Topic 1: Models in Optics

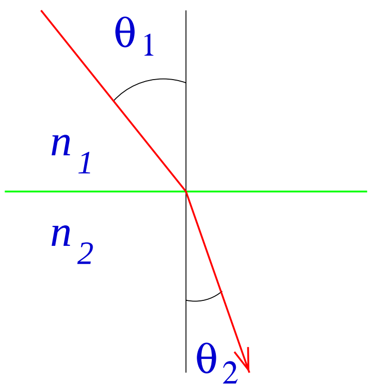
Aim: Review the of models used in optics, and the range of validity of each

Contents:

- Ray Optics
- Ray Wave Theory
- Vector Ray Theory
- Scalar Wave Theory
- Vector Wave theory
- Photon Models (QED)

Ray Optics

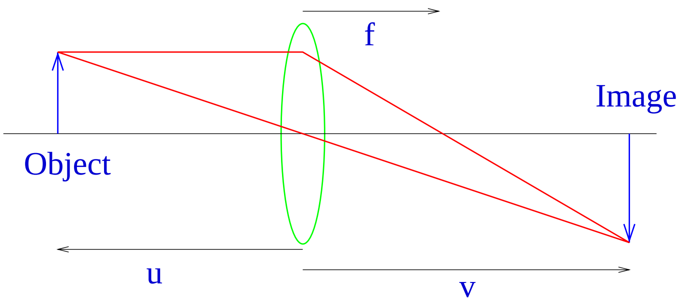
Model: Steam of “balls” that obeys Snell’s Law of refraction at a surface.



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

Is this simple model really useful ?

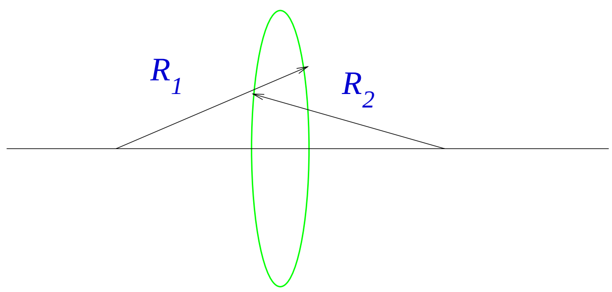
Simple Lens



Imaging properties of

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \quad \text{and} \quad M=\frac{v}{u}$$

Thin Lens



The focal length is given by

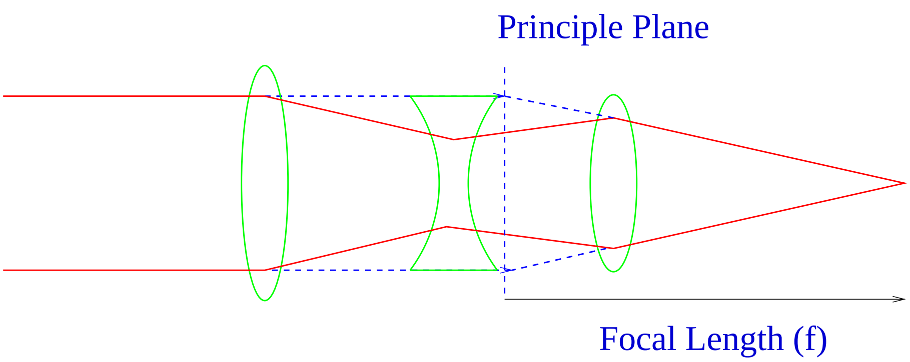
$$\frac{1}{f}=(n-1)\left[\frac{1}{R_1}+\frac{1}{R_2}\right]$$

These expressions will also appear in the more advanced theories.

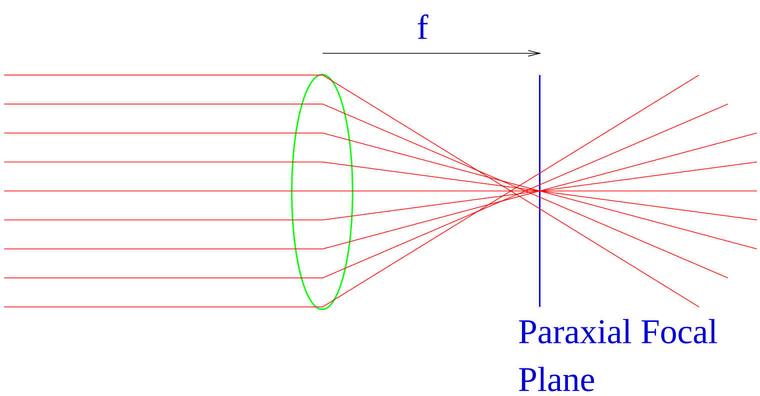
Seen in Physics 2 Lab and Physics 3 Optics.

Use of Ray Optics

Tracing rays through complex systems



Ray tracing to determine lens characteristics



For “ideal” lens we get single point, but for aberrated lens we get indication of Point-Spread-Function (PSF).

