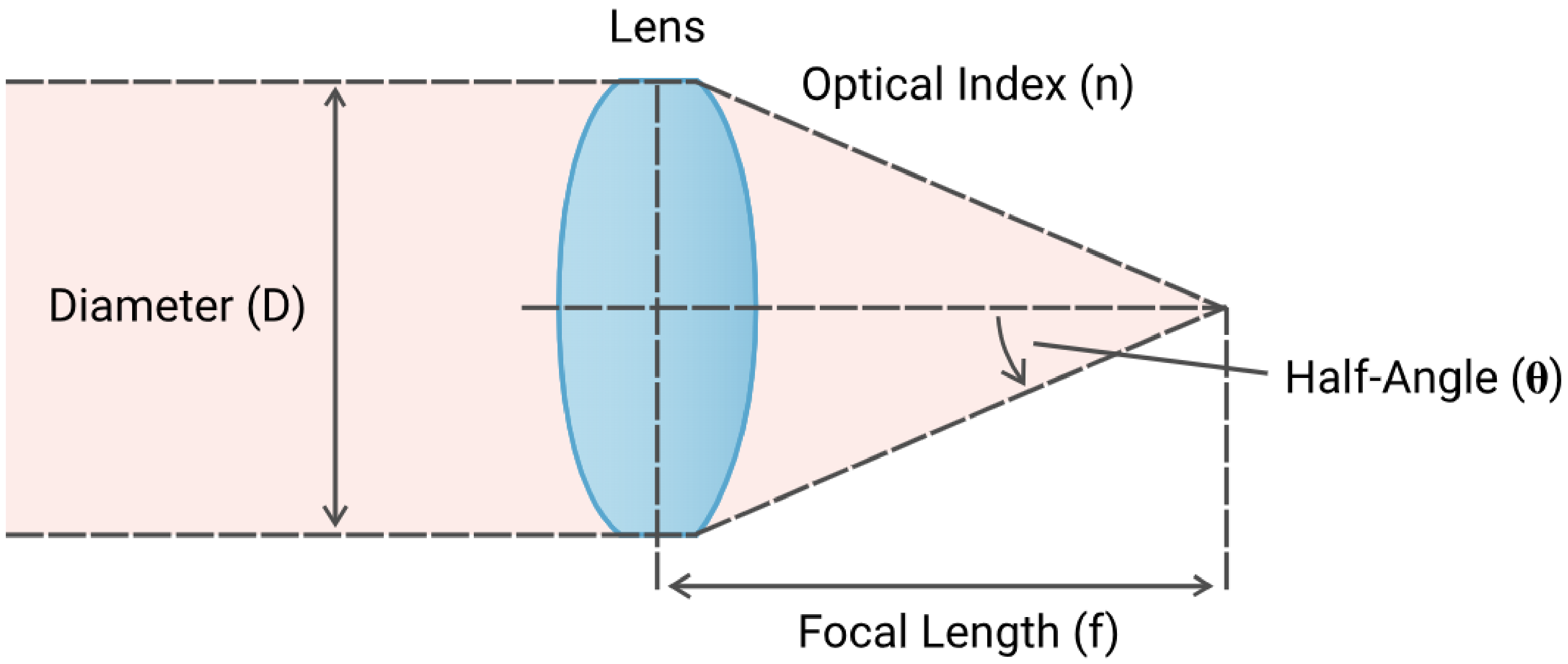
Light waves that maintain a fixed phase relationship, typically produced by lasers.



Glossary

Numerical Aperture (NA)

