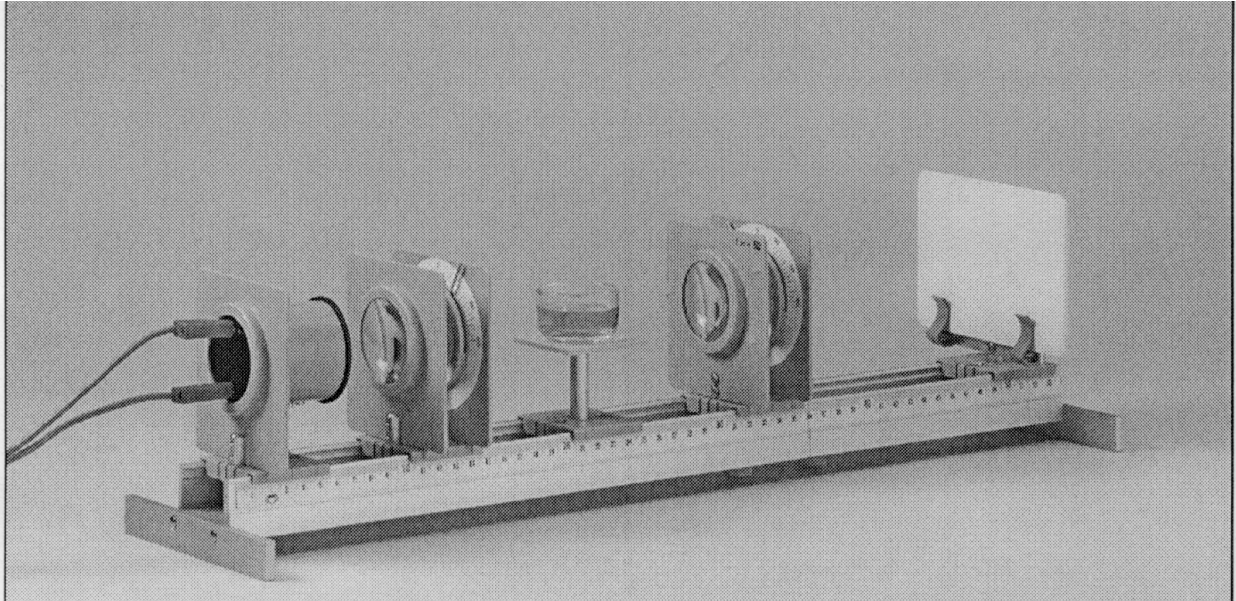# Basic Optics Experiments

1 Introduction

This chapter describes 6 experiments in basic optics that can be carried out using the Cornelsen Student Optics Kit, shown above, and a HeNe laser.

The contents of the kit and a guide to interpreting the setup drawings are included in the following two pages.

Each experiment can be done in only a couple of hours, but you will need to use the rest of the available class time for analyzing your results, fitting data, etc. That extra time is the best time to get help from the instructor(s) on error analysis, data fitting, ray tracing, significant figures, etc.
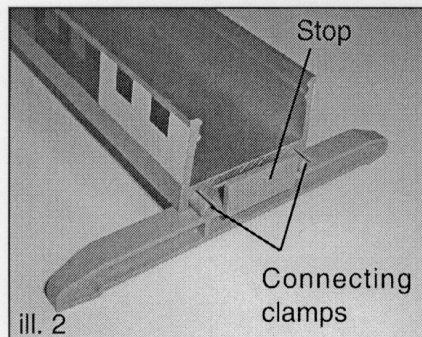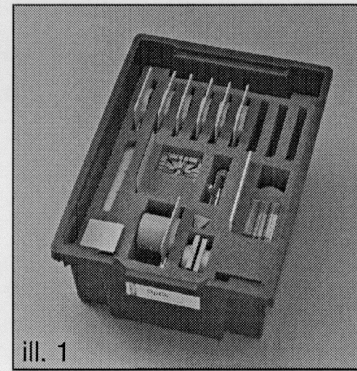The experiments are:

- Experiment I

    Reflection at a plane mirror

    Reflection at a curved mirror

    Refraction

- Experiment II - Image formation and ray tracing

    Pinhole camera

    Converging lenses

    Diverging lenses

- Experiment III

  Lens shape and spherical aberration

  Dispersion

- Experiment IV

  Diffraction and interference; Fourier optics

  Resolution

- Experiment V - Magnifiers, Microscopes, and Telescopes

- Experiment VI

  Polarization

  Chiral molecules and optical activity

1. General Notes

The CorEx Student´s experiment kit Optics 1 (art.-no. 47525) contains all necessary parts to carry out basic experiments in geometrical optics. The additional kit Optics 2 (art.-no. 47550) consists of supplementary materials for experiments in wave optics (ill. 1).

All parts are stored for easy handling in a storage tray with foam insert which also has space for the additional parts of the kit Optics 2.

ill. 1

Stop

Connecting clamps

ill. 2

The base for all experiments is the especially designed rail profile which can be stabilised by two feet plugged at the ends of the rail (ill. 2).

The feet are made of plastic and fastened siedeways in the slots of the rail profile.

Ensure that the feet are not bent when slided in.

Equally avoid benting when removing the feet.

To ensure this turn the rail profile and squeeze the feet proportional out of the slots (ill.3).

ill. 3

1
2
3
ill. 4
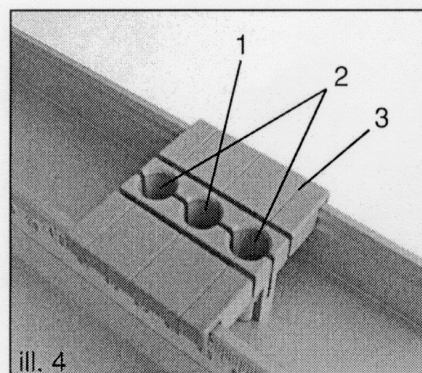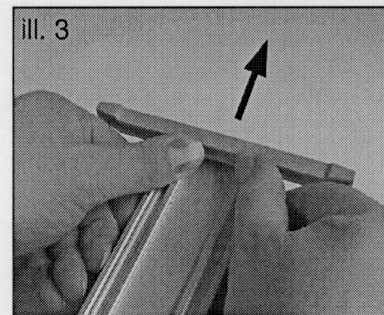
Clamp sliders can be installed quickly onto the rail. The pins of the optical elements are put vertically into the holes of the clamp sliders. With the pin in one of the exterior holes the slider can be shifted on the rail, whereas putting the pin into the central hole fixes the slider on its position. Thereby an exact alignment of the elements on the optical axis is assured (ill. 4).