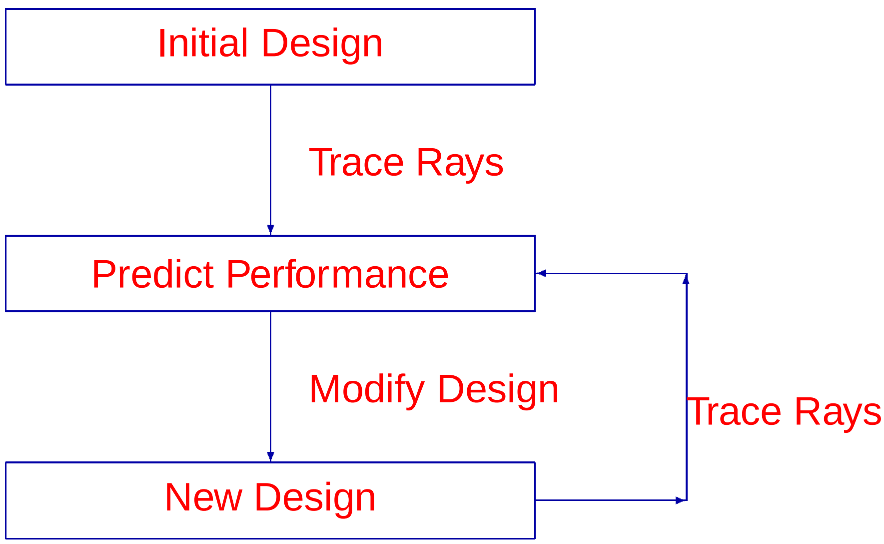
NO DIFFRACTION EFFECTS INCLUDED

Design of Lens System

Typical systems:

- Camera Lens [4 to 20 Elements]
- Microscope Objective [3 to 10 Elements]
- Photocopier objective [6 to 8 Elements]
- Telescope [2 Mirrors plus 0 to 4 glass elements]

Mostly complex system with multiple glass surfaces (almost always spherical).



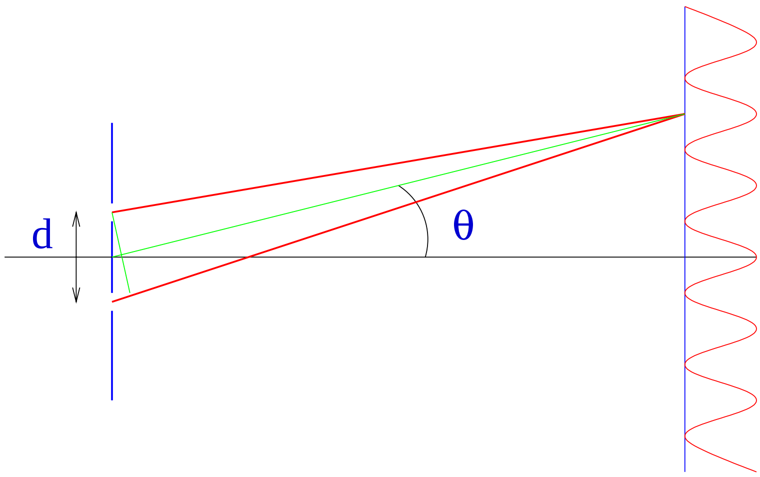
Iterative error reduction, (highly non-linear).

Ideal Computer application, one of the first tasks ever transferred to computer [1956].

Look at this again in Lecture 9/10.

Ray Wave Theory

Add “wave nature” of light by considering light to be rays that spread out and interfere to give “node” and “anti-nodes”.



Young’s Slits we get a bright fringe at:

$$d \sin\theta = \pm n\lambda$$

This theory gives the correct resuults for:

- Diffraction Gratings, so spectroscopy.
- Interferometry: (Michelson, Twyman-Green, Fabre-Perot, thin films.)

This theory introduces wave properties to get interference, but still

No Diffraction

Very useful theory, used in most of Physics 3 Optics. We will use this again for Holography at end of this course.

Vector Ray Theory

Add “vector” properties of light to ray model by assuming orthogonal **E** and **B** field. Solve continuity equations at boundries.

This gives Polarisation effects, for example,

- Polarisation on reflection: Brewster’s angle, Fresnel’s Equations.
- Malus Law: transmission of polarisers, quarter/half wave plates.
- Birefrigence: Linear crystal optics, beam-splitters, Nicol prisms.
- Evanescent Waves: classical barrier penetration, skin depth, planar waveguides.

This theory typically does not contain infererence **or** diffraction.

Seen in Physics 3 Electromagnetism and Physics 3 Optics.

Simple polarisation problems can be formulated as Jones Matrices (very similar to spin operators), more complex, mixed polarisation, by Stokes Matrices.

