Geometric Optics
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Outline of sections

1
Electromagnetic waves emanating from a point source
Wavefronts, waves
Waves traveling through a homogeneous medium where the speed is uniform (also called an isotropic medium) or through a medium where the waves' speed varies
Mirage
The speed of a wave of visible-spectrum light is slowed, passing through a medium, because the light causes electron clouds to vibrate. The vibrations of electrons (moving electric charges) create electromagnetic waves, whose phase lags behind the phase of the incident light. Summing the two waves, the resulting wave travels more slowly than the incident light. (The explanation isn't really part of geometric optics, but we discuss it briefly.)
Deformation of wavefronts and therefore deflection of rays as light passes through an interface between media or is reflected
Specular or diffuse transmission and reflection
Viewing an object that is underwater from the air above – it appears to be further away than it is.
Aperture, pencil of rays, diffraction
Rays of a pencil may be diverging, parallel, or converging, and this can be altered by lenses and mirrors.
Bundles, pencils, beams
Collimated beams, moonbeams, slide projector
Focusing sunlight to start a fire

2
Form a bright image of an object on a screen by gathering pencils of light, focusing them on the screen. If the screen isn't at the correct distance where the pencils focus, the image is blurred.
Forming a dim image using a pinhole, there is not a unique focal distance.
A smaller pinhole reduces overlap of pencils, which reduces blur, but yields a dimmer image. If the pinhole is too small, diffraction causes blur.
When rays are reflected, the angle of reflection equals the angle of incidence.
Snell's law and the law of reflection govern the deflection of rays at an interface between media, whether the interface is flat or curved. The incident rays and refracted or reflected rays lie in the same plane.
Rays passing through a parallel plate emerge headed in the same direction, laterally displaced.
Geometric optics studies the manipulation of pencils of light pencils using flat and curved surfaces, reflected by mirrors and passing through interfaces between media where light travels at different speeds.
Paths of rays passing through prisms
The minimal angle of deviation for a prism held in the path of a ray is the one such that the angle between the prism face and ray is the same on the two sides of the prism.

A lens is seen to be a like a stack of prisms with powers chosen to focus a pencil to become another pencil of rays headed to or from a focal point.

3
Snell's law of refraction. Index of refraction. The law of reflection. These laws are implied by Fermat's principle, which is implied by modern theories of physics.
Dispersion, Abbe number
The critical angle of total internal reflection, finding it using Snell's law. Examples: fiber optics, gonioscopy, prisms used as mirrors in optical instruments, cutting of gems, windshield rain sensor

4
Define vergence: inverse of the distance to the place where the rays focus towards or emanate from
Preview of the vergence equation, to see why vergence is useful
Stigmatic optical system: a pencil of rays becomes another pencil of rays, diverging from or converging to a point
Conjugate points and planes
How a lens is designed to focus wavefronts: The lens is shaped so that the ray paths emanating from an object point and passing through various parts of the lens all require the same time for light to pass from that object point to its image point. All of the wavefront leaving the object point, that passes through the lens, therefore arrives at the image point at the same time, in the same phase, when reaching the image point.
Reversibility of optical pathways: if a path is least-time one way, it's also least-time going back along the same path.
Descartes found that various rotated conic sections are needed for stigmatic refraction and reflection, but of the various conic sections, spherical surfaces are easiest to manufacture.
Gauss found the spherical surfaces give good approximations and simplify computations, provided the rays are paraxial.
In Gaussian or first-order optics, there is a simple vergence equation,
$U + P = V$ (Vergence arriving at a lens or mirror) + (power of the lens or mirror) = (vergence leaving the lens or mirror.) Also, we know the behavior of 3 cardinal rays associated with three cardinal points.
Cardinal points for convex and concave lenses and mirrors.
A central ray passes through the intersection of the lens and the optical axis undeviated.
A ray passing through or aimed at the primary focal point travels parallel to the optical axis after refraction. A ray arriving at the lens, traveling parallel to the optical axis, aims in the direction that passes through the secondary focal point after passing through the lens. Spherical mirrors have analogous points and rays.
We will add some more "cardinal" points to the collection later, in Part 6, when we consider thick lenses and passage through multiple lenses.

5
Focal planes perpendicular to the optical axis pass through the focal points.

Real objects and images are on the same side of the lens as their rays. Virtual objects and images are on the other side of the lens, and we draw dotted lines to show the rays aiming towards them. Pencils of rays in which the rays are parallel to each other focus from and to "optical infinity." Follow vergence changes through a series of lenses along the optical axis.

Ray diagrams for plus and minus lenses

Use the central ray and vergence calculation to find the location, size, and orientation of the image of an object, using similar triangles.

Magnification:

Transverse (linear, lateral) magnification = (image height)/(object height)

Axial magnification = the square of lateral magnification. Here, we are comparing the depth along the optical axis of the image to that of the object.

Angular magnification = (angle subtended at the eye with an instrument)/(angle subtended at the eye without the instrument)

6

How does an image move along the axis, as an object moves or the power of a lens changes?

As the object slides to the right along the optical axis, the image moves in the same direction, maybe passing through optical infinity.

Increasing power of a plus lens draws a real image closer to the lens. Increasing power of a minus lens pushes it further away, possibly through optical infinity.

Generalizing to analysis of thick lenses and systems of lenses, using more "cardinal" points, the nodal points, principal points and principal planes

Generalizing the central ray: A ray coming to the first nodal point emerges from the second nodal point, headed in the same direction as the original ray.

Primary and secondary focal points are generalized with the assistance of the principal planes: A ray from the primary focal point strikes the first principal plane, and comes out the second principal plane the same distance from the optical axis, and heads parallel to the axis.

A ray arriving at the first principal plane parallel to the optical axis exits the second principal plane, the same distance from the optical axis as it struck the first principal plane, and heads for the secondary focal point.

If there is air on the left of a thick lens and water replaces air on the right, the nodal points and secondary focal point slide to the right.

Meniscus lenses, locations of their focal and principal points

Rear-vertex power is more plus (or more minus) power than true power, which is more than front-vertex power, for + or – power meniscus lenses. When you put the back surface of glasses on the nose cone of a lens meter, you measure rear-vertex power.

Power of a surface, reduced vergence

Examples: power of the cornea with air on one side, and aqueous on the other

Power of the cornea, when swimming underwater

How to tell whether a surface has + or – power: draw a box into the medium with higher index of refraction, and look at the shape of the lens enclosed by the box.

Power of an implant lens compared to its power in air

7

Reflection from a flat surface,

Focal points and ray diagrams for convex and concave mirrors

What do you see when you look in a flat mirror?
Prisms: real and virtual objects and images

8
Angular magnification
Galilean telescope: an afocal system providing angular magnification. (We won't go through details of the computation of angular magnification.)
Astronomical telescope
For both telescopes:
Angular magnification =   - (power of ocular)/(power of objective)
Using a mirror, instead of a lens, as objective of an astronomical telescope

9
Astigmatism, focal lines
Toric lens
Conoid of Sturm
Aberrations of first order optics
Aberrations causing blur:
 Chromatic aberration
 Monochromatic aberrations:
   Spherical aberration
   Astigmatism of oblique incidence
   Coma – not important to us here
(You will see elsewhere these and higher order aberrations described with "Zernike polynomials.")
Aberrations deforming the image:
   Distortion
   Curvature of field
Aspheric design of lenses
20 foot (6 meter) examining lane vs. short lane without or with mirror