With help of marks on the clamp slider the position of the optical element can be red from the scale of the rail (ill. 5).

ill. 5
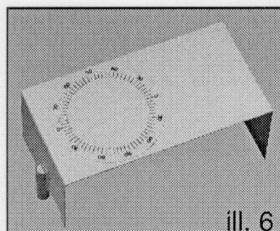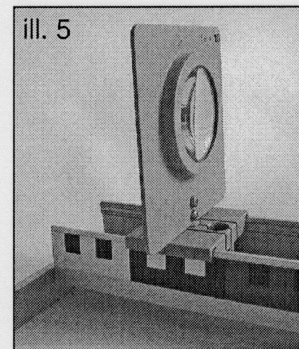
ill. 6

A special screen table is used for the projection of light beams through optical bodies. The table is put into a clamps slider with its pin. A circular scale on the table allows the reading of refraction angles (ill. 6).

3. Single part list
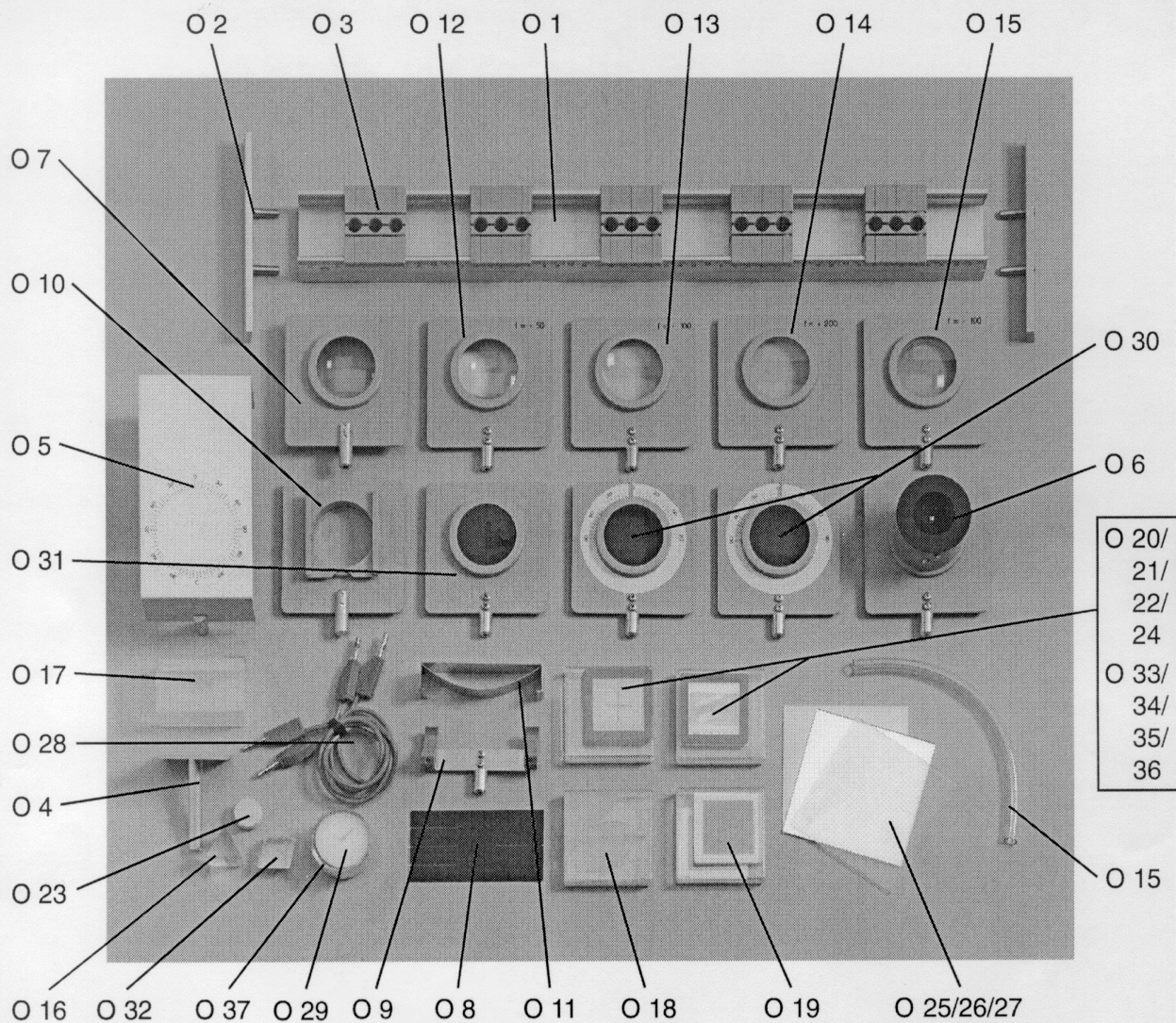
All single parts can also be ordered individually as spare parts with the following art.-no.

3.1 Geometrical optics kit Optics 1 (art.-no. 47525)

Part.-no.	Order-no.	Description	Part.-no.	Order-no.	Description
O 1	40810	Rail profile, 50 cm long	O 9	47256	Screen and mirror holder
O 2	40861	Pair of feet	O 10	47517	Diaphragm and slide holder
O 3	40820	Clamp slider (5x)	O 11	47090	Universal mirror
O 4	47215	Object table	O 12	47134	Biconvex lens in frame f = +50 mm
O 5	47513	Projection table			
O 6	47514	Optics lamp 12 V / 20 W	O 13	47135	Biconvex lens in frame f = +100 mm
O 7	47515	Condenser with diaphragm- and slide holder	O 14	47136	Biconvex lens in frame f = + 200 mm
O 8	47155	Slit diaphragm 1 / 3 slits			

4

Part.-no.	Order-no.	Description		Part.-no.	Order-no.	Description
O 15	47138	Biconcave lens in frame $f = -100$ mm		O 25	47022	Plane mirror 90 x 90 mm
				O 26	13731	Screen, white 90 x 90 mm
O 16	47241	Equilateral prism		O 27	13723	Screen, transparent 90 x 90 mm
O 17	47508	Cuve		O 28	15742	Connecting leads, 50 cm (2x)
O 18	47509	Set (5) optical bodies		O 29	12816	Tea light
O 19	47045	Set (3) colour filters red, blue, green			43150	Plastic box 64 x 64 x 15 mm
O 20	47142	Hole diaphragm d = 2 mm			475251	Experimental instructions
O 21	47143	Hole diaphragm d = 4 mm			75031	Storing tray
O 22	47162	Arrow diaphragm			75041	Lid for tray
O 23	47510	Shadow pin			47531	Foam insert
O 24	47070	Color slide				

3.2 Additional equipment for wave optics kit Optics 2 (art.-no. 47550)

Part.-no.	Order-no.	Description		Part.-no.	Order-no.	Description
O 30	47344	Polariser and analyser in frame		O 35	47282	Slide with grating, 300 lines/mm
O 31	47320	Slit, adjustable		O 36	47285	Slide with grating, 8 lines/mm
O 32	47405	Limespar-crystal		O 37	14020	Glass tube
O 33	47407	Slide with mica probe		O 38	63692	Piece of PVC tubing
O 34	47406	Slide with cross				