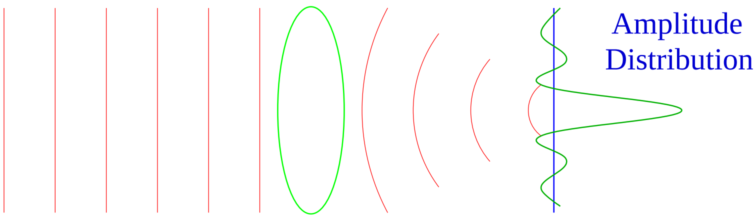
Scalar Wave Theory

Electro-magnetic theory with light field characterised by Scalar Potential.

Valid for objects & apertures $\gg \lambda$.

Gives diffraction as integral expression (mathematical version of Hygen's Secondary Waves)

Uses:



Able to calculate analytic PSF of lens.

Allows use of Fourier Techniques to predict effect of diffraction. Basis of Image Formation, Holography, and Optical Processing. (This Course)

Problems:

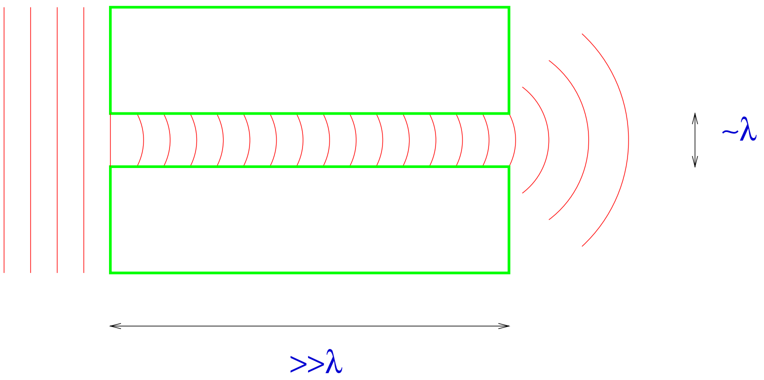
1. Monochromatic light assumed (developed to include Partial Coherence).
2. No polarisation effects, (added by Jone's matrices)
3. Breaks down at wavelength structures
4. Breaks down an very high & low intensities.

Vector Theory

Light is electro-magnetic wave with $\mathbf{E}$ and $\mathbf{B}$ vectors linked by Maxwell's Equations.

If we know boundary conditions, solved for $\mathbf{E}$ and $\mathbf{B}$ fields.

Example: The Thick Slit.



Here Scalar Diffraction not valid, due to "Waveguide" effects in the slit.

In Practice only able to solve for very simple systems,

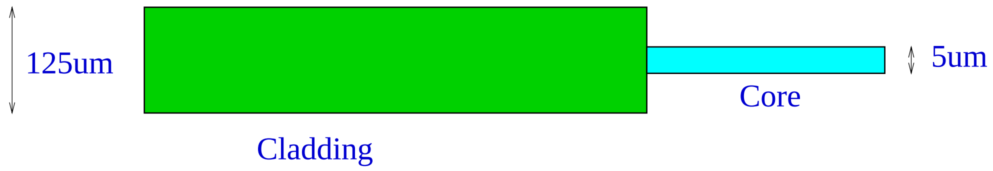
1. Thick Slit
2. Edge
3. Infinite metal grating
4. Infinite dielectric grating

Even then with great difficulties.

Fibre Optics

Glass “fibre” with core down to 1.5μm.

Typical fibre, 5μm glass core and 125μm cladding.



Needs vector treatment, but simple geometry. Solutions identical to wave guide, including mode structure.

Thinnest fibre’s support only one mode, (mono-mode)

Other Areas:

- Radar systems ($\lambda \approx 3$cm)
- Radio transmissions ($\lambda \approx 3cm$ to km)
- Radio telescopes ($\lambda \approx 1$cm to 1m).

Design of these systems requires solution of the vector field problem. Either approximated by scalar field (with care), or solved by numerical simulation.

Quantum Theories

Light is “really ?” and quantised vector field with light propagating as photons.

Quantum effects at High & Low Intensities

High Intensities

At low intensities, elastic scattering of photons from material, but at high energies Inelastic Scattering.

Non-linear effect which are Intensity Dependent.

Examples

- Raman scattering (non-linear photon)
- Frequency Doubling (two photon processes)
- Four Wave mixing (intensity dependent refractive index)
- Optical Bi-stability (intensity dependent refractive index)

Non-linear effects can be induced in any material, with enough power.

Range of “Optically Active” materials, get non-linear effect at low(ish) powers

$$BSO_6 \quad BaTiO_4 \quad GaAs \quad LiNbO_3 \quad LiquidCrystals$$

Some discussion in Atomic and Molecular Physics and Laser Physics courses.

Low Intensities:

Linear interaction with materials, but detect a quantised intensity, (whole Photons).

Measure a probability function, (approximate a probability function), but also quantum effects.

Effects

1. Noise in detected signal (fundamental problem at low light levels).
2. Intensity correlations (quantum effect used in radio interferometry).
3. Squezzed States: quantum states at low light levels, similar to low temperature statistical effects.

Modern, specilised area of optics, not able to put much of this in an undergraduate physics course.