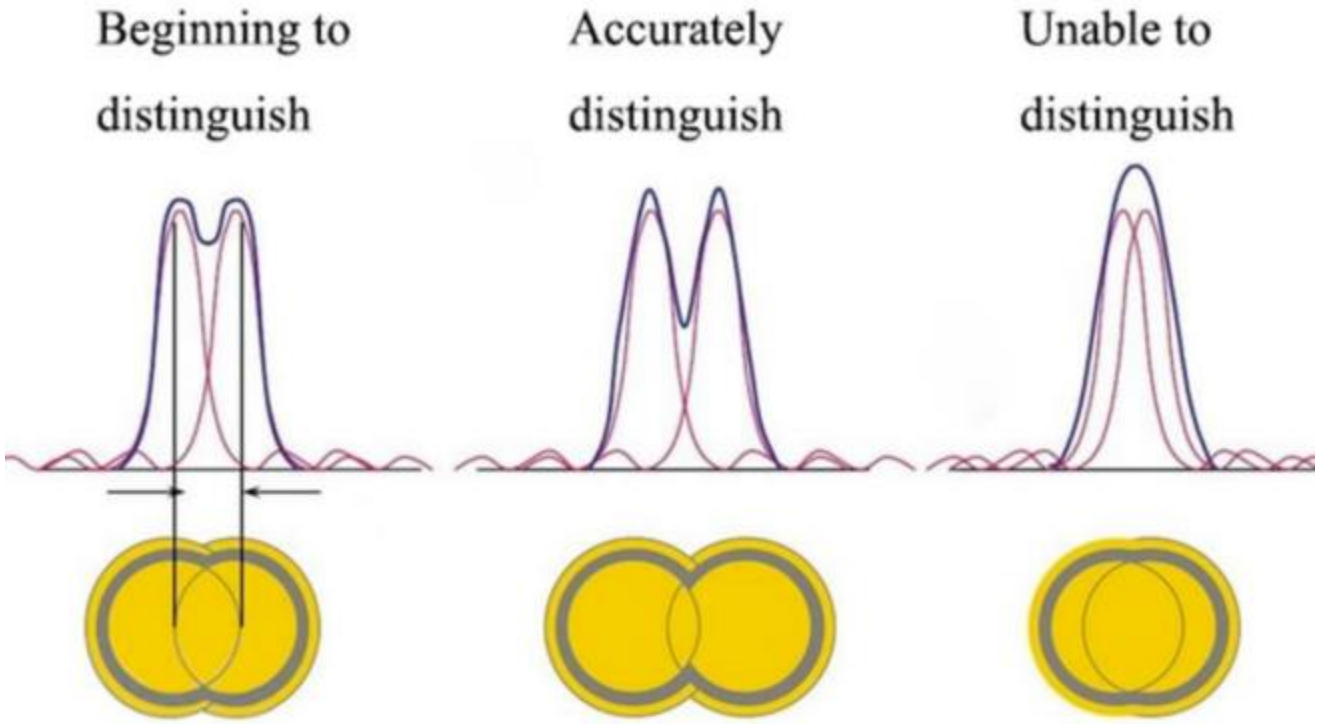
A measure of the light-gathering ability of an optical system, defined as NA = n sin(θ).



Glossary

Resolution

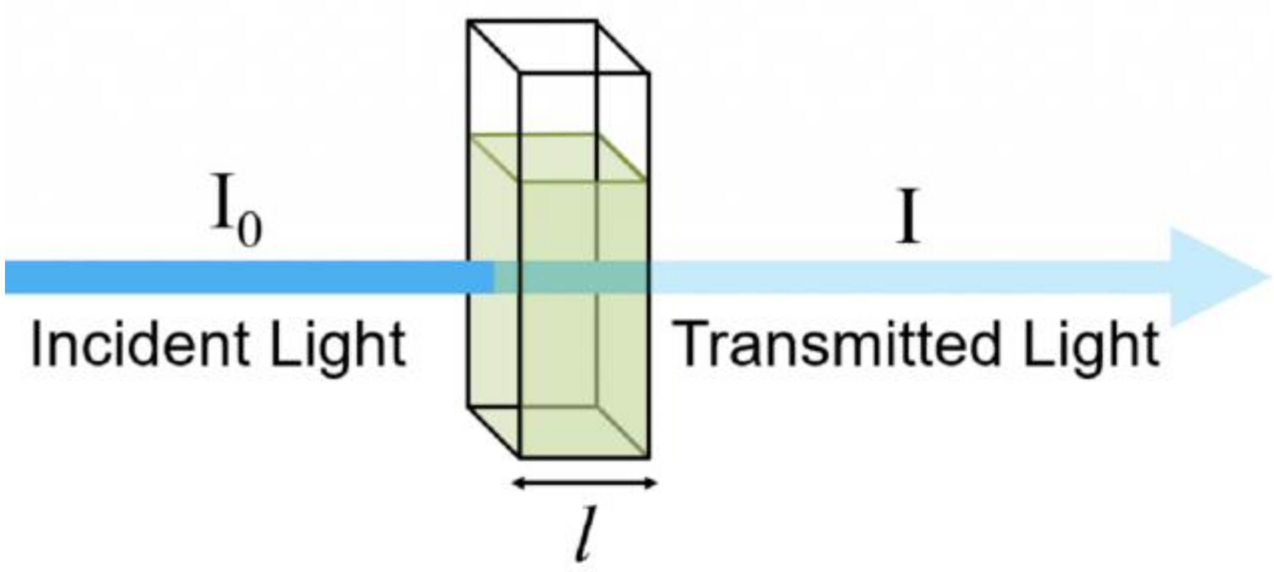
The ability of an optical system to distinguish two closely spaced points as separate.



Glossary

Transmittance

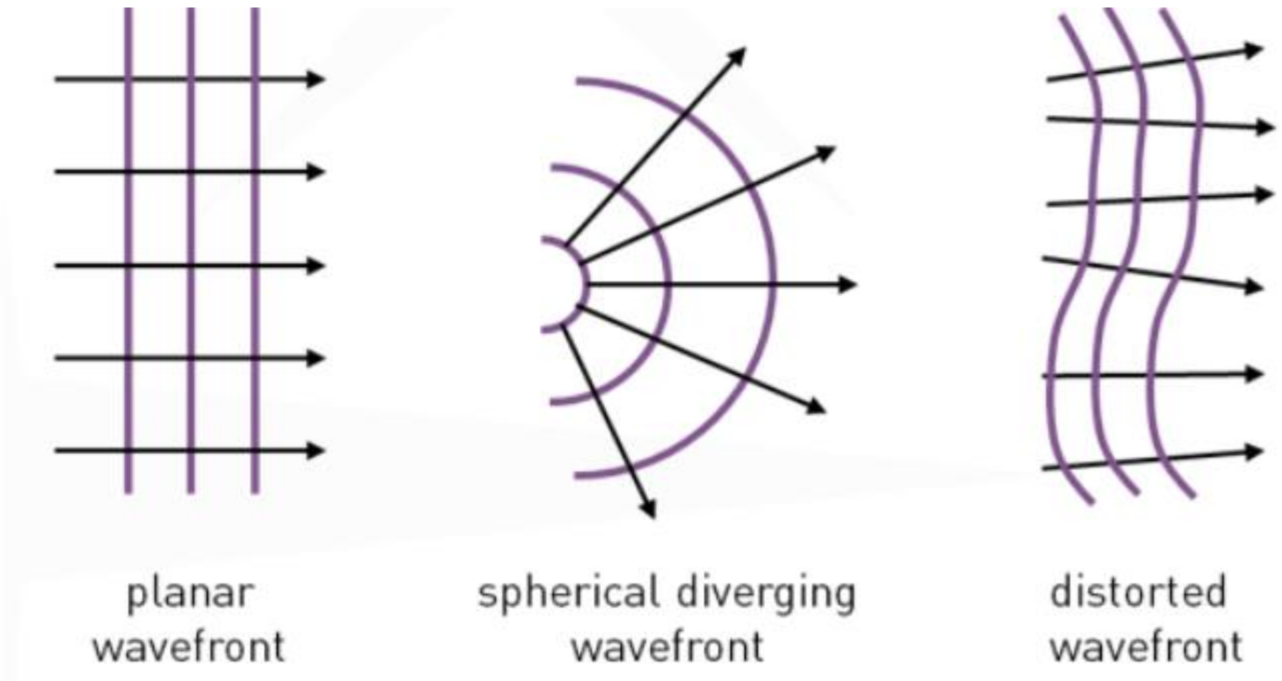
The fraction of incident light that passes through a sample or optical element.



Glossary

Wavefront

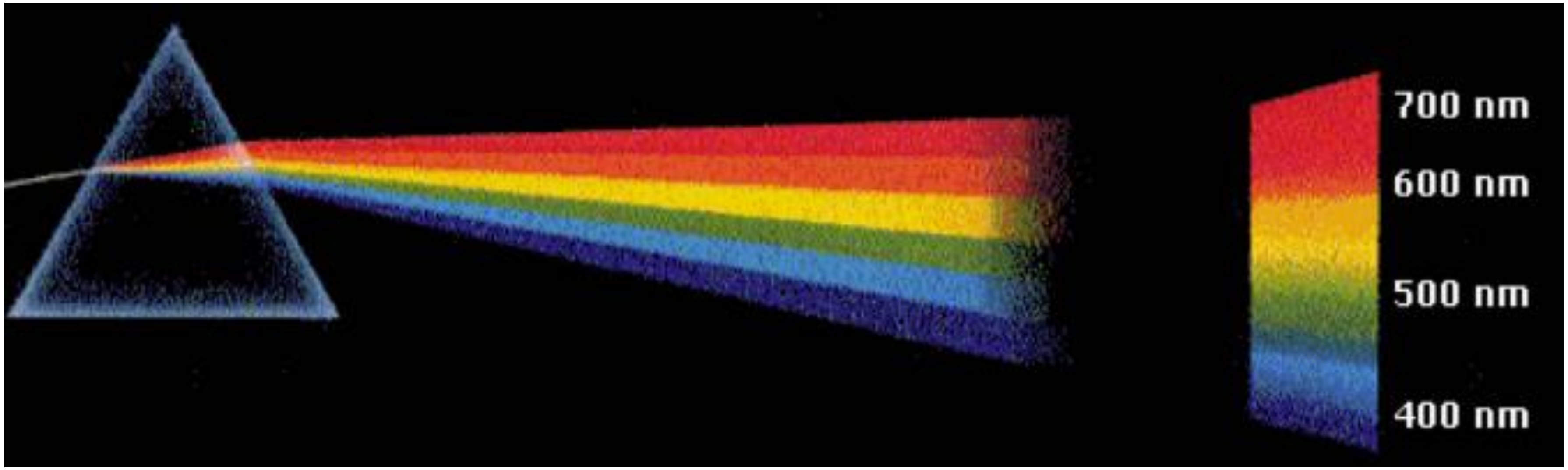
A surface over which the phase of light waves is constant, representing the propagation of light.



Glossary

Dispersion

The phenomenon in which the phase velocity of a wave depends on its frequency, leading to separation of colors in a prism.



Glossary

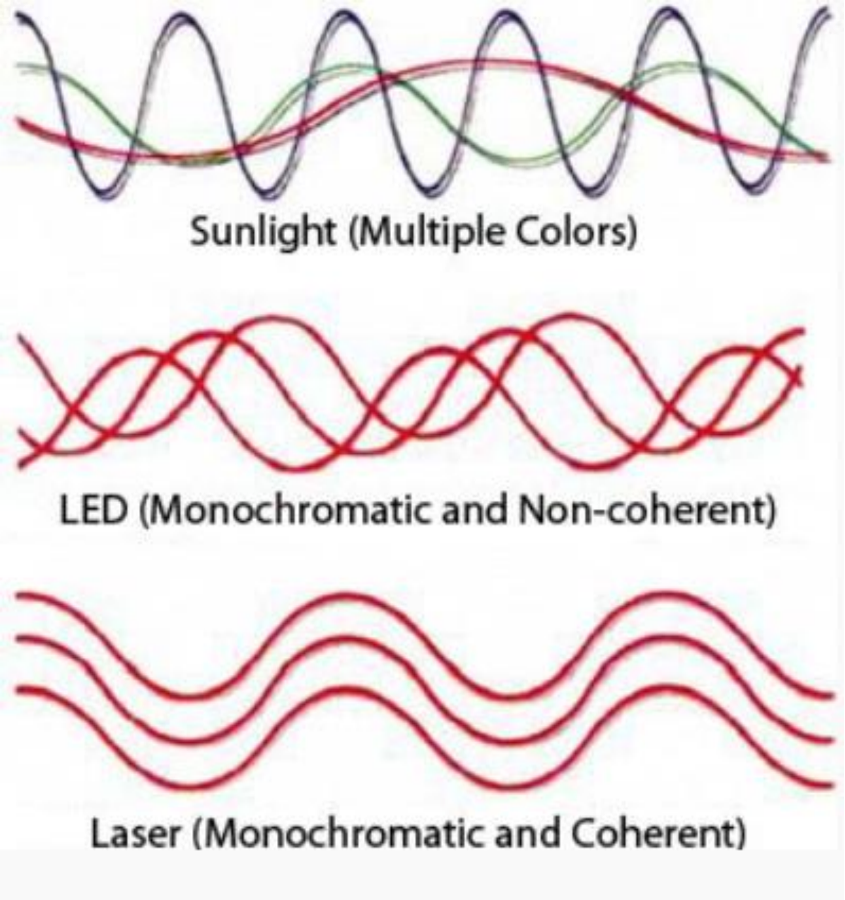
Fluorescence

The emission of light by a substance that has absorbed light or other electromagnetic radiation, usually at a different wavelength.

Glossary

Monochromatic light

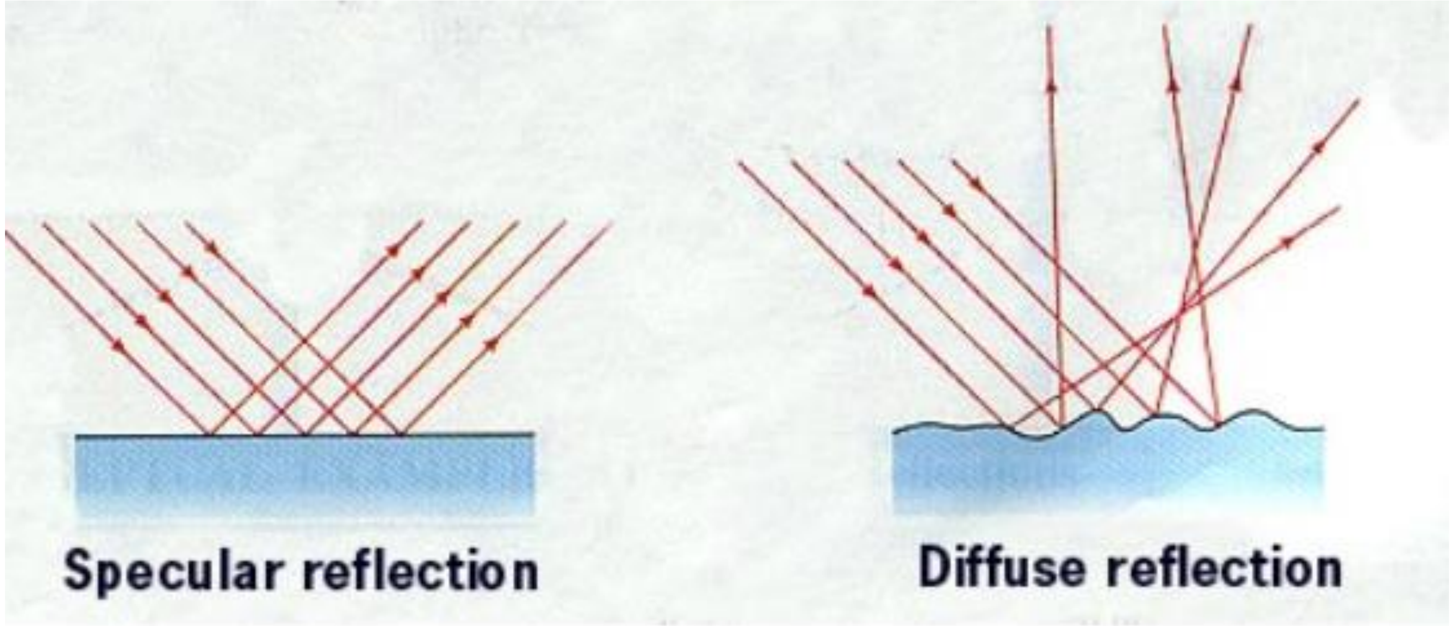
Light that consists of a single wavelength or color



Glossary

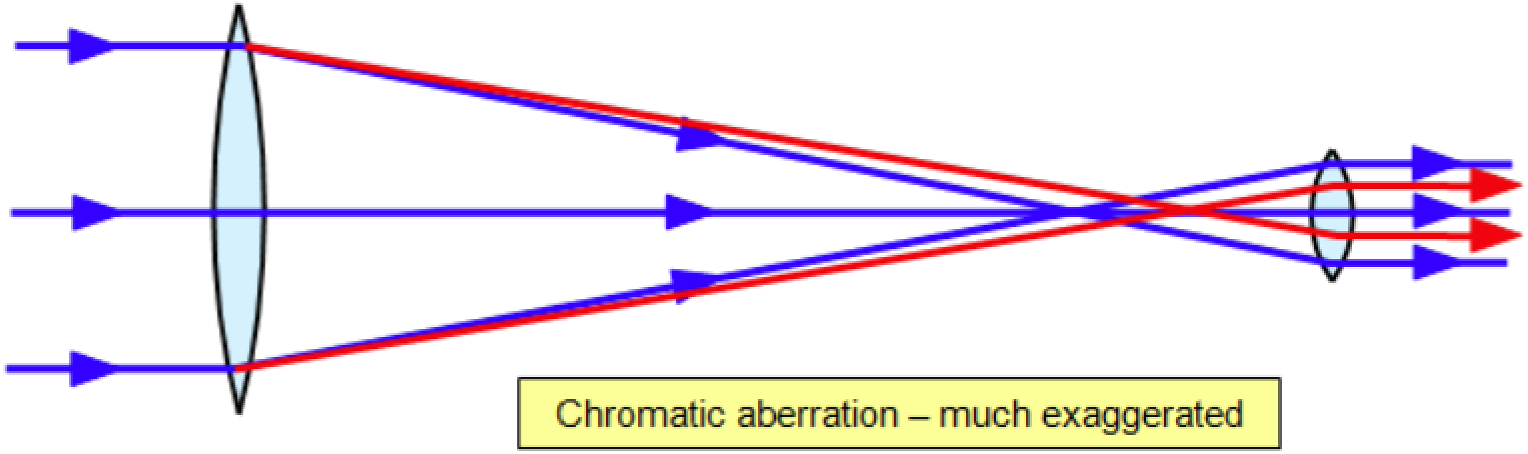
Specular reflection

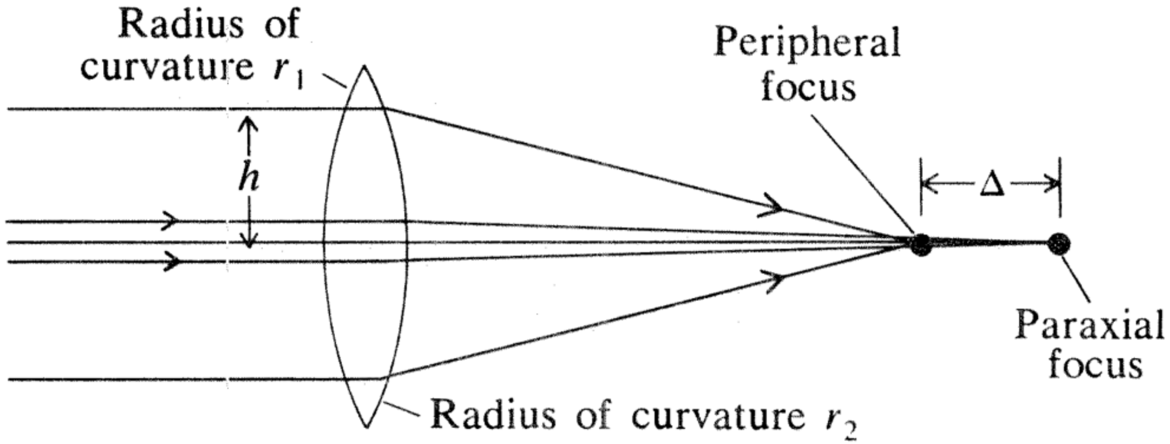
Reflection from a smooth surface, where the angle of incidence equals the angle of reflection.



Glossary

Aberrations





Basic optical elements

Elements

Lens

A transparent optical element that refracts light to converge or diverge rays to form images.

Elements

Mirror

A reflective surface that redirects light, typically made of glass coated with a metallic or dielectric layer.

Elements

Beam splitter

An optical device that divides a beam of light into two or more separate beams.

Elements

Polarizer

A device that filters light waves to transmit only specific polarization states (linear, circular).

Elements

Filter

A device that selectively transmits light of certain wavelengths while blocking others (e.g., color filters, ND filters).

Elements

Grating

An optical component with multiple slits or grooves that disperses light based on wavelength, producing a spectrum.

Elements

Pinhole

A small aperture used to spatially filter light or create simple images

Elements

Waveplate

A transparent optical element that alters the phase of polarized light, such as half-wave and quarter-wave plates.

Elements

Photodetector

A device that converts light into an electrical signal, including photodiodes, photomultipliers, and CCD sensors.