4. Icons of the optical elements shown in the experiment´s illustrations:

optics lamp

projection table

lens

condenser

screen

slide holder

polariser/analyser

object table

adjustable slit

screen or mirror holder
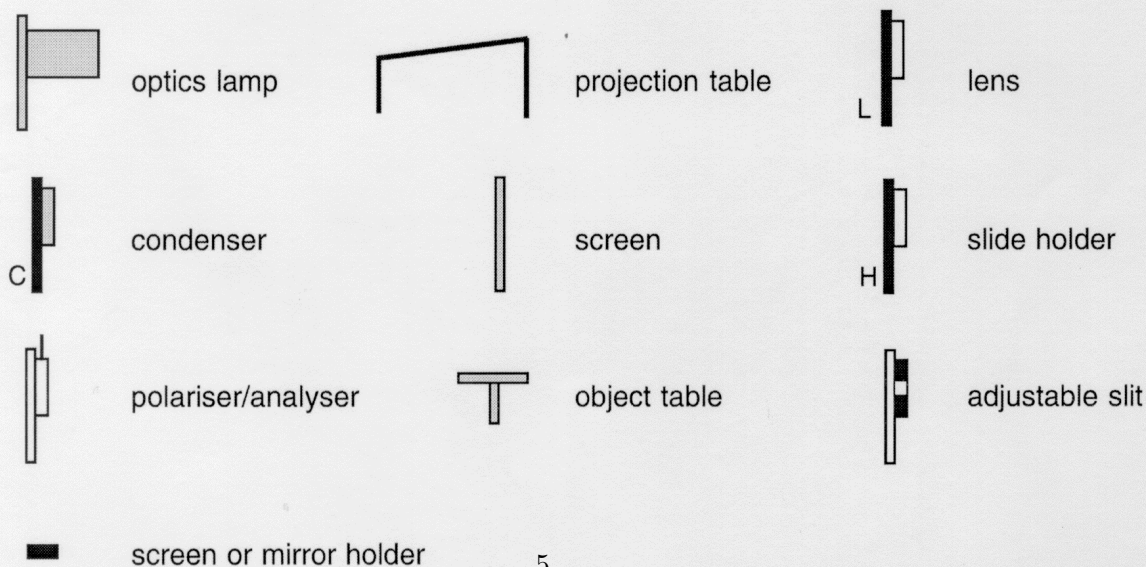
2 EXPERIMENT I

2.1 Reflection at a Plane Mirror

Arrange the optics lamp, the condenser lens, and the table as shown in the drawing. Put in the 1-slit aperture vertically. Put the "universal mirror" on the table, flat side toward the light.
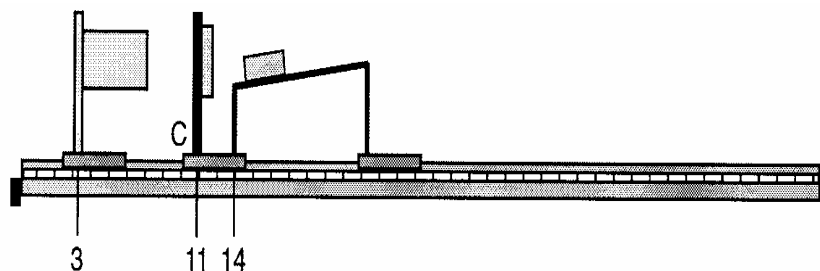
Adjust the condenser to obtain a straight beam of light. Measure the angle of incidence and angle of reflection for six different positions of the mirror. Estimate the uncertainty in your measurements (and explain in your report *how.*)

In your report, plot the angle of reflection vs. the angle of incidence on a graph. What law can you deduce that relates reflection to incidence? How confident are you that this law is correct, *based on your own experiment*? Can you be quantitative about your confidence?

2.2 Reflection at a Curved Mirror

Use the three-slit aperture instead of the 1-slit aperture, and arrange the condenser to obtain 3 parallel rays of light. Reflect the rays off a concave mirror, and note the position of the crossing point. Reflect the rays off a convex mirror, and note the position where the reflected rays *appear to emanate from.* Determine the curvature radius of the mirrors.

When a ray reflects off of a curved mirror, it only "sees" a small part of the mirror. That small part of the mirror may be assumed to be flat - thus, the law of reflection obtained in part 2.1 (angle of incidence = angle of reflection) should be correct. Note, however, that different parallel rays hit different parts of the mirror, and thus have different angles of incidence.

A convex mirror can be used to focus parallel light rays (such as rays from a distant star.) Use the law of reflection to predict at what distance from a concave mirror (radius r) parallel rays will focus (i.e., cross). (You will have to consider only parallel rays that pass close to the center of curvature, point p in the diagram.) Does this prediction accord with your observations? Discuss your results and the uncertainties in your measurements.
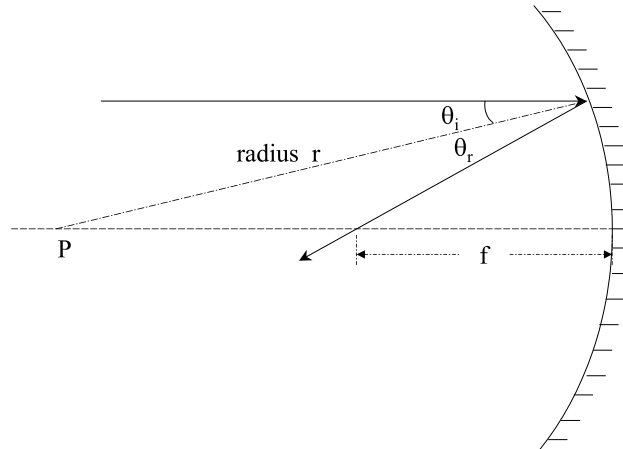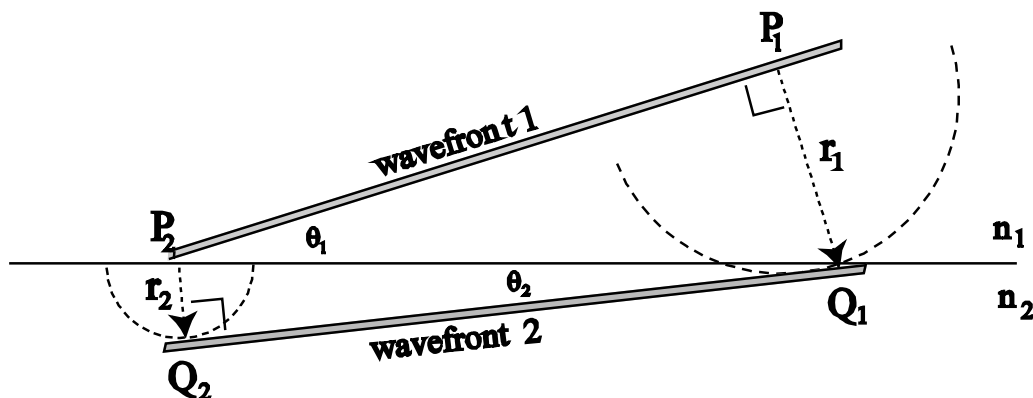
2.3 Refraction

Light propagates with speed c in vacuum, but at a slower speed through materials (even air!) The ratio of the speed of light in vacuum to the speed in a material is the *refractive index* of the material, n.

A consequence of the reduced speed of light is that light changes direction at interfaces between materials with different n. You can (and should) derive the law that describes the change of direction (the "law of refraction", or Snell's law) using a Huygen's wavelet construction, as shown here. Wavefront 1 approaches the interface at an angle. The angle the wavefront makes with the surface (at point P2) is also the angle of incidence of the ray that corresponds to this wave. (Recall that rays are perpendicular to wavefronts, and that the angle of incidence of a ray is measured with respect to the surface normal.) At a short time later, the wave at P2 will propagate into the material 2 and be at point Q2. In the meantime, the wave at P1 will have reached the surface at point Q1. Note that the distances the wave travels in material 2 (P2 to Q2) is shorter than the distance the wave travels outside (P1 to Q1), because the speed is faster outside.

You should use the diagram below to derive the relationship between θ_1 and θ_2.

Experimental:

Use the 1 slit aperture with the condenser and lamp, as in expt. 2.1, and use the semicircular optical flat as shown. Measure the angles of incidence and refraction for light as it enters the glass, and for light refracting as it leaves the glass. (You need to make sure that light hits one (of the two) interfaces at normal incidence, so that no refraction occurs at that interface. Then, all refraction is caused by the interface that is not normal to the beam propagation.) You should make measurements at eight different angles for both entering and leaving light beams. Also, you **must** determine the uncertainties in your angle measurements, and discuss in your report **how**.
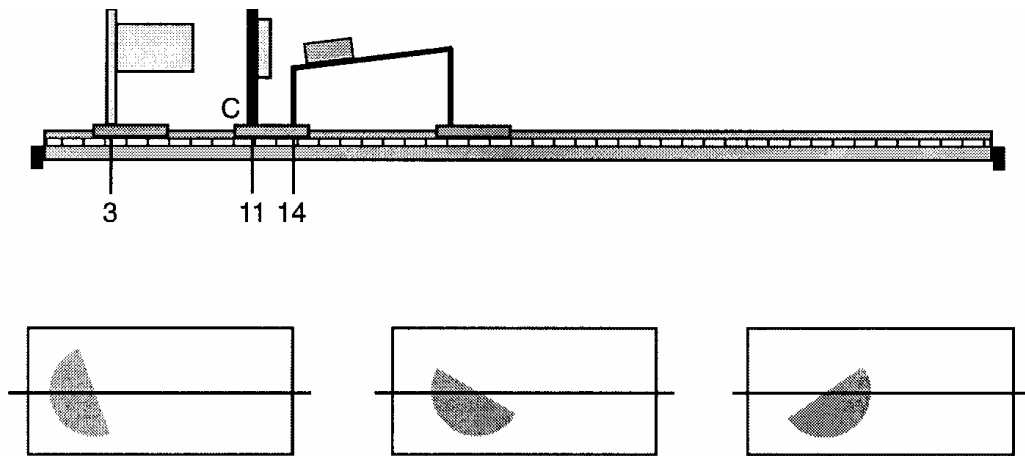
Fit your data to the theory (Snell's law) and determine the index of refraction of the semicircular optical flat. Include error bars on your data points. Do **not** "connect the dots" between your data points - any continuous lines or curves on a plot should be "theoretical", fit curves or lines. For this experiment, you may choose whether to fit to a plot of θ_2 vs. θ_1 (requires fitting to a slightly complicated function) or to fit to a plot of $\sin\theta_2$ vs. $\sin\theta_2$. If you choose the latter, you **must** consider carefully how the sizes of your error bars may vary: you should discuss this point in your report.

As a historical note: Isaac Newton observed the refraction of light toward the normal in glass. He noted that this bending might be caused by an attractive force between light particles and the glass... similar to how a ball will be deflected by a small, sloping step down. What prediction would Newton's theory of refraction make that we now know is wrong?

3 EXPERIMENT II - Image Formation and Ray Tracing

A "ray" can be thought of as the path of a narrow beam of light, such as a laser pointer. Drawing rays can help to analyze the behavior of an optical system: you have already used rays to analyze mirrors in experiment 1. Rays indicate the direction of propagation of light, and are always perpendicular to wavefronts.

3.1 Pinhole camera

Arrange the aperture support and the viewing screen on the optical rail as shown in the drawing. Put the tea light (candle) onto the clamp slider and the slider on the optical rail. Select a pinhole slide, or use the home-made pinhole.
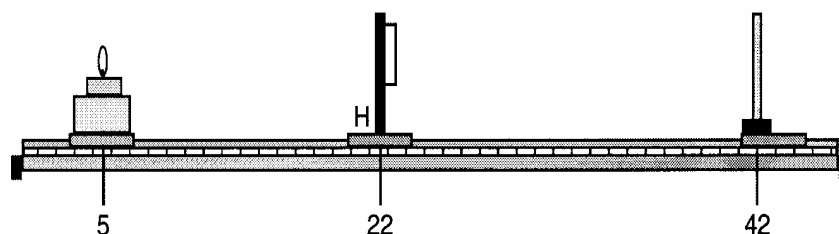
Light the candle, and completely darken the room. Observe the image of the candle on the screen. Measure the size of the image for six different positions of the pinhole (screen and candle fixed) and for six different positions of the screen (candle and pinhole fixed.) Be sure to note your uncertainty in image size, and in your report say **how** you determined that uncertainty. Plot the image size vs. position. Compare your results to what you expect from simple ray tracing.

Try using a larger pinhole. What is the qualitative effect on the image?

3.2 Converging lenses

The most important parameter describing a lens is the *focal length*, which is the distance beyond the lens where incident parallel rays will focus to a point. (If the focal length is negative, it indicates that the lens causes the rays to diverge; they will appear to emanate from a point "upstream" of the lens.)

1. All rays parallel to the optical axis (an axis through the center of the lens and perpendicular to it) will cross the optical axis at the focal point.

2. For an ideal, thin lens, rays that go through the center of the lens are undeflected. You can see this by noting that the surfaces of an ideal, thin lens are parallel and the lens has no thickness at its center. (Of course, this is an idealization - all real lenses have some thickness. But even real lenses have parallel surfaces at their centers, and so the deflection even in a real thinnish lens is negligible.)

The information in **1.** and **2.** above allow you to graphically determine where a lens will form an image of an object. When an object is illuminated, it will scatter light in all directions.

Consider the tip of the arrow object in the figure. Rays of light emanate from the tip in all directions. We will trace the paths of only a few of those rays: ideal lens theory tells us that if a few of the rays from the arrow tip cross (i.e. focus at a point), then all the rays (deflected by the lens) will cross at the same point. So, the trick to **ray tracing** is to figure out **which rays to trace**, and ignore all the other rays... you know they will focus at the same point as the special rays you choose to trace.

You must choose only rays whose path you know! We know that **1.** the ray parallel to the optical axis is deflected through the focal point, and **2.** the ray through the center of the lens is undeflected. A little quick work with a straightedge shows these rays cross a bit to the right of the focal point. **This is where the image of the tip of the arrow will be**. As a matter of nomenclature, the distance from the lens to the object (**op**) is called o (the object distance) and the distance from the lens to the image (**os**) is called i (the image distance.)
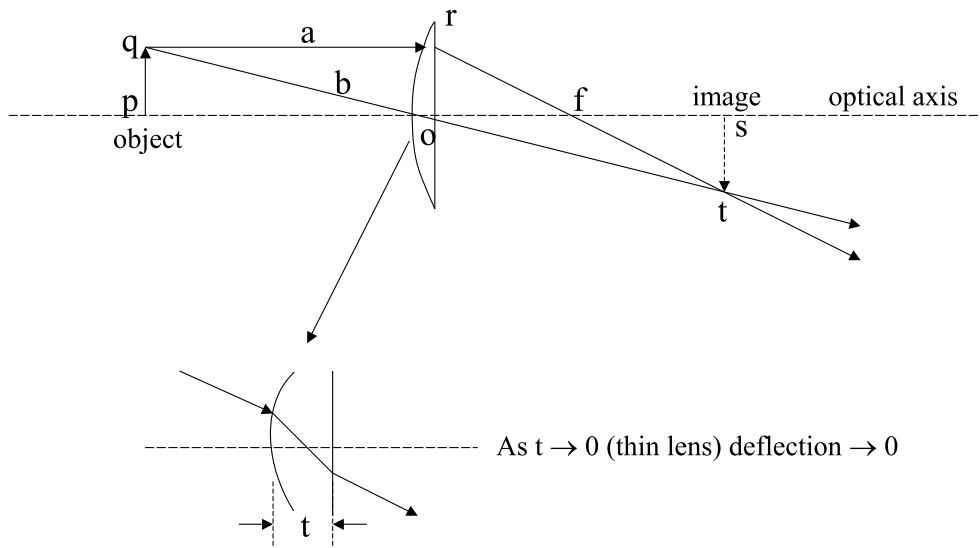
The ray diagram is more than a cartoon: you can use it to derive the lens equation. Consider the **similar triangles** in the diagram: **pqo** $\sim$ **sto**, and **orf** $\sim$ **stf**. Use these two pairs of similar triangles to write down two equations containing o, i, f, and the height of the object (distance **pq**) and the height of the image (distance **st**). (Hint: don't use the hypotenuses in your equations!) You can then eliminate the image and object heights to obtain the lens equation. **Do this in your report**.

Note that you can quickly calculate (from the similar triangles) the ratio of the height of the image to the height of the object, in terms of o and i. We call this ratio the **magnification**.

Experimental: Use the wooden rack to hold the lamp source. (You need more length for this experiment than the optical rail has.) Put a slide holder at one end of the optical rail, and place the $f = +50$ lens about 15 cm in. Put the viewing screen in a holder and place it at the other end of the optical rail. Put a slide of an arrow in the slide holder. Place the optical rail on a block of wood so that light from the lamp passes through the slide and the lens. Adjust the viewing screen to obtain the best focus of the image of the arrow.

For ten different positions of the lens, measure the object distance, the image distance (for best focus), and the size of the image. Be sure to note uncertainties in your measurements. (It might be useful to have each team member independently locate the position of "best focus".) Use your data to check the lens equation,

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f} \tag{1}$$

What value of f do you obtain from a best fit of your data? Also, check whether magnification $= i/o$, as expected. Is the image right-side up, or inverted?

Observe the text on this page while viewing through the $f = +50$ lens, and then the $f = +100$, $f = +200$, and $f = -100$ lenses. In your report, comment on these observations.

3.3 Diverging lenses

Remove the arrow from the slide holder, and place a picture slide in it. Put a diverging lens $(f = -100)$ in the lens holder. Can you form a focused image on the viewing screen?

Remove the viewing screen and look "upstream" towards the source. Where does the image appear to be located? In your report, construct a ray diagram showing the object, the diverging lens, and the image. As with converging lenses, the ray through the center of the lens is undeflected; a ray parallel to the optical axis is bent by the lens so that it appears to come from a point a distance f "upstream" of the lens.

Images formed from light rays that pass through the image location are called **real** images; images formed from light rays that only appear to emanate from the image location are called **virtual**.

4 EXPERIMENT III

4.1 Lens shape and Spherical Aberration

Lenses are able to bring light rays to a focus because the rays are refracted at the lens surfaces. The easiest (non-flat) shape to grind is a spherical section. Thus, most lenses are made in this shape.

Consider a ray approaching a plano-convex lens, parallel to the optical axis, as shown in the diagram. With the assumption that the ray is close to the axis (compared with the lens radius, r), you can use Snell's law to determine f, the focal length. (Hints: use the fact that $\alpha + \theta_1 = \theta_2$. Also, for small angles, $\sin\theta \approx \theta$.) **Do this in your report**. You will observe from your calculation that all parallel rays cross the optical axis at the same point f, *provided they are close to the optic*
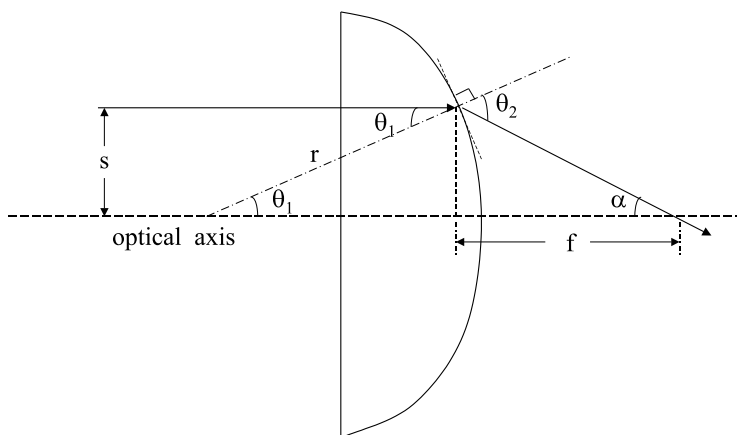

Next, consider rays that are not close to the optical axis. Where do you calculate that they will cross the optical axis? In other words, *derive* f as a function of r/R, r being the distance from the optical axis of the parallel ray, and R being the radius of the lens.

The fact that f, the focal length, varies for rays far from the optical axis is called **spherical aberration**.

Experimental: Align the HeNe laser so the beam moves straight down the center of the wooden board, just grazing the surface. (You may have to shim the board or the laser with some paper.) Place the semicircular optical flat on a piece of paper as shown, and tape it down at the top and bottom edges. Place the optical flat in the center of beam, with the flat surface upstream and perpendicular to the beam. (When adding a centered optical component, you should make sure the beam still goes on the same path, downstream of the new component, as it did before the component was added.) Mark the left edge of the paper; then mark the point where the beam enters the "lens" and mark the path of the beam as it leaves the lens for about 10 cm. Next, slide the paper and lens down four millimeters, keeping the flat side perpendicular to the beam. Mark the entry point and the exit path again. Repeat. At the end of your experiment, you should have a paper that looks like the Figure on the following page.

Use the rays near the axis to estimate the focal length of the "lens", and calculate the index

of refraction of the lens glass. Plot the expression you derived for f vs r/R along with your measured data points. Is there agreement?
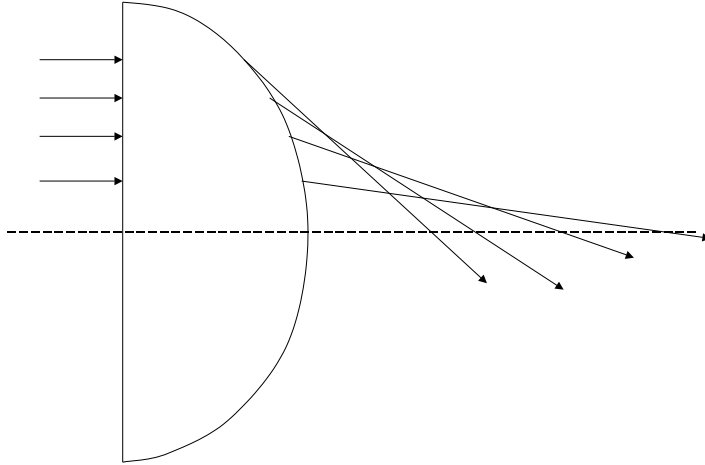
4.2   Dispersion

Another source of aberration in optical systems is dispersion. Dispersion refers to the fact that the index of refraction, n, varies with the frequency of light.

Qualitatively, this phenomenon can be understood by analogy to forced harmonic oscillators. Materials (such as glass) contain atoms with orbital electrons that will be driven to and fro by the oscillating electric field from an impinging light beam. Because accelerating charges radiate, the electrons will radiate electromagnetic energy. The combination of the impinging field and the reradiated fields give rise to the light beam that propagates through the material.

The electrons in the material act like forced oscillators under the influence of the impinging field. What is their behavior?

An oscillator always moves at the frequency at which it is driven; its amplitude is highest if it is driven at resonance. More importantly for this discussion, there is a phase difference between the driving force and the response. If the driving force is at a low frequency (compared with resonance), the phase difference is very small. The oscillator tracks the driving force. If the driving force is at a very high frequency, the oscillator will be 180° out of phase. At resonance, the oscillator will lag behind the driving force by 90°. It turns out that summing the re-emitted waves over the plane adds an additional phase lag of 90° (the interested student is referred to the Feynman Lectures on Physics.) **Thus, below resonance, the re-emitted wave lags by less than** 180°. When added to the original wave, this produces a retardation of the phase of the wave. **Above resonance, the re-emitted wave lags by more than** 180°. When added to the original wave, this produces an apparent advance of the phase of the wave.

Thus, the speed with which the combined (impinging plus reradiating) wave moves through the material depends on the phase of the reradiated waves which depends on the frequency. (It should be stated that by "speed", we are referring to how fast wave fronts move through the material. This is called the "phase velocity".) Note that, above resonance, the phase of the wave moves more quickly! The light "moves" faster than c, and the index of refraction is less than 1! In fact, at x-ray frequencies, most materials do have $n < 1$, and it is possible to get "total external reflection" of x-rays off of water or other materials.

Experimental:
Set up the lamp, the condenser, a converging lens and a prism as shown in the figure.
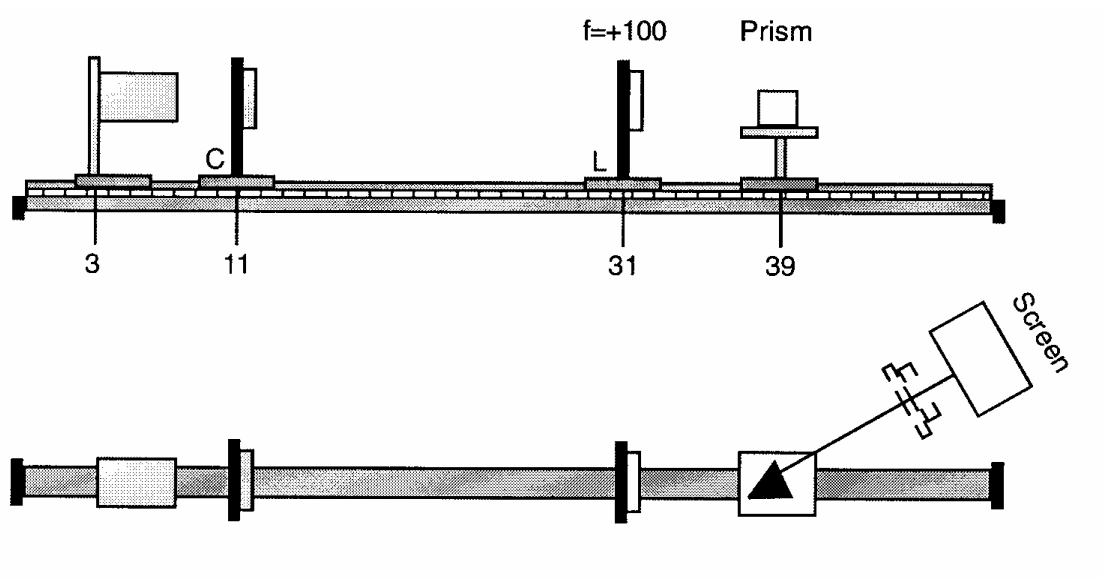
Observe the effect of the prism on white light. Next, insert color filters into the beam path and observe the refraction of each color separately. Carefully measure the angles of the prism and the refracted beams to determine the index of refraction of the prism glass for each color. Is there a "resonant" frequency for the electrons in the glass? Can you estimate what it is?

What do you expect the effect of the variation of n with frequency will be on focusing by a convex lens? Can you observe the aberration (**chromatic aberration**)?

Does the $f = +100$ lens improve the experiment? If so, how?

5 EXPERIMENT IV

5.1 Diffraction and Interference; Fourier Optics

Though ray tracing treats light as if it were made up of particles, propagating light is best described as a wave. (Absorption and emission of light reveal its quantum-mechanical particle-like nature ... not propagation.)

One of the most straightforward observations that demonstrate the wave nature of light is the behavior of a **grating**. A grating is simply a plate with a spatially periodic variation in transmissivity (an **amplitude grating**) or a variation in optical pathlength (a **phase grating** - the variation in path length causes the light waves to have spatially varying phase after passing through the grating.
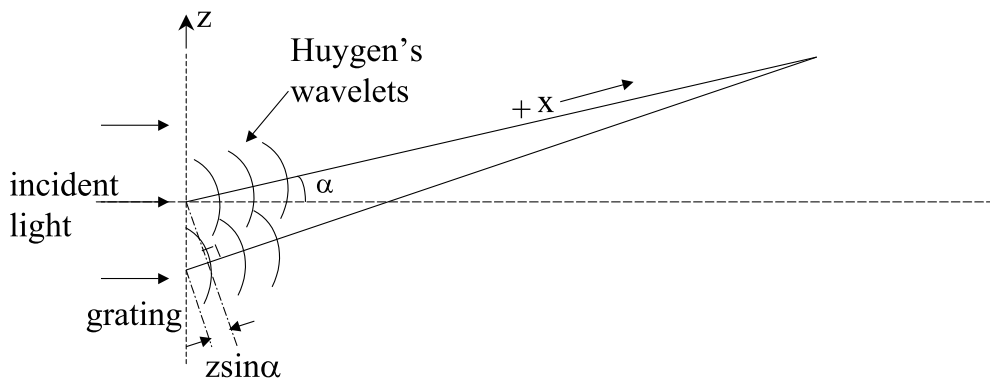
Far from a grating, the light that has passed through will create an interference pattern. We use the principle of Huygen's wavelets to analyze the pattern: each point on the exit side of the grating acts as a source of light, as shown in the figure. We sum up all these sources (keeping track of phase differences) to find the light intensity at a point far downstream. The best way to keep track of phase differences is to use **complex notation**. The electric field of a light wave traveling in the $+x$ direction can be written as

$$E(x,t) = E_0 \cos(\omega t - kx + \varphi), \tag{2}$$

where $k = 2\pi/\lambda$ and φ is the phase of the wave. It is generally convenient to write that

$$E(x,t) = Re\left[e^{i(\omega t - kx + \varphi)}\right], \tag{3}$$

using the Euler identity that $e^{i\theta} = \cos\theta + i\sin\theta$.

Far from the grating (and near to the optical axis), all the Huygen's wavelets will have about the same amplitude (or, more precisely, they will have the same attenuation from their initial amplitudes at the grating.) At the exit side of the grating, the amplitudes (or phases) of the wavelets depend on the position on the grating. In other words,

$$E_0 = E_0(z) \tag{4}$$

Note that E_0 is a real function for an amplitude grating, but is a complex function for a phase grating.

Far downstream, at an angle α the Huygen's wavelets all add together. As can be seen in the drawing, wavelets from lower down on the grating have a longer path to travel (for positive α), so we need to take this into account. The extra path length is $z\sin\alpha \approx z\alpha$ for small α. So x, the distance the wavelet must travel, is

$$x = x_0 + z\alpha \tag{5}$$

The extra path length will cause the wavelets from lower down on the grating to have a **phase lag**.

$$E(t,z) = \mathrm{Re}[E_0(z)e^{i(\omega t - kx_0 + kz\alpha + \varphi)}] = \mathrm{Re}[E_0(z)e^{i(\omega t - kx_0 + \varphi)}e^{ikz\alpha}] \tag{6}$$

The total field at this point on the screen is obtained by summing over the entire grating, i.e. integrating over z.

$$E(t, k\alpha) = \int E_0(z)e^{i(\omega t - kx_0 + \varphi)}e^{ikz\alpha}dz = e^{i(\omega t - kx_0 + \varphi)}\int E_0(z)e^{ikz\alpha}dz \tag{7}$$

(It is implied that only the real part of the complex result is kept, so we can dispense with the "Re" notation.) The term outside the integral is just a "phase factor" (it has unit magnitude). When we measure (or see) light, we detect a time average of the square of the electric field, and the exponential prefactor vanishes.

The more mathematically inclined will recognize the integral as a Fourier transform of the source distribution, $E_0(z)$. The far-field angular distribution of light is the **Fourier transform** of the source distribution.

From elementary physics, you may remember that interference maxima from an amplitude grating (with narrow slits) appear when $m\lambda = d\sin\alpha \approx d\alpha$. You can show that this is a special case of the general expression above. The Fourier transform of
Is just:
Notice that the diffraction peaks occur when $k\alpha = 2\pi m/d$, i.e. when $m\lambda = d\alpha$ (For this example, $d = 10\mu$m).

Because different colors have different wavelengths, a diffraction grating can be used to separate colors and to determine the spectrum of light from a source. With an infinite number of slits, the grating would have infinite resolving power: no matter how close in wavelength two colors were, they would still form clearly separated lines from the grating. With a finite number of

16
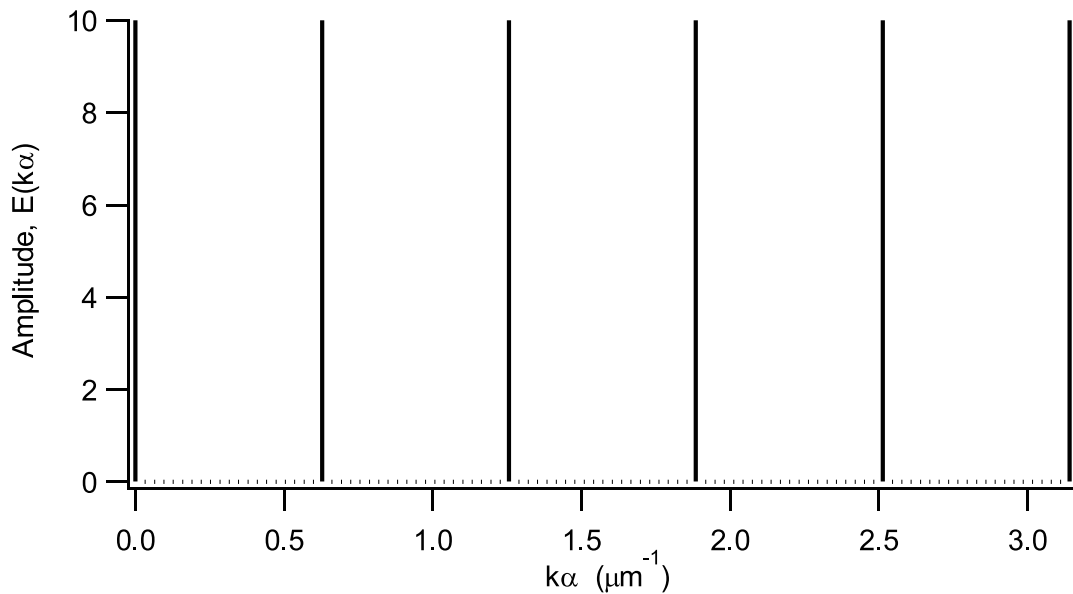
slits, however, the maxima are spread out a bit, and it becomes impossible to separate two closely spaced wavelengths.

The width of the maxima can be estimated by determining the separation (in angle) from the top of the peak to the nearest minimum. That minimum occurs when the phase shift from one slit to the next is $\delta\phi = 2\pi/N$, where N is the number of slits. We wish to know how much of a change in wavelength will put the new diffraction maximum right in this nearest minimum: this is called the resolution of the grating. Since the phase shift at a given slit is

$$\phi = \frac{2\pi}{\lambda} d \sin\theta \tag{8}$$

$$\delta\phi = \frac{2\pi}{\lambda} d \cos\theta \delta\theta = \frac{2\pi}{N} \tag{9}$$

$\delta\theta$ is the angular shift to the nearby minimum.
(Note: we do not need to use the small angle approximation here.)

The diffraction maximum is at $d\sin\theta = m\lambda$. We use this equation to find out how a small change in λ affects θ: $d\cos\theta\delta\theta = m\delta\lambda$. Combining this with the previous equations, we find:
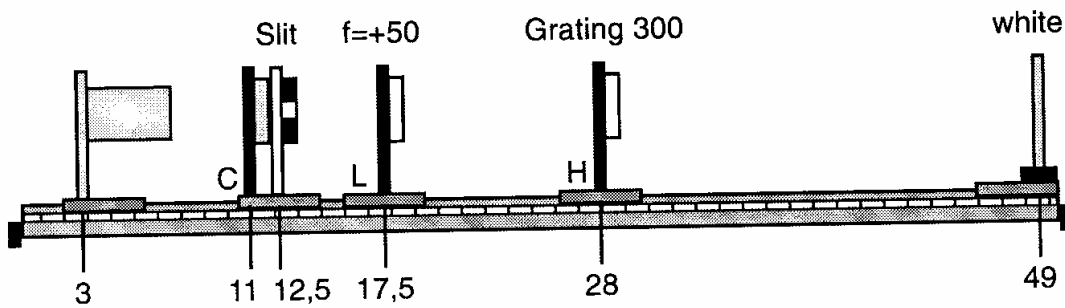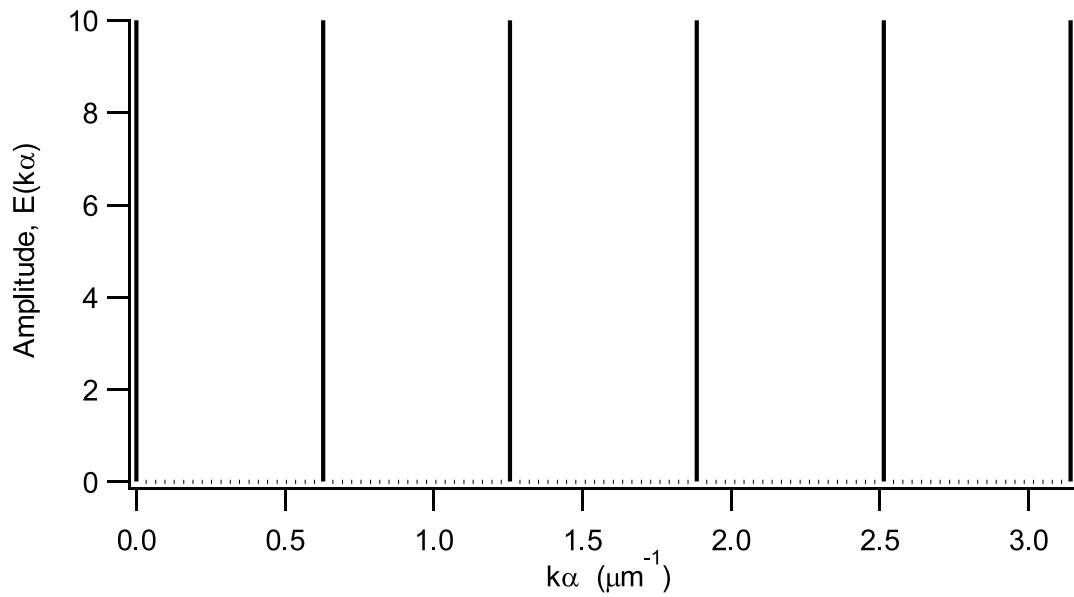
$$\frac{\lambda}{\delta\lambda} = mN, \tag{10}$$

which is the chromatic resolving power of the grating.

Experimental:

Arrange the lamp, adjustable slit, lens, grating, and screen on the optical rail:
Observe the appearance of the interference fringes, and record the positions of the different colors. Are both 1st order fringes of the same intensity? If not, what could explain the difference?

What is the purpose of the slit and the lens in this experiment?

Calculate the resolving power of the grating. How many slits does the light actually hit? If you can get hold of a photodiode, measure the light intensity as a function of theta after the grating, for both the "white" light lamp, and with a color filter in place. Find the approximate transmittance of the filter as a function of wavelength.

Remove the lamp, slit, and lens, and shine a HeNe laser on the grating. What is the resulting pattern now? Measure the positions of the diffracted beams, and calculate the grating spacing.

5.2 Resolution

If we place a lens downstream of the diffraction grating, we can make an image of it. You have
seen that the diffraction grating will spread the light out into different beams, called diffraction
orders. Consider a couple of diffraction orders created with the HeNe laser and a square wave
grating, as shown in the diagram, collected by a lens and focused. If the lens is far from the
grating, the diffraction orders will cross (i.e. focus) at the focal point of the lens, *which is exactly
where we expect to form an image of the grating.* Even if the lens is closer to the grating, the
point where the diffraction orders cross is always where we expect to form the image of the grat-
ing. This is simply because all the diffraction orders come from the same place (the illuminated
spot on the grating) - they are just like rays emanating from the object.

A lens forms an image of a grating by capturing and focusing (crossing) the diffraction orders.
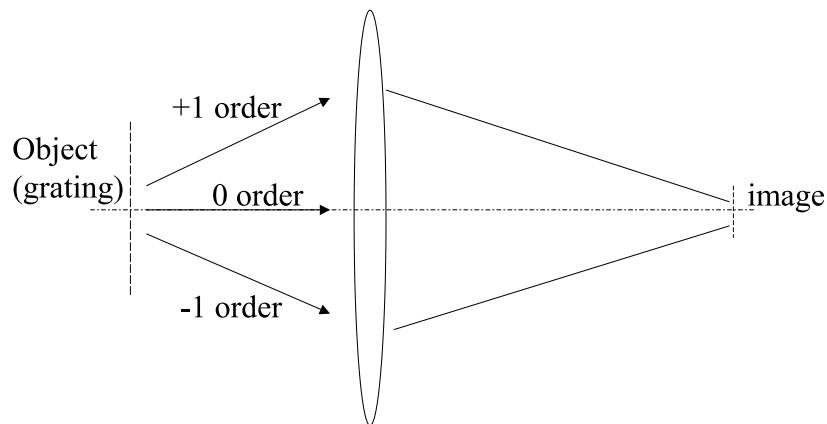
Closeup view of the focus (i.e. crossing) of the zero and 1st order diffraction beams:
How do the diffraction orