Optics Overview

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 momentum!

Energy E=$h\nu$ $\Longrightarrow$ relates the dual particle & wave nature of light;

h=Planck's constant

=6.6262×10^{-34} J sec

ν is the temporal oscillation frequency of the light waves

Wave properties of light

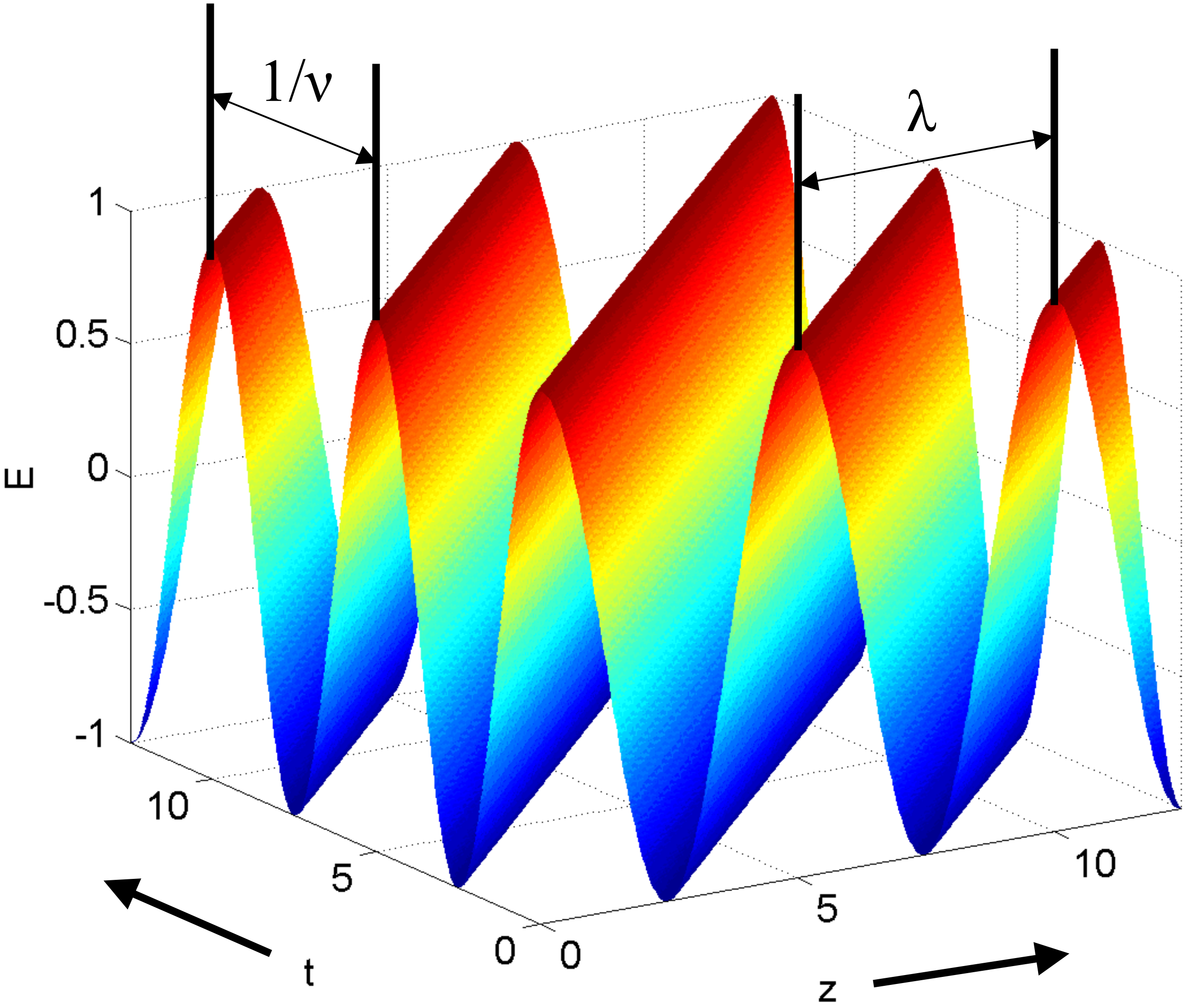
λ: **wavelength** (spatial period)

$k=2\pi/\lambda$ wavenumber

ν: temporal **frequency**

$\omega=2\pi\nu$ angular frequency

E: electric field



Wave/particle duality for light

Photon=elementary light particle

Mass=0

Speed $c=3\times10^8$ m/sec

Energy $E=h\nu$

h=Planck's constant

$=6.6262\times10^{-34}$ J sec

ν=frequency (sec^{-1})

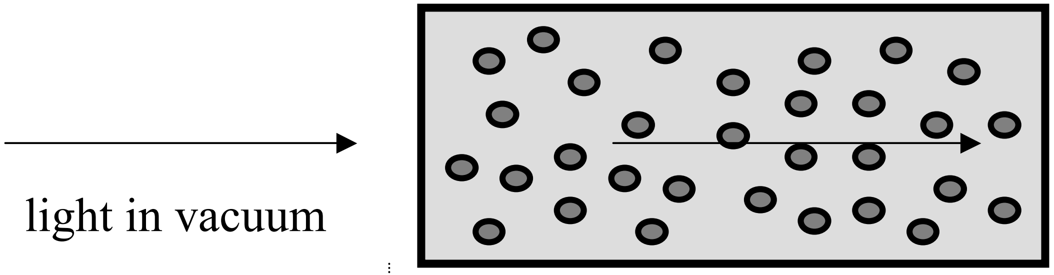
λ=wavelength (m)

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

"Dispersion relation"

(holds in vacuum only)

Light in matter



Speed $c=3\times10^{8}$ m/sec

Absorption coefficient 0

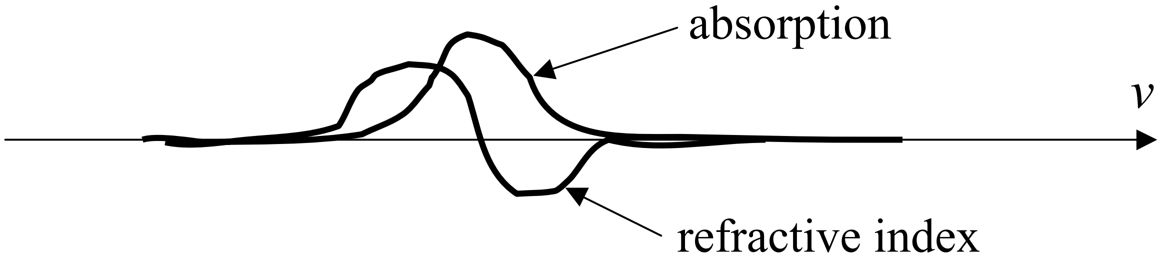
Speed c/n
n : refractive index
(or index of refraction)

Absorption coefficient α
energy decay coefficient,
after distance L : $e^{-2\alpha L}$

E.g. vacuum $n=1$, air $n \approx 1$;
glass $n\approx1.5$; glass fiber has $\alpha \approx 0.25$dB/km=0.0288/km

Materials classification

- Dielectrics
  - typically electrical isolators (e.g. glass, plastics)
  - low absorption coefficient
  - arbitrary refractive index
- Metals
  - conductivity ⇒ large absorption coefficient
- Lots of exceptions and special cases (e.g. "artificial dielectrics")
- Absorption and refractive index are related through the Kramers–Kronig relationship (imposed by *causality*)



Overview of light sources

non-Laser

Thermal: polychromatic, spatially incoherent (e.g. light bulb)

Gas discharge: monochromatic, spatially incoherent (e.g. Na lamp)

Light emitting diodes (LEDs): monochromatic, spatially incoherent

Laser

Continuous wave (or cw): strictly monochromatic, spatially coherent (e.g. HeNe, Ar^+, laser diodes)

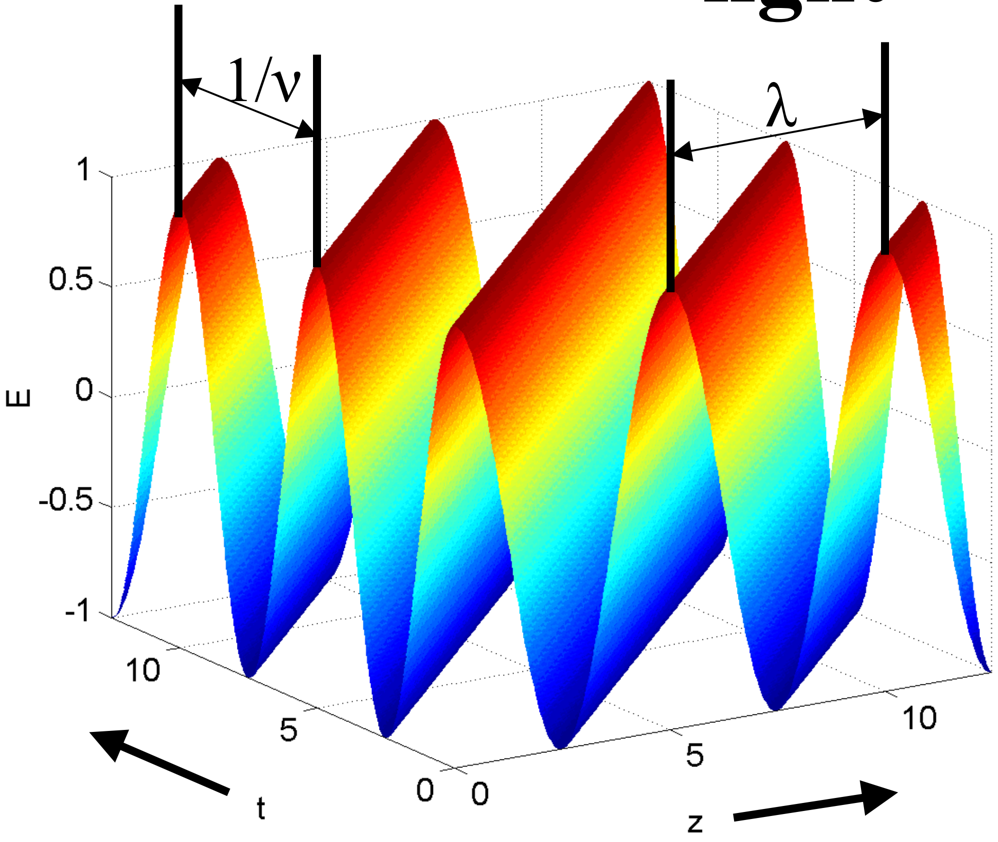
Pulsed: quasi-monochromatic, spatially coherent (e.g. Q-switched, mode-locked)

~nsec ~psec to few fsec

pulse duration

mono/poly-chromatic = single/multi color

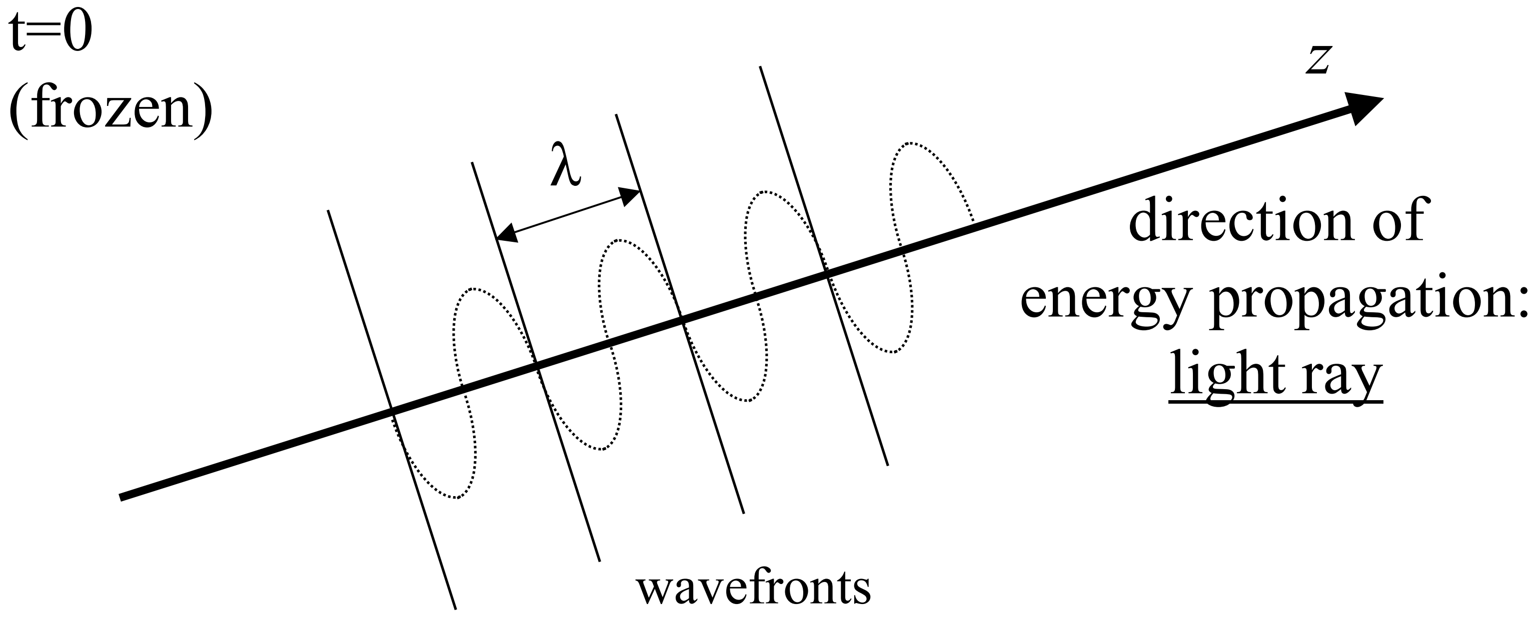
Monochromatic, spatially coherent light



- nice, regular sinusoid
- λ, ν well defined
- stabilized HeNe laser good approximation
- most other cw lasers rough approximation
- pulsed lasers & non-laser sources need more complicated description

Incoherent: random, irregular waveform

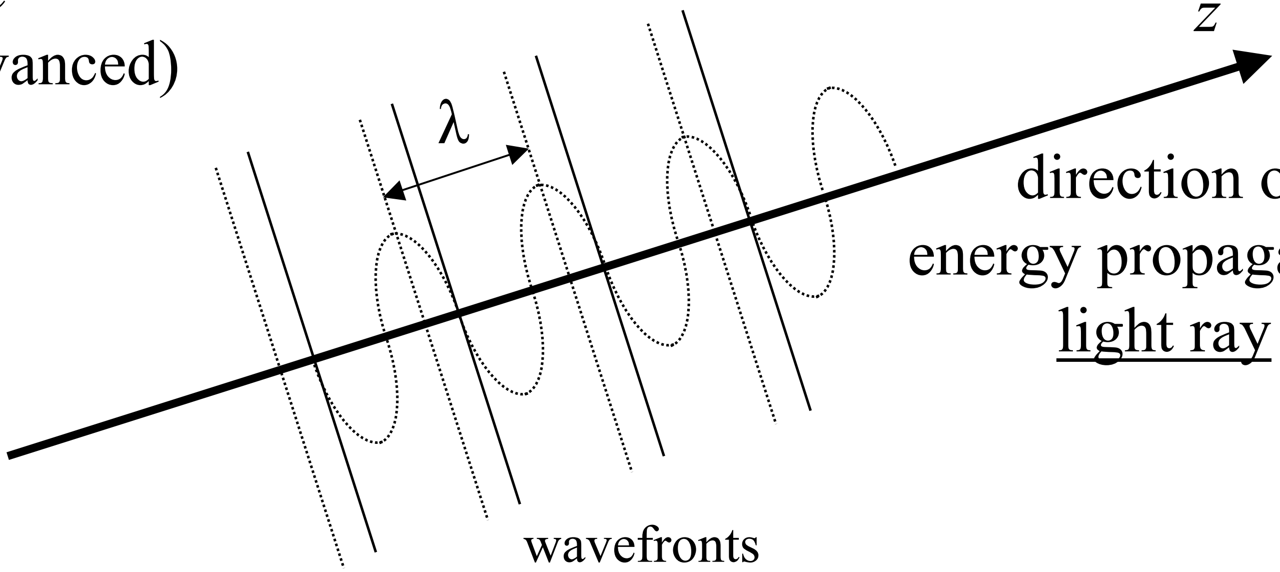
The concept of a monochromatic "ray"



In homogeneous media,
light propagates in rectilinear paths

The concept of a monochromatic "ray"

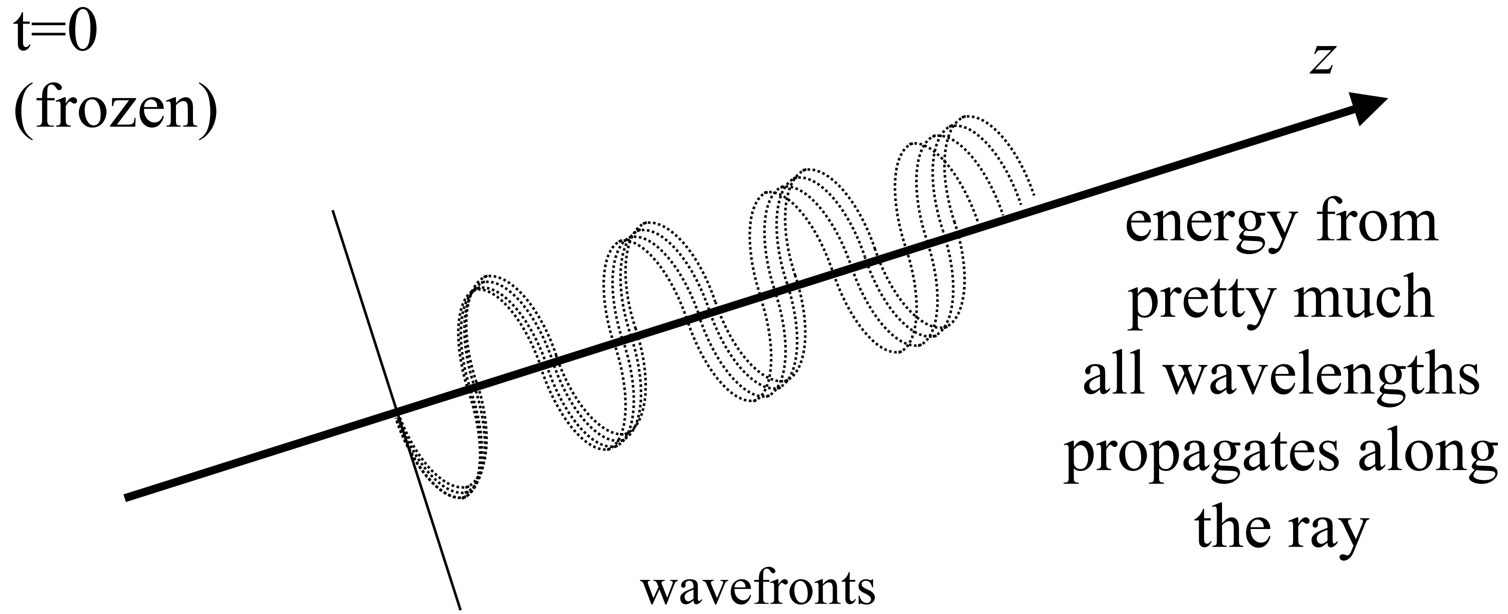
t=Δt
(advanced)



direction of
energy propagation:
<u>light ray</u>

In homogeneous media,
light propagates in rectilinear paths

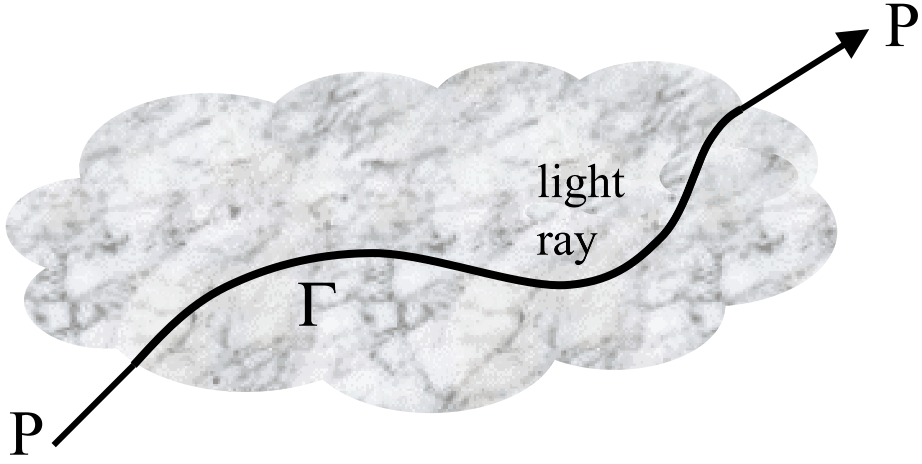
The concept of a polychromatic "ray"



energy from
pretty much
all wavelengths
propagates along
the ray

In homogeneous media,
light propagates in rectilinear paths

Fermat principle

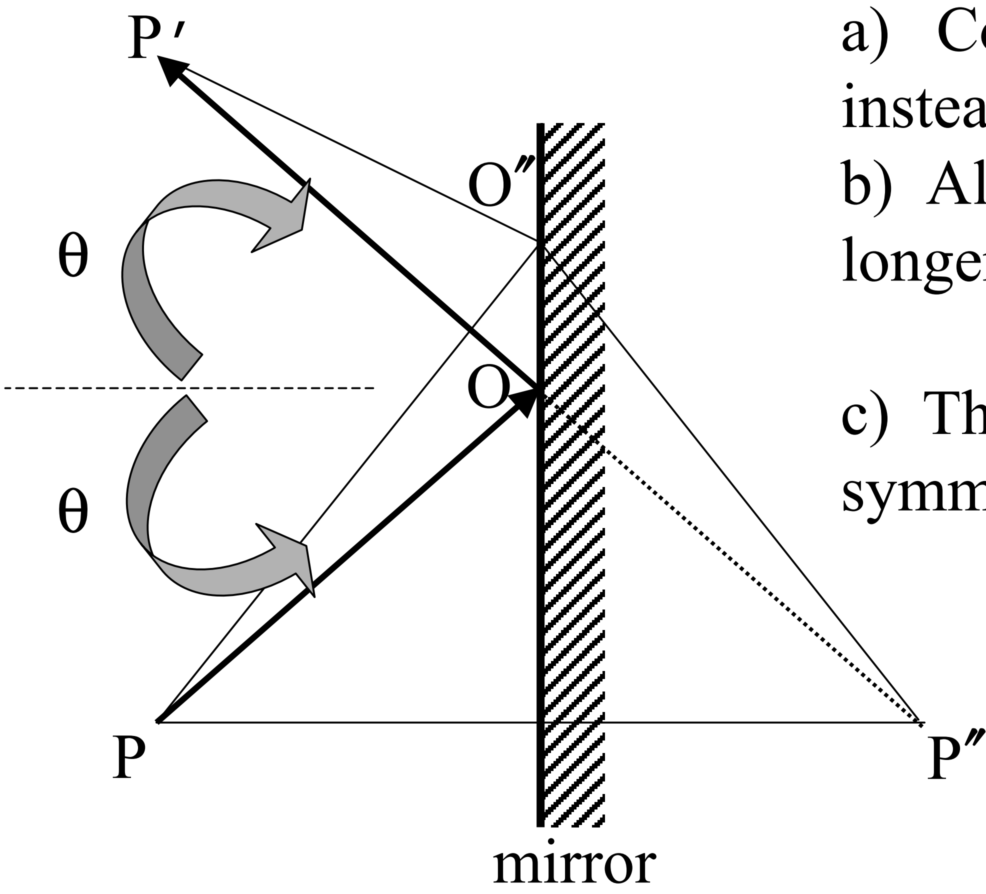


$$\int_{\Gamma} n(x, y, z)\,\mathrm{d}l$$

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

(aka **minimum path** principle)
Consequences: law of reflection, law of refraction

The law of reflection

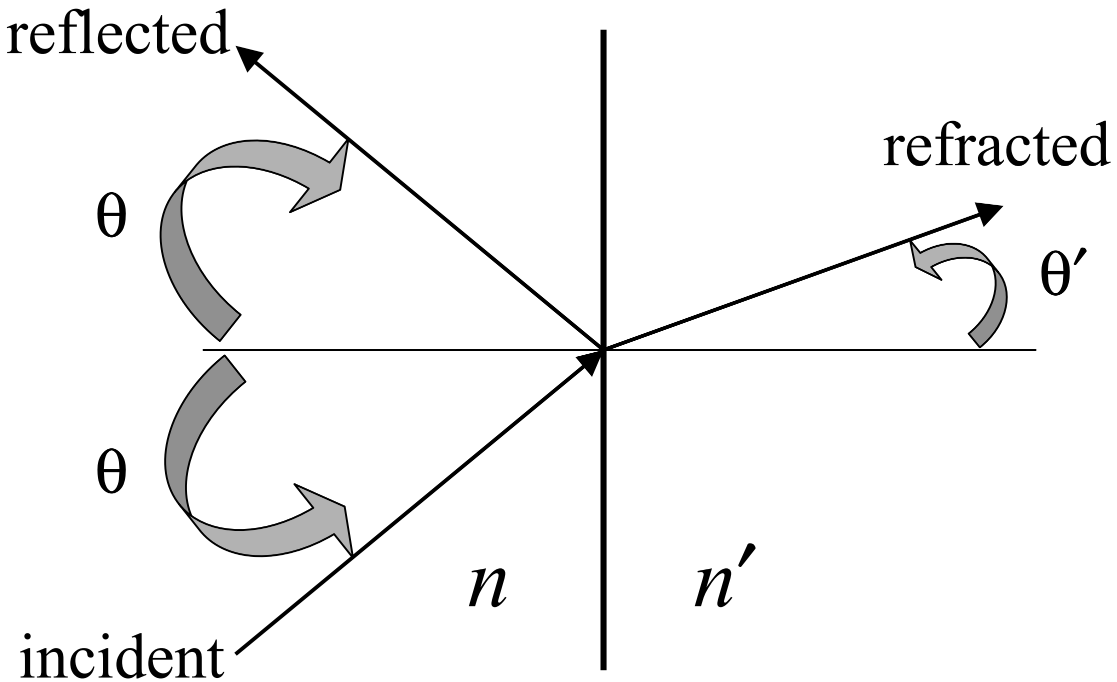


a) Consider virtual source P" instead of P

b) Alternative path P"O"P' is longer than P"OP'

c) Therefore, light follows the symmetric path POP'.

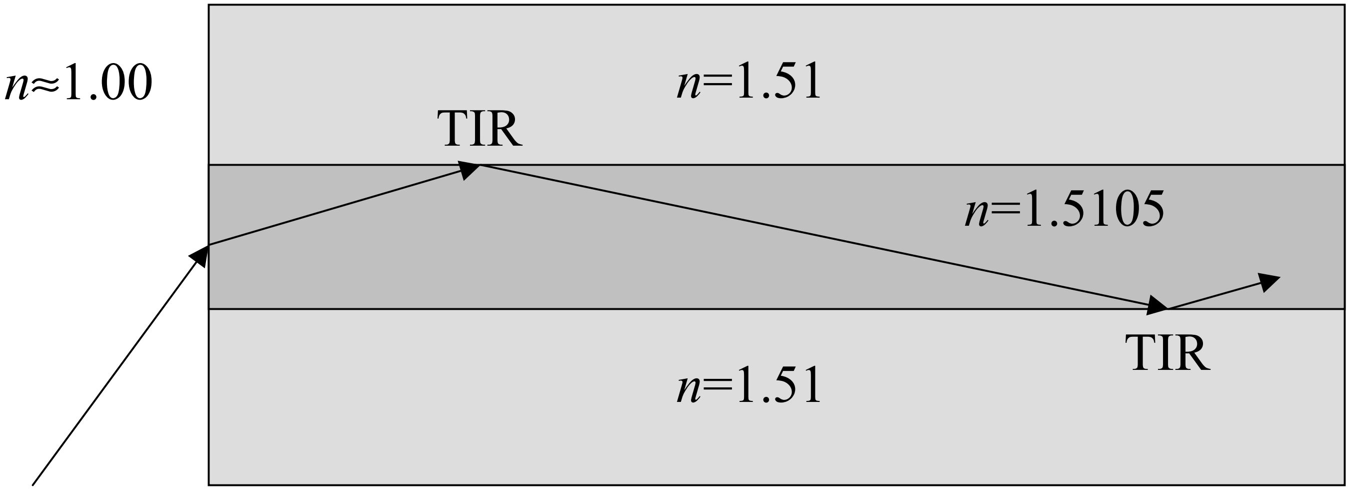
The law of refraction



$$\boxed{n\sin\theta = n'\sin\theta'}$$

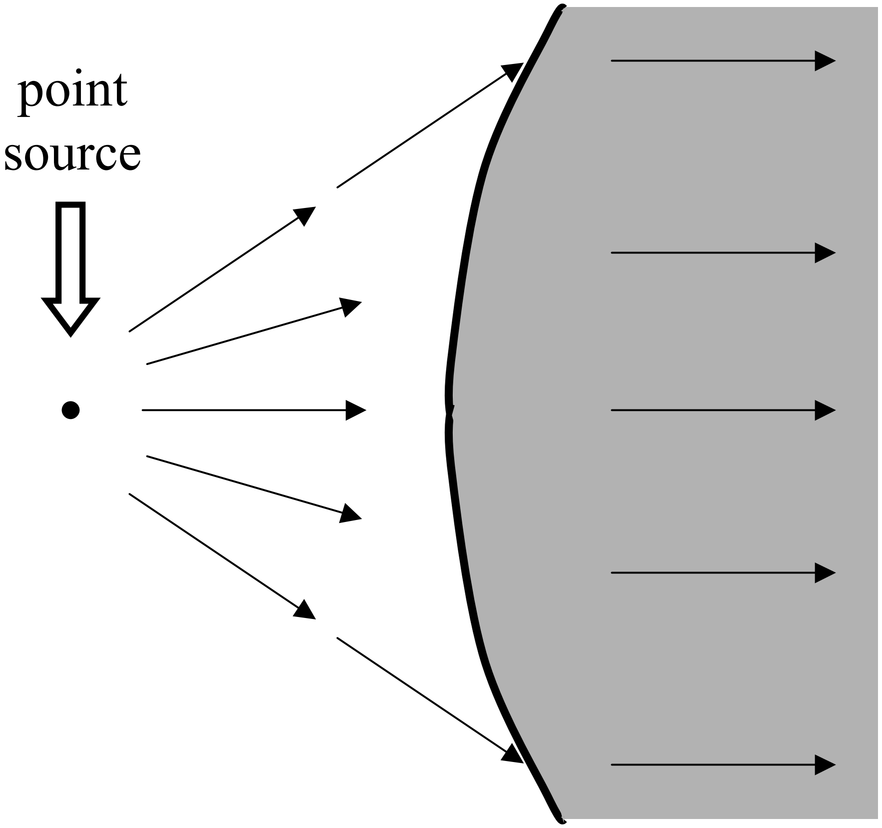
Snell's Law of Refraction

Optical waveguide

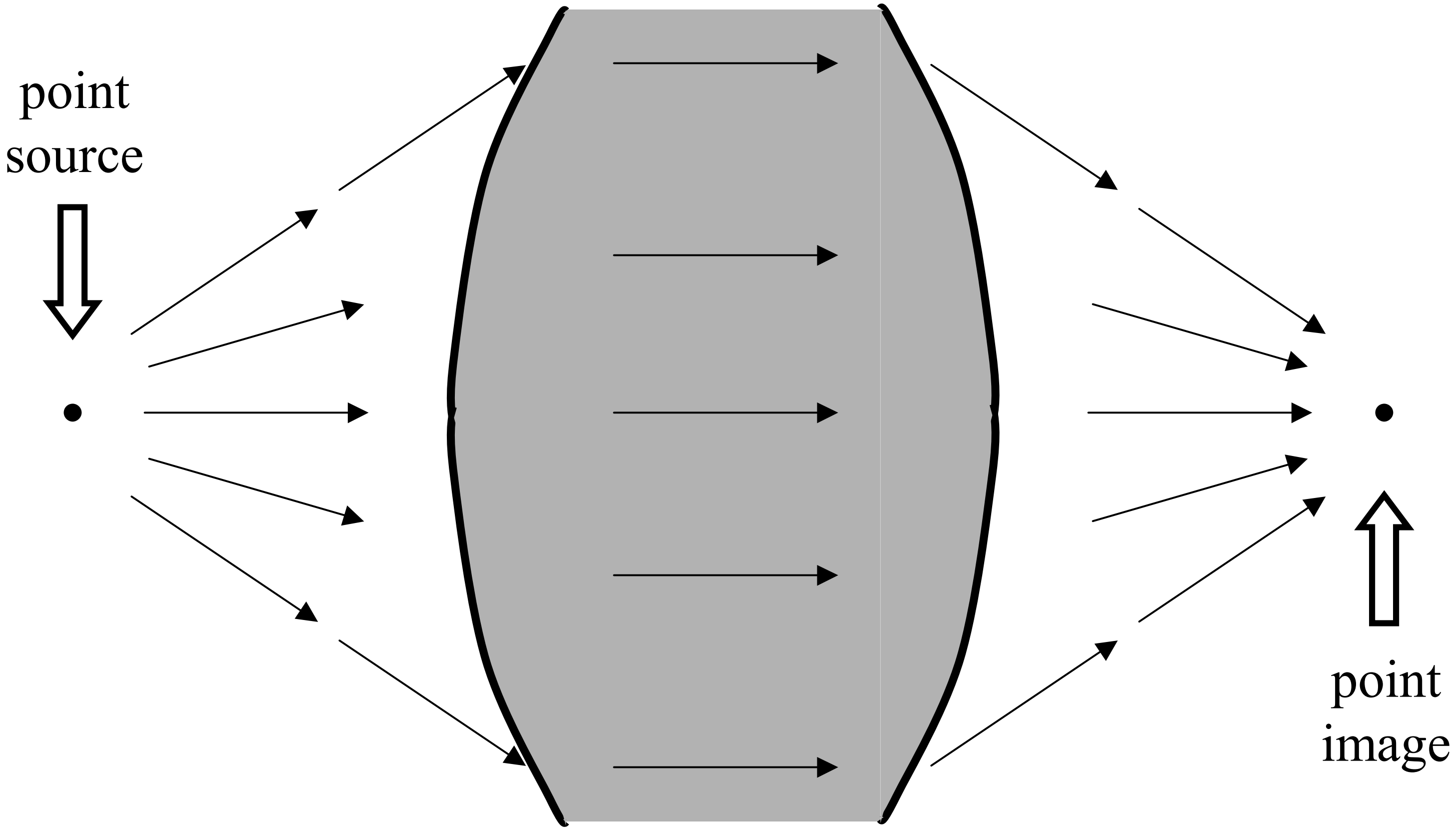


- Planar version: *integrated optics*
- Cylindrically symmetric version: *fiber optics*
- Permit the creation of “light chips” and “light cables,” respectively, where light is guided around with few restrictions
- Materials research has yielded glasses with very low losses (<0.25dB/km)
- Basis for optical telecommunications and some imaging (e.g. endoscopes) and sensing (e.g. pressure) systems

Refraction at a spherical surface



Imaging a point source

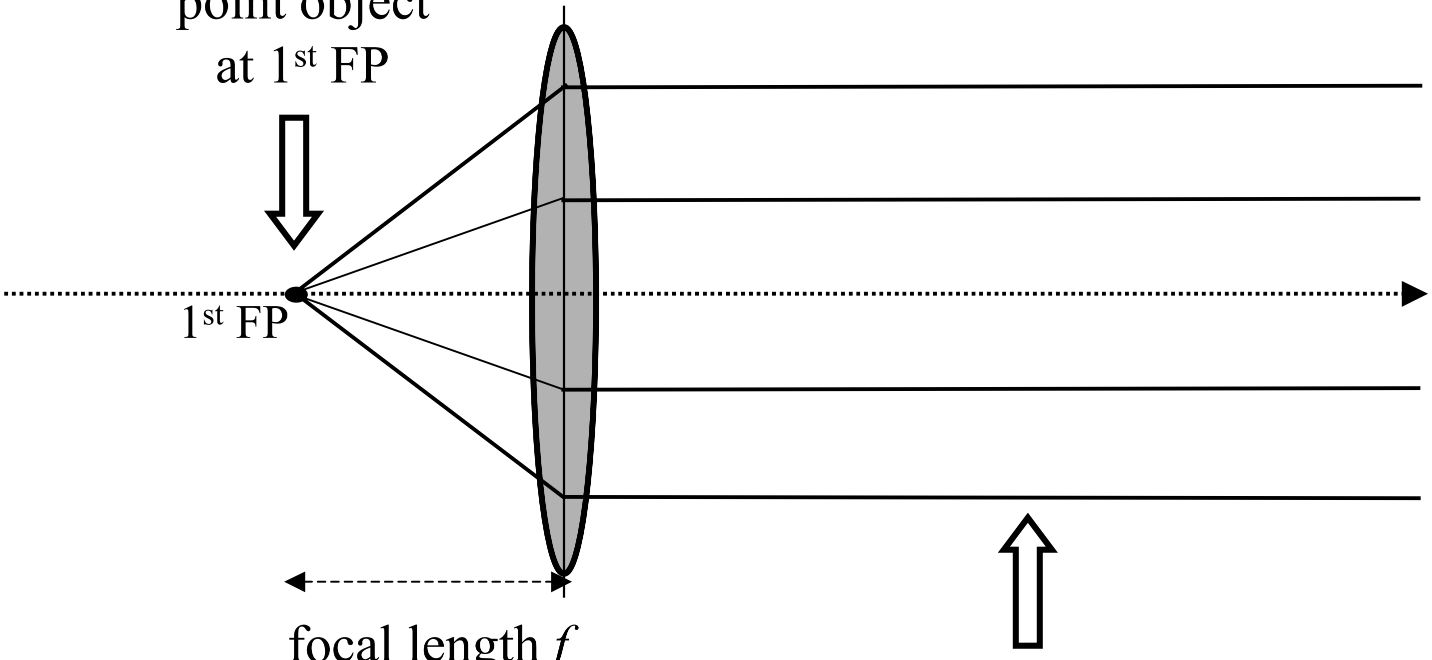


point source

point image

Lens

Model for a thin lens



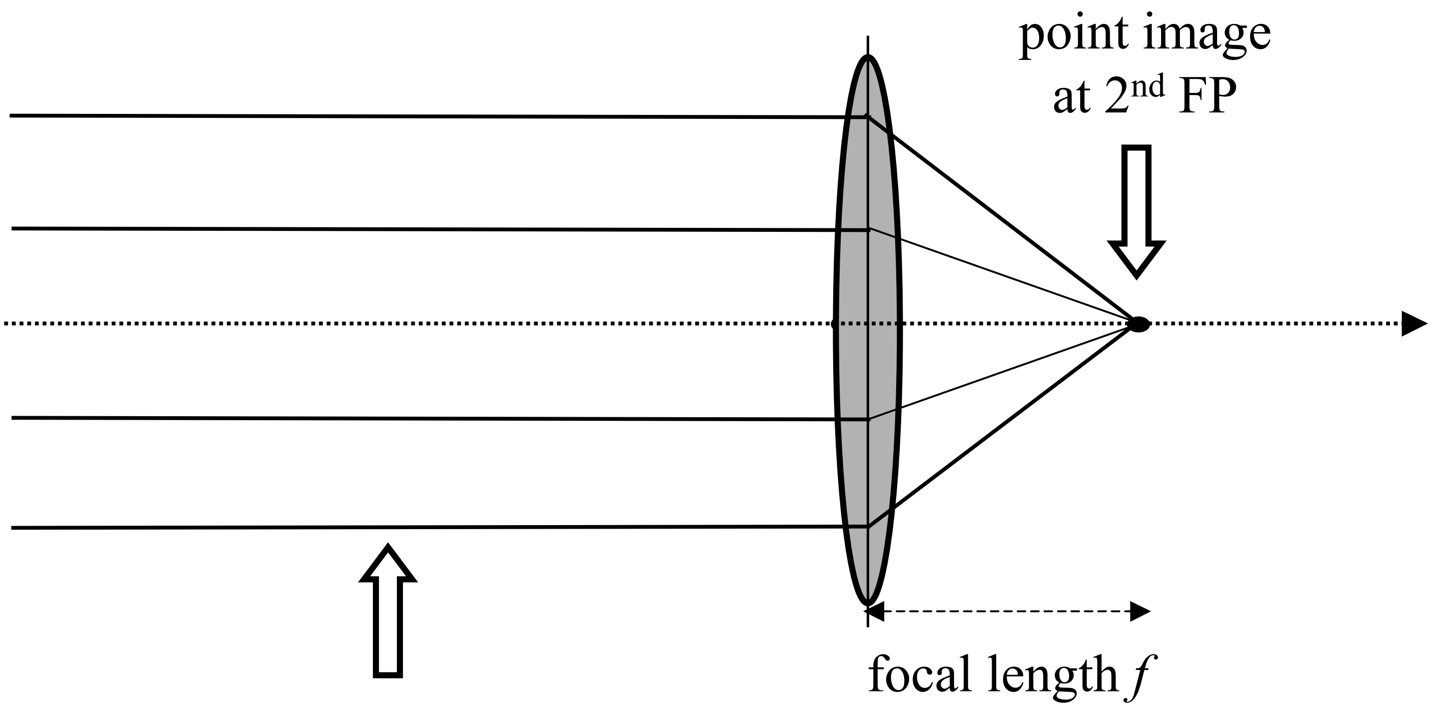
point object
at 1st FP

1st FP

focal length *f*

plane wave (or parallel ray bundle);
image at infinity

Model for a thin lens

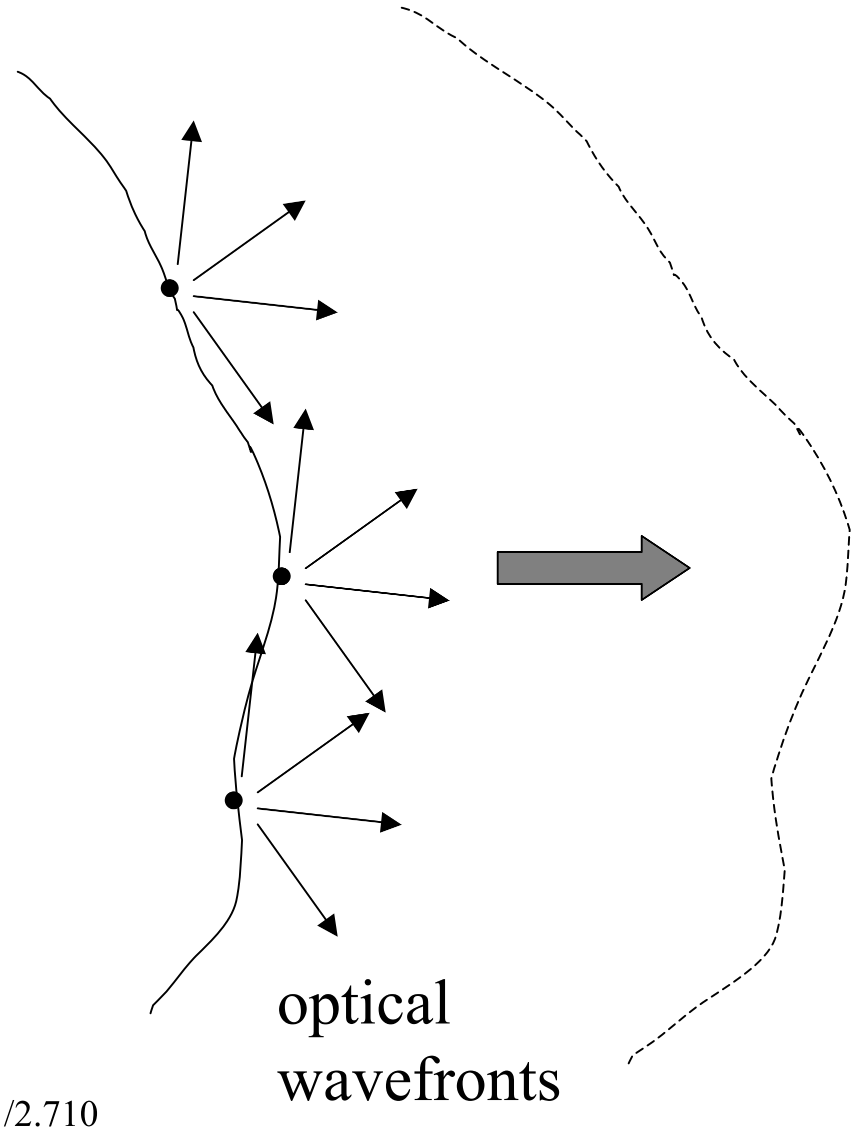


point image at 2nd FP

focal length *f*

plane wave (or parallel ray bundle);
object at infinity

Huygens principle

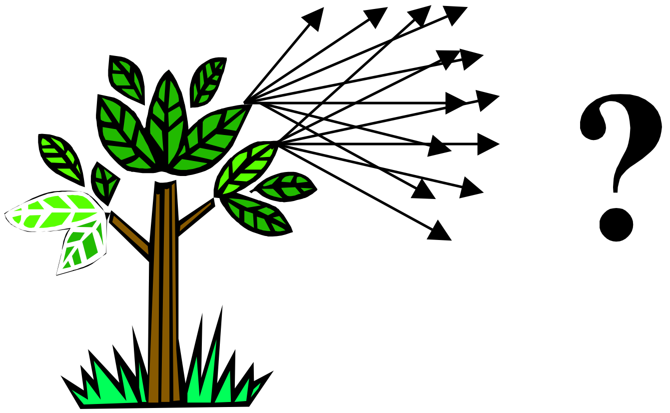


Each point on the wavefront acts as a secondary light source emitting a spherical wave

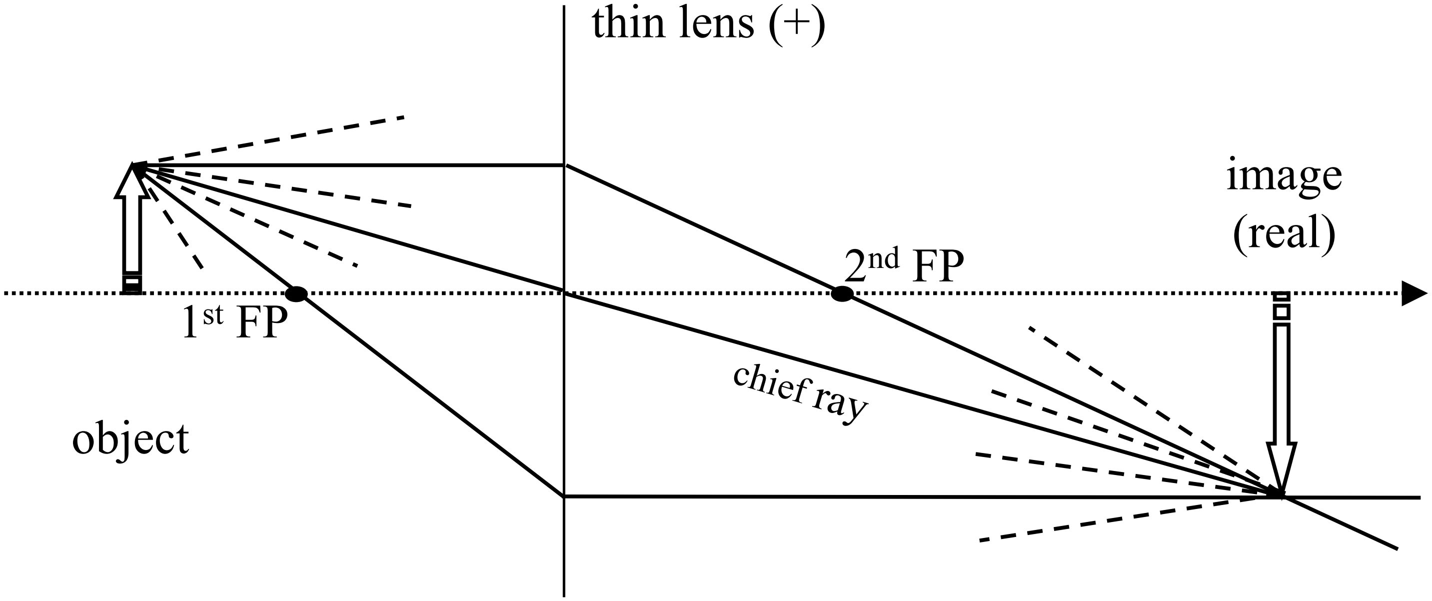
The wavefront after a short propagation distance is the result of superimposing all these spherical wavelets

Why imaging systems are needed

- Each point in an object scatters the incident illumination into a spherical wave, according to the Huygens principle.
- A few microns away from the object surface, the rays emanating from all object points become entangled, delocalizing object details.
- To relocalize object details, a method must be found to reassign ("focus") all the rays that emanated from a single point object into another point in space (the "image.")
- The latter function is the topic of the discipline of Optical Imaging.

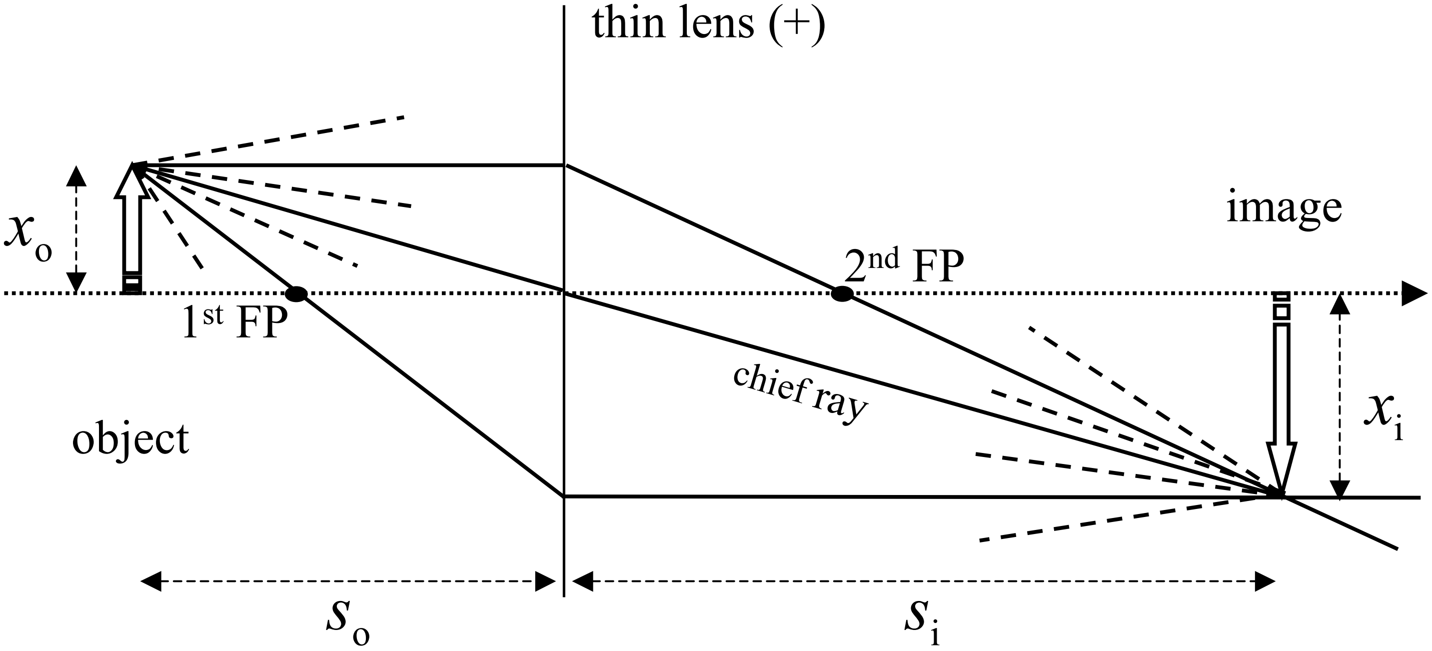


Imaging condition: ray-tracing



- Image point is located at the common intersection of *all* rays which emanate from the corresponding object point
- The two rays passing through the two focal points and the chief ray can be ray-traced directly
- The real image is **inverted** and can be **magnified** or **demagnified**

Imaging condition: ray-tracing



Lens Law

$$\frac{1}{s_o}+\frac{1}{s_i}=\frac{1}{f}$$

Lateral magnification

$$M_x=\frac{x_i}{x_o}=-\frac{s_o}{s_i}$$

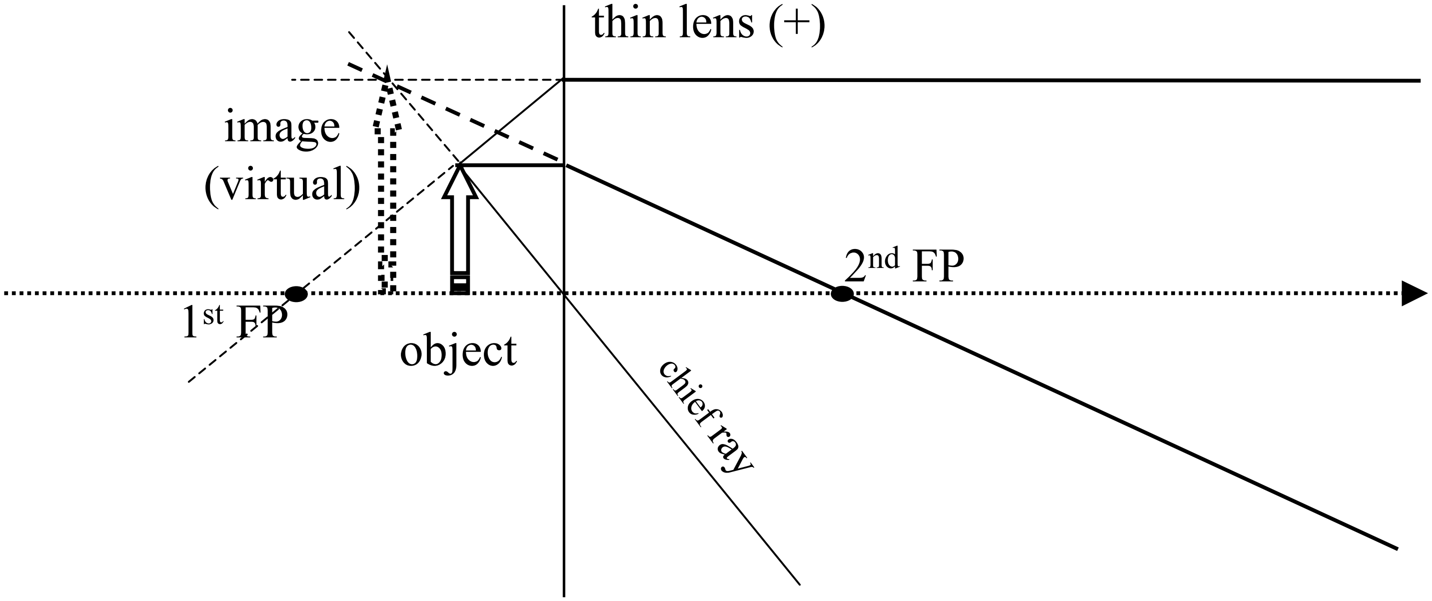
Angular magnification

$$M_a=-\frac{s_i}{s_o}$$

Energy conservation

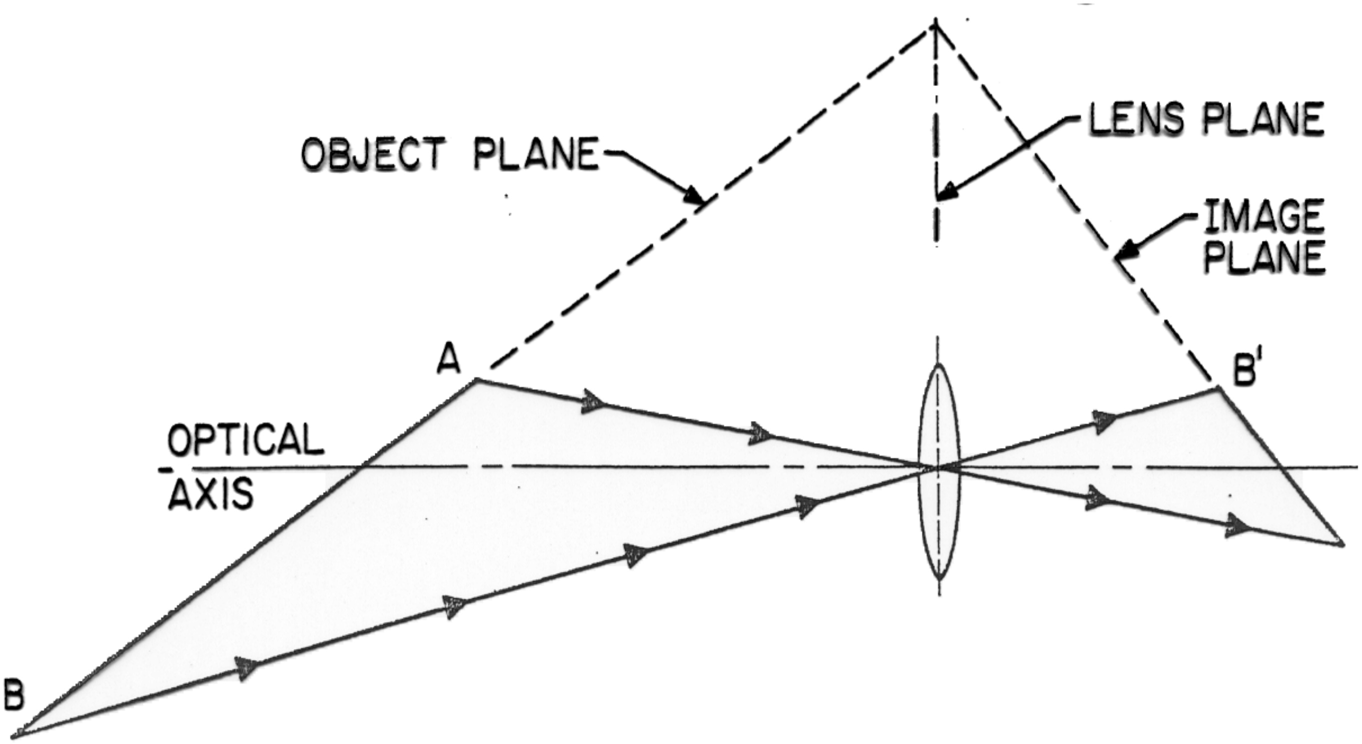
$$M_xM_a=1$$

Imaging condition: ray-tracing



- The ray bundle emanating from the system is divergent; the virtual image is located at the intersection of the backwards-extended rays
- The virtual image is **erect** and is **magnified**
- When using a <u>negative</u> lens, the image is always virtual, erect, and demagnified

Tilted object:
the Scheimpflug condition

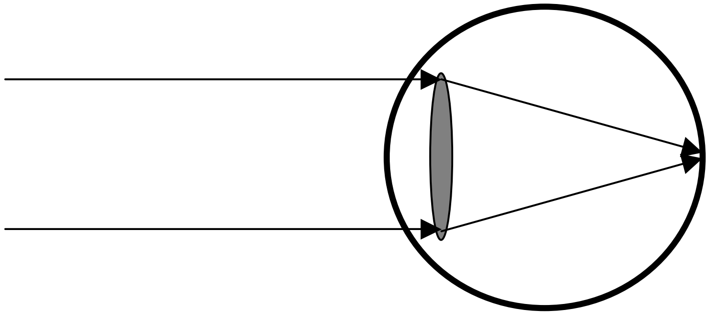


The object plane and the image plane intersect at the plane of the thin lens.

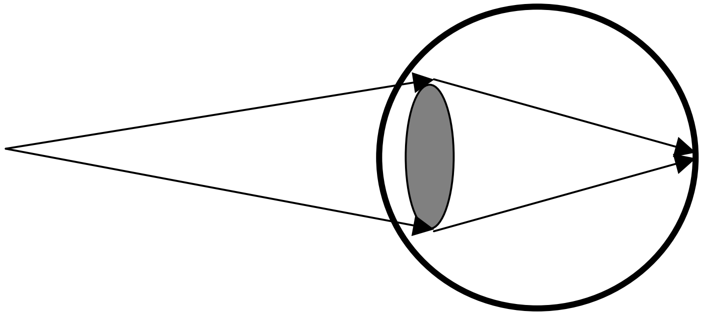
Lens-based imaging

- Human eye
- Photographic camera
- Magnifier
- Microscope
- Telescope

The human eye

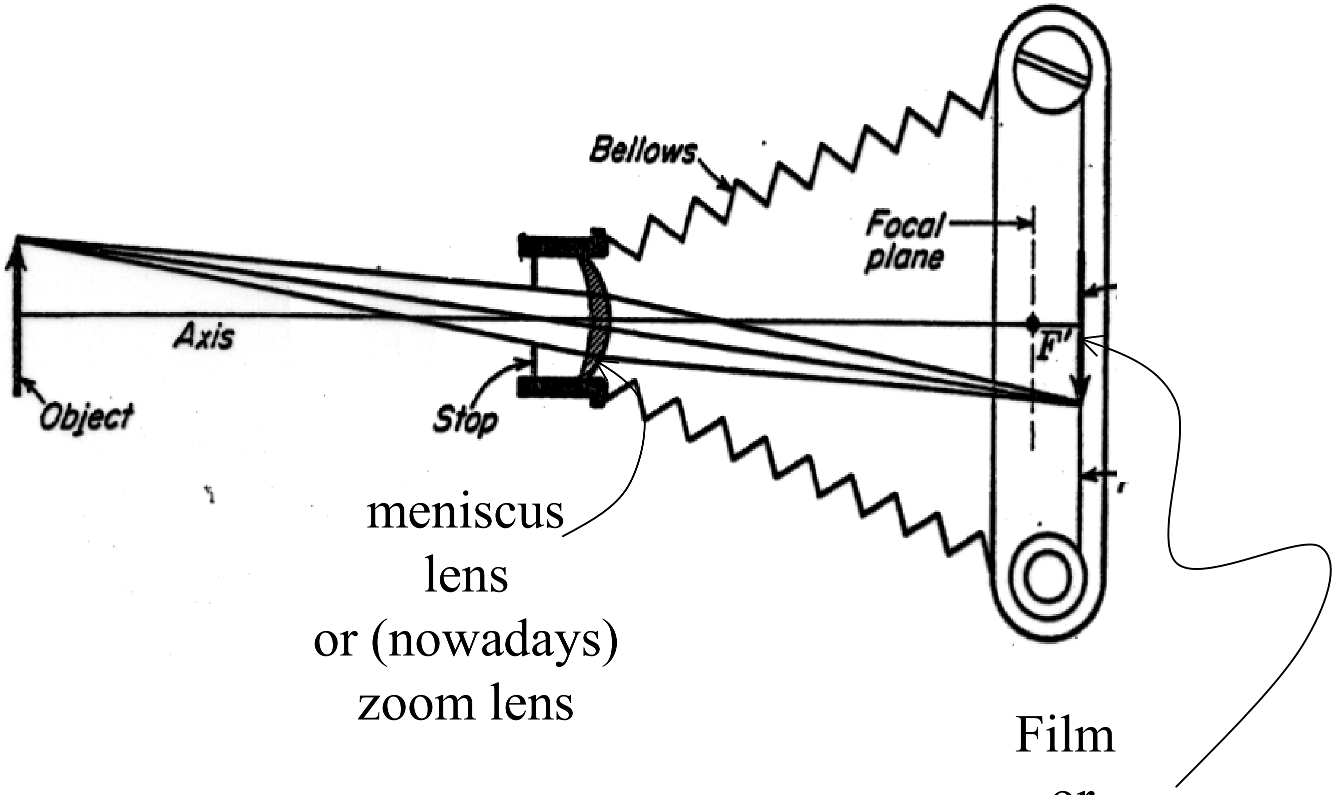


Remote object (unaccommodated eye)



Near object (accommodated eye)

The photographic camera

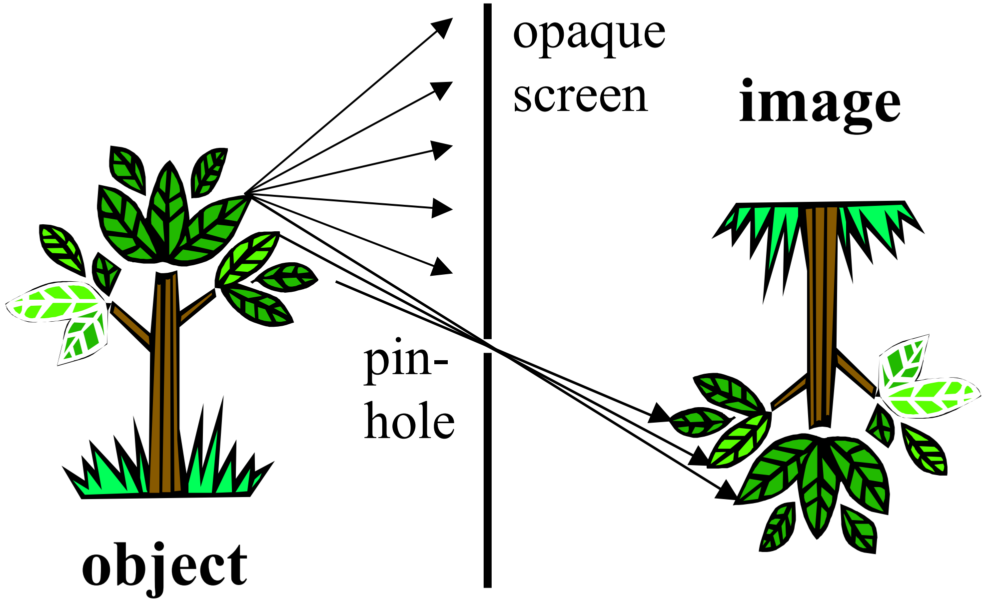


meniscus
lens
or (nowadays)
zoom lens

Film
or
detector array (CCD or CMOS)

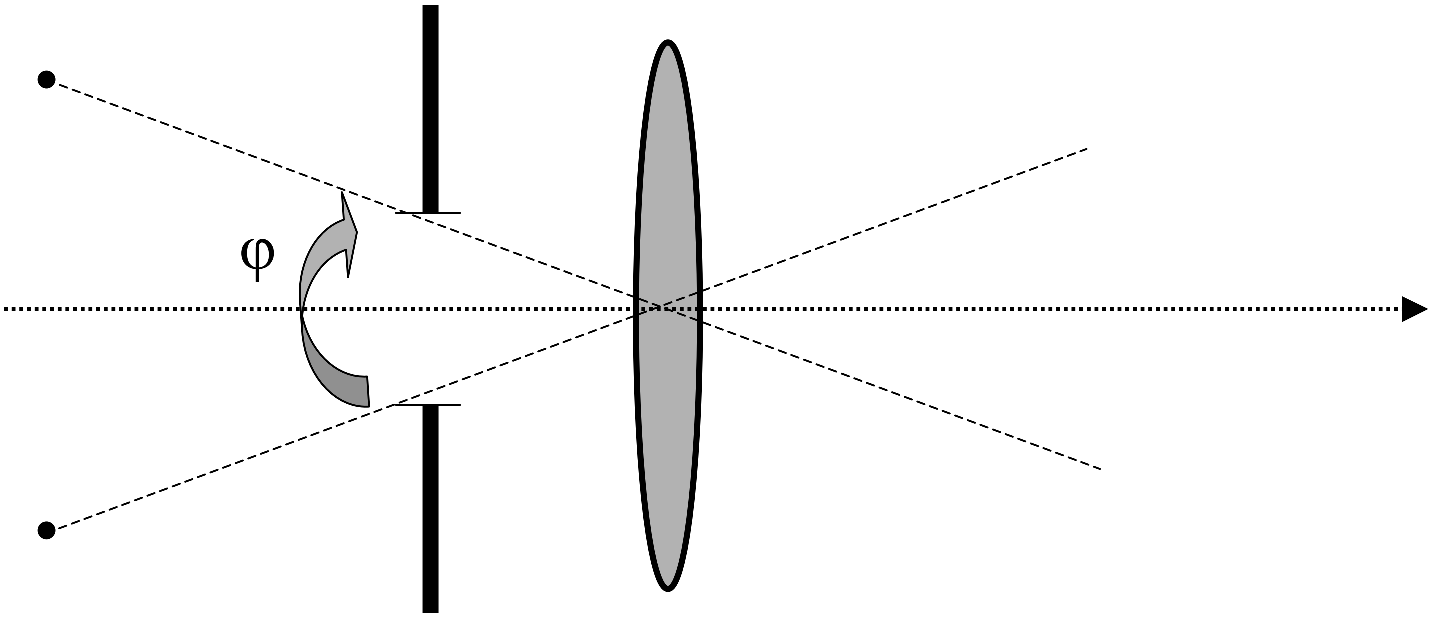
“digital imaging” ⇨ detector array (CCD or CMOS)

The pinhole camera



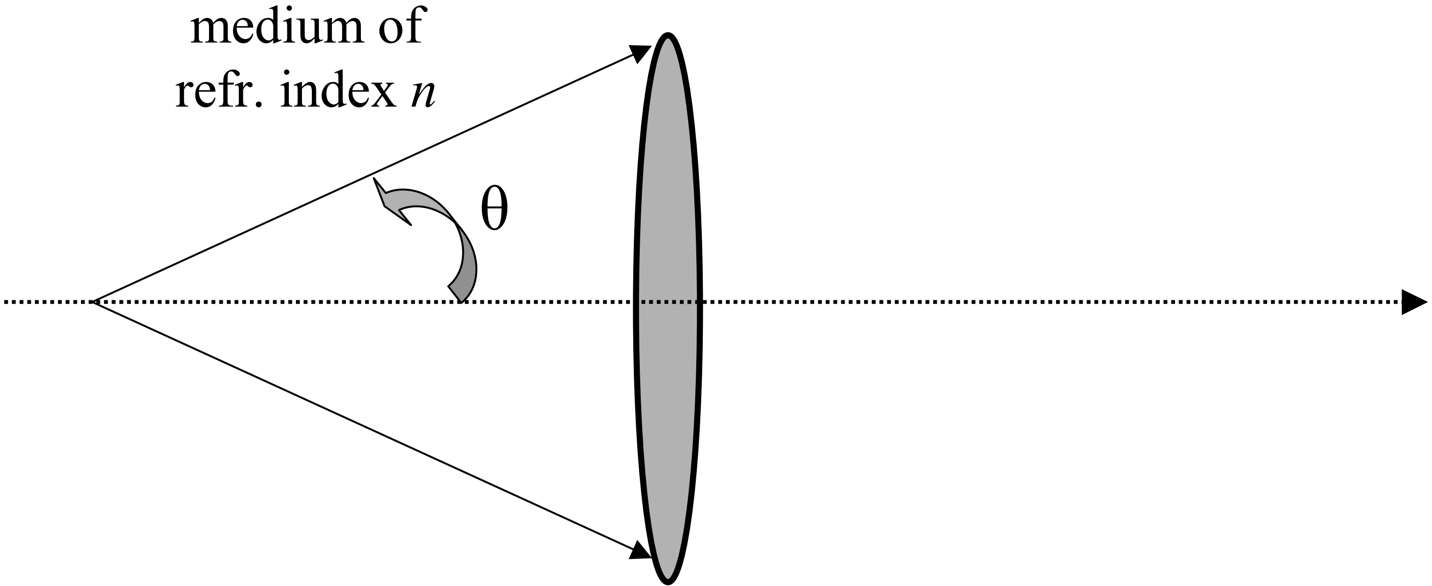
- The pinhole camera blocks all but one ray per object point from reaching the image space ⇒ an image is formed (*i.e.*, each point in image space corresponds to a single point from the object space).
- Unfortunately, most of the light is wasted in this instrument.
- Besides, light diffracts if it has to go through small pinholes as we will see later; diffraction introduces undesirable artifacts in the image.

Field of View (FoV)



FoV=angle that the *chief ray* from an object can subtend towards the imaging system

Numerical Aperture

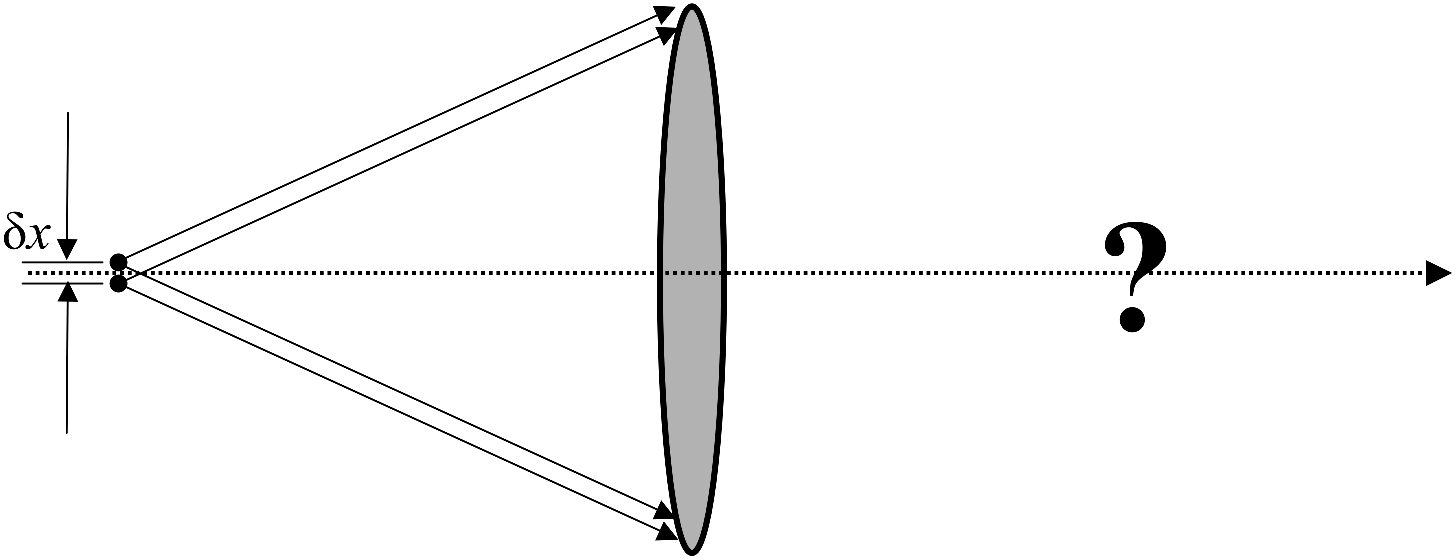


θ: half-angle subtended by the imaging system from an *axial* object

Numerical Aperture (NA) = $n \sin\theta$

Speed (f/#)=1/2(NA)
pronounced f-number, e.g. f/8 means (f/#)=8.

Resolution



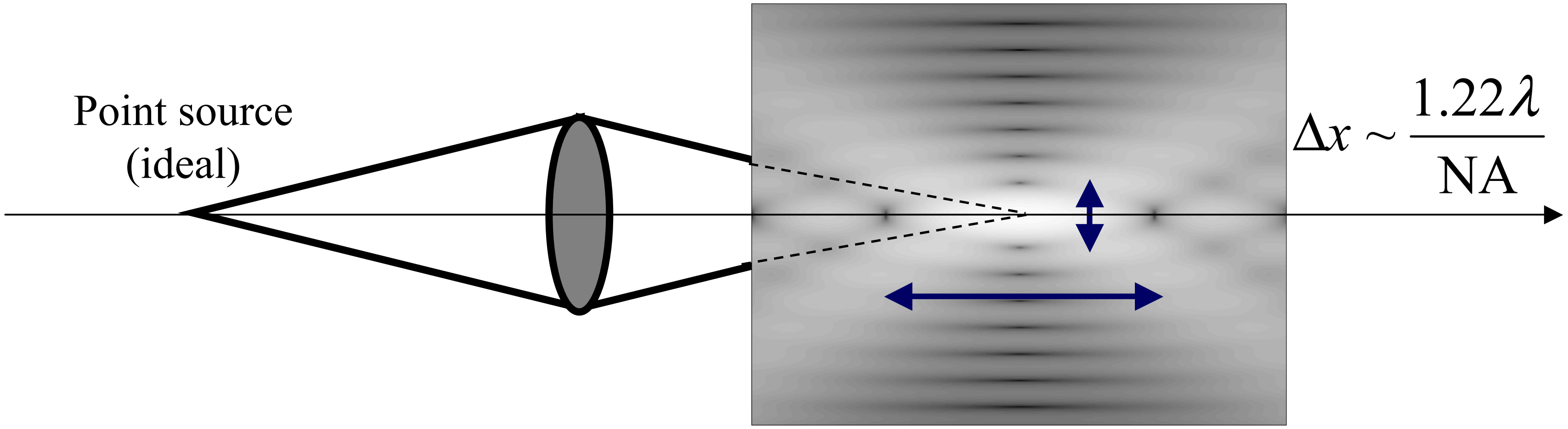
How far can two distinct point objects be before their images cease to be distinguishable?

Factors limiting resolution in an imaging system

- Diffraction
- Aberrations
- Noise
  - electronic noise (thermal, Poisson) in cameras
  - multiplicative noise in photographic film
  - stray light
  - speckle noise (coherent imaging systems only)
- Sampling at the image plane
  - camera pixel size
  - photographic film grain size

Intricately related; assessment of image quality depends on the degree that the "inverse problem" is solvable (i.e. its *condition*)
2.717 sp02 for details

Point-Spread Function



Light distribution near the Gaussian (geometric) focus = **PSF** (rotationally symmetric wrt optical axis)

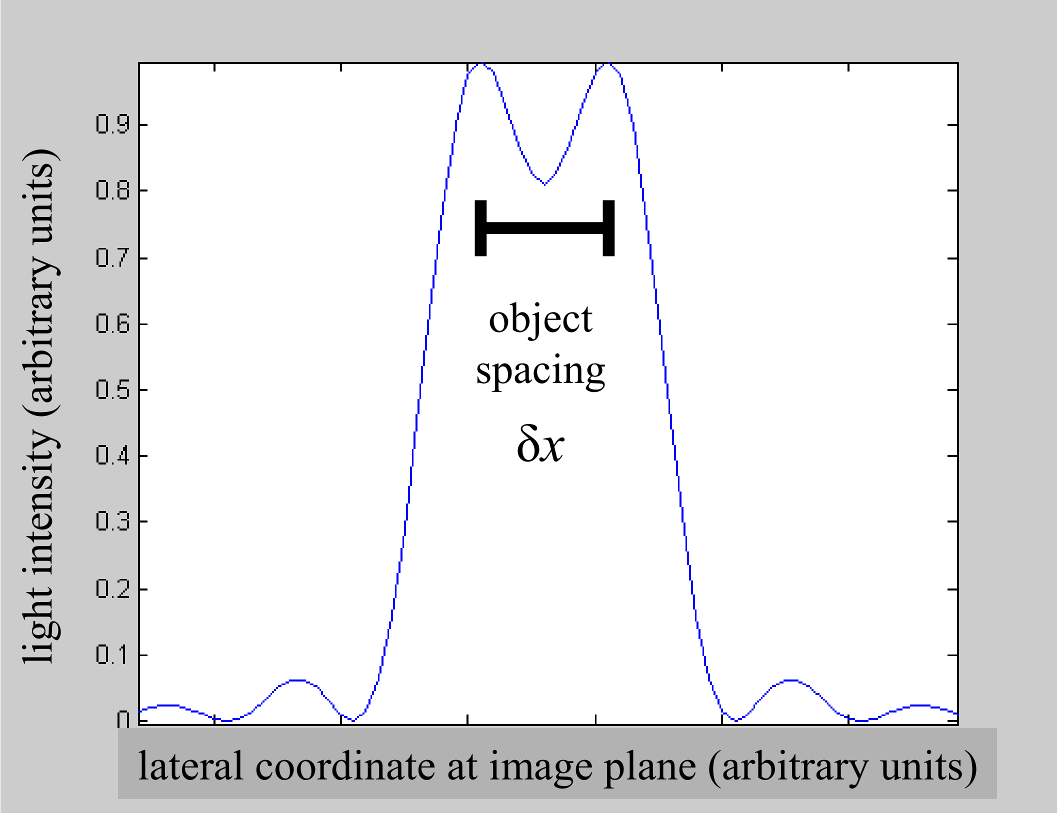
Point source (ideal)

$$\Delta x \sim \frac{1.22\lambda}{\text{NA}}$$

$$\Delta z \sim \frac{2\lambda}{\text{NA}^2}$$

The finite extent of the PSF causes blur in the image

Diffraction limited resolution



Point objects "just resolvable" when

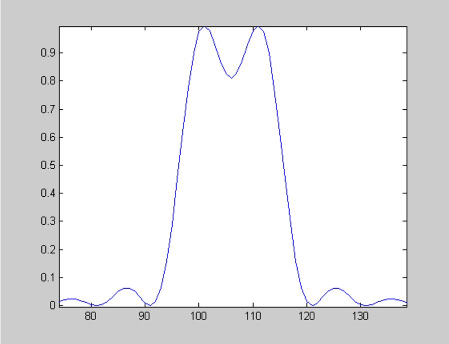
$$\delta x \approx \frac{1.22\lambda}{(\text{NA})}$$

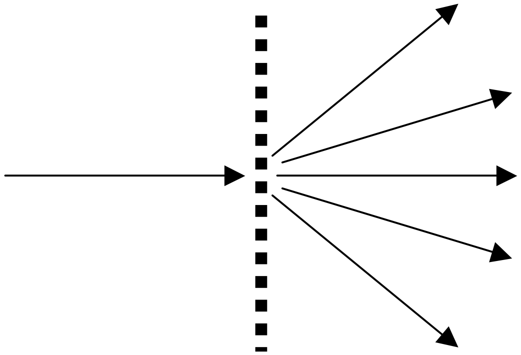
Rayleigh resolution criterion

Wave nature of light

- Diffraction

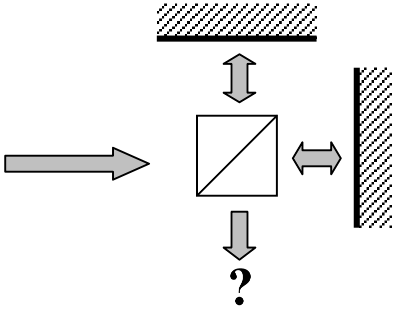
broadening of
point images



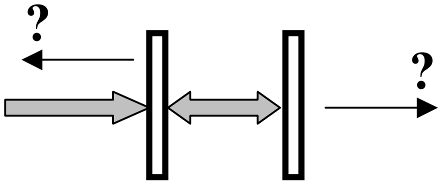


diffraction grating

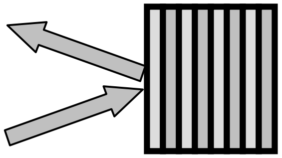
- Inteference



Michelson interferometer



Fabry-Perot interferometer

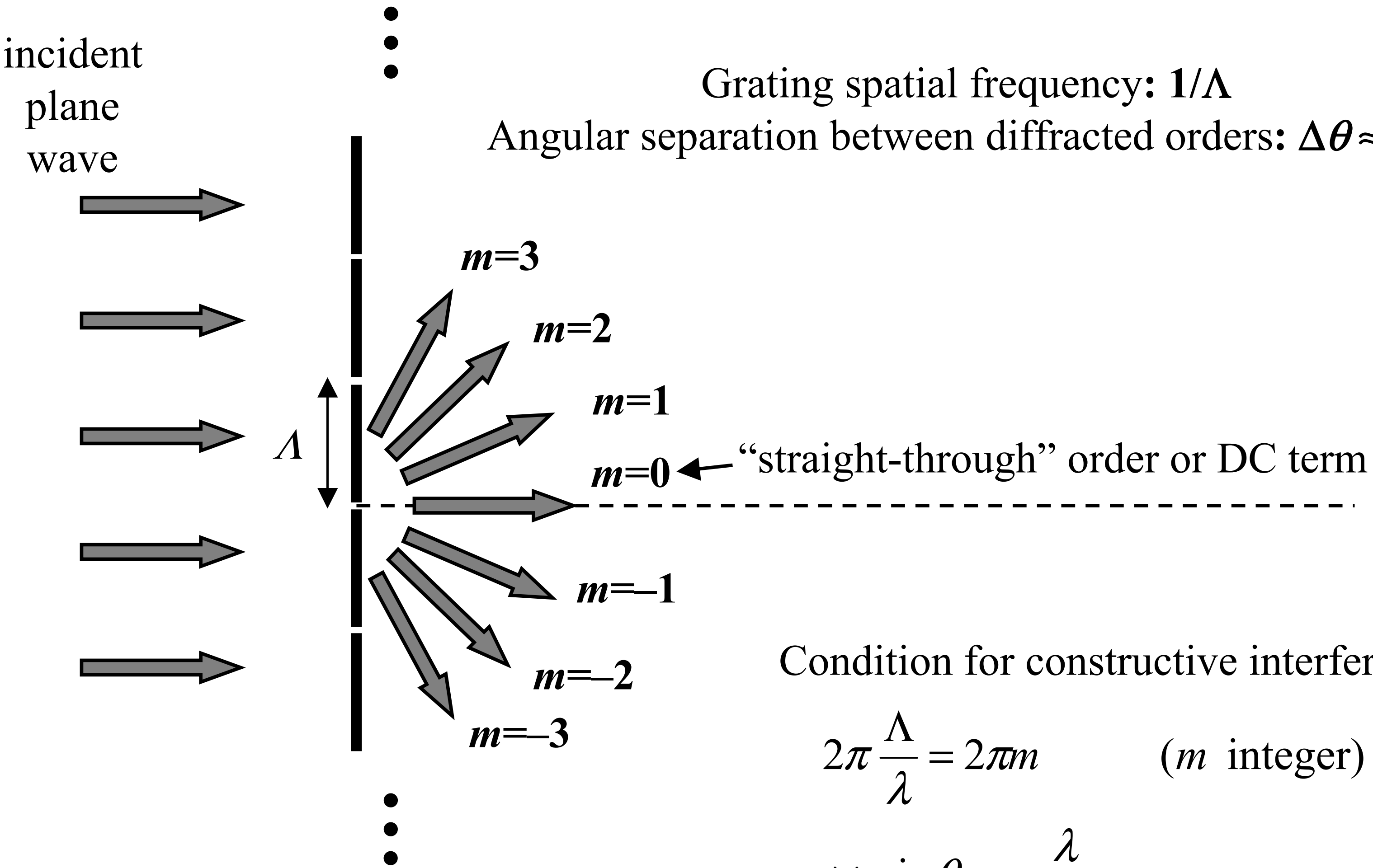


Interference filter
(or dielectric mirror)

- Polarization: polaroids, dichroics, liquid crystals, ...

Diffraction grating

Grating spatial frequency**: 1/Λ**
Angular separation between diffracted orders**: $\Delta\theta\approx 1/\Lambda$**



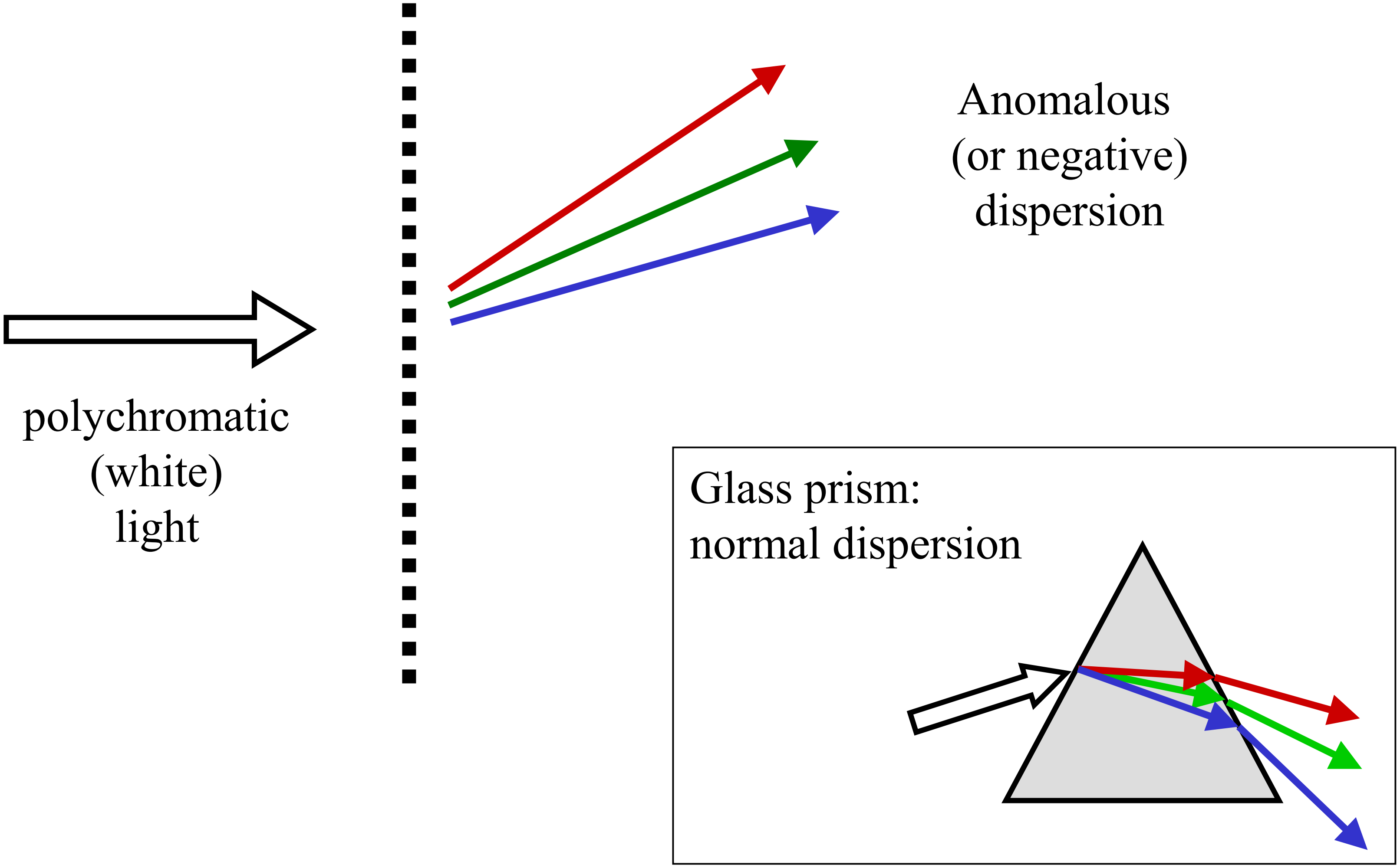
Condition for constructive interference:

$$2\pi\frac{\Lambda}{\lambda}=2\pi m \qquad (m\ \text{integer})$$

$$\Leftrightarrow \sin\theta = m\frac{\lambda}{\Lambda}$$

diffraction order

Grating dispersion

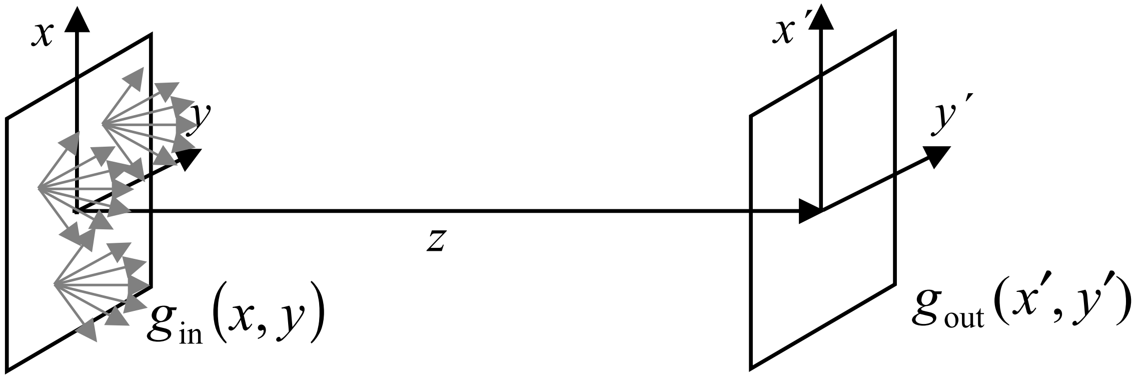


Anomalous
(or negative)
dispersion

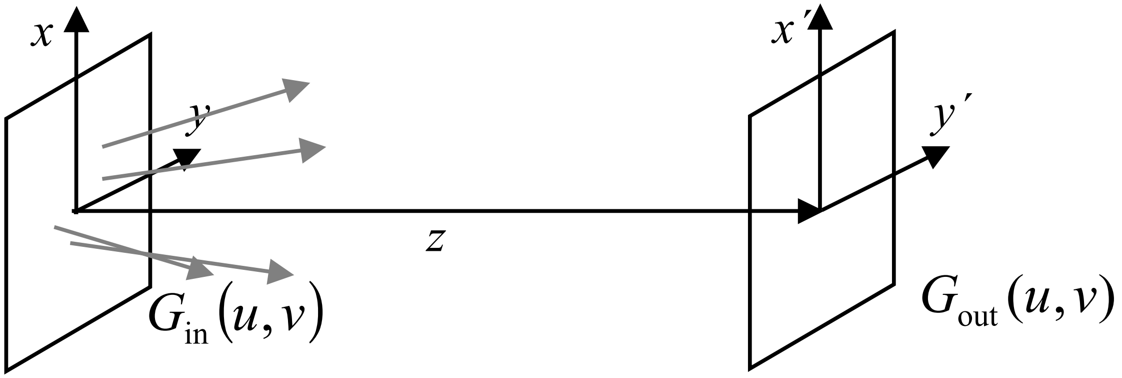
polychromatic
(white)
light

Glass prism:
normal dispersion

Fresnel diffraction formulae



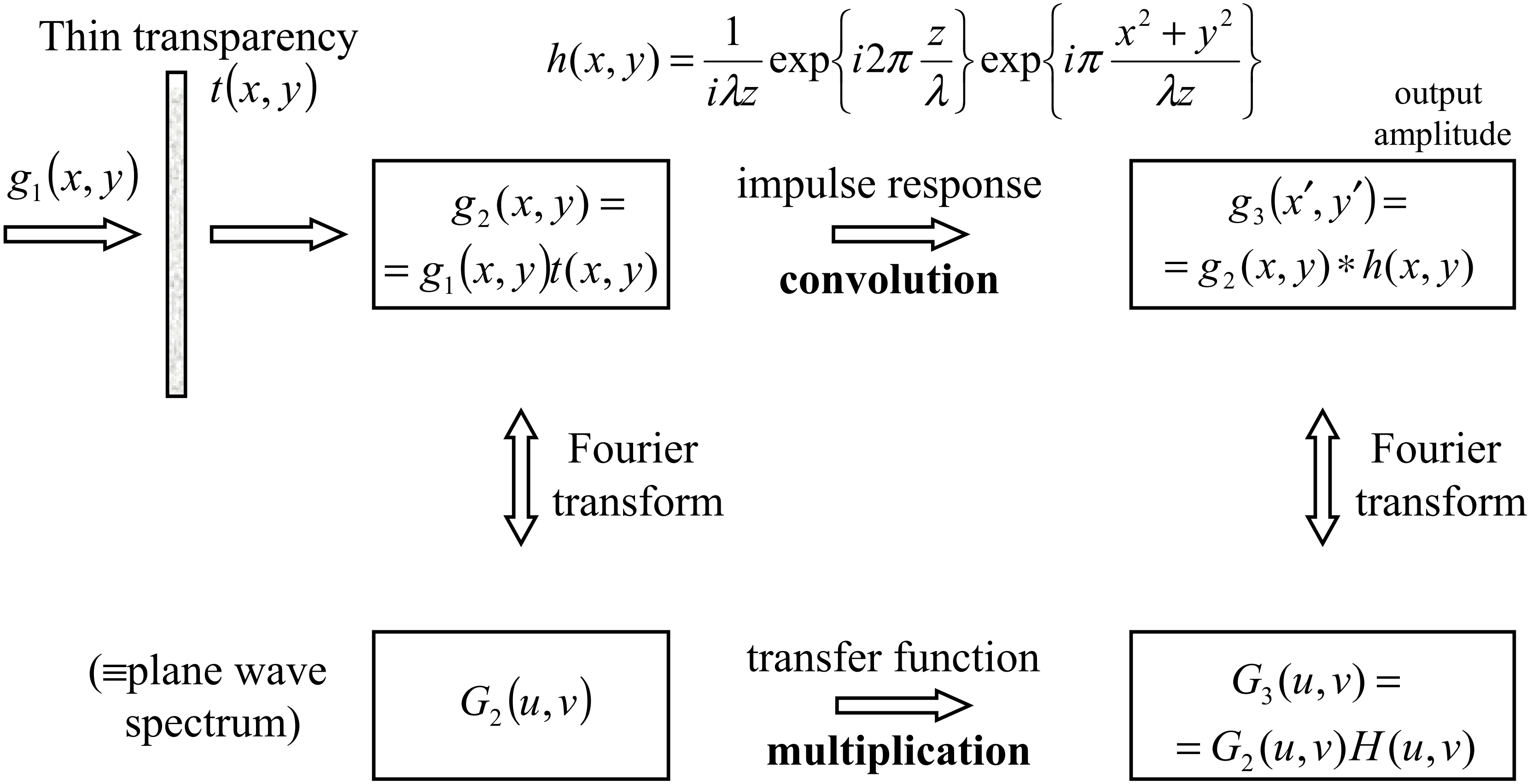
$$g_{\text{out}}(x',y';z)=\frac{1}{i\lambda z}\exp\left\{i2\pi\frac{z}{\lambda}\right\}\int g_{\text{in}}(x,y)\exp\left\{i\pi\frac{(x'-x)^2+(y'-y)^2}{\lambda z}\right\}\mathrm{d}x\mathrm{d}y$$



$$G_{\text{out}}(u,v;z)=\exp\left\{i2\pi\frac{z}{\lambda}\right\}G_{\text{in}}(u,v)\exp\left\{-i\pi\lambda z\left(u^2+v^2\right)\right\}$$

Fresnel diffraction

as a linear, shift-invariant system



Thin transparency

$t(x,y)$

$$h(x,y)=\frac{1}{i\lambda z}\exp\left\{i2\pi\frac{z}{\lambda}\right\}\exp\left\{i\pi\frac{x^2+y^2}{\lambda z}\right\}$$

output amplitude

$g_1(x,y)$

$g_2(x,y)=$
$=g_1(x,y)t(x,y)$

impulse response

convolution

$g_3(x',y')=$
$=g_2(x,y)*h(x,y)$

Fourier transform

Fourier transform

(≡plane wave spectrum)

$G_2(u,v)$

transfer function

multiplication

$G_3(u,v)=$
$=G_2(u,v)H(u,v)$

$$H(u,v)=\exp\left\{i2\pi\frac{z}{\lambda}\right\}\exp\left\{-i\pi\lambda\left(u^2+v^2\right)z\right\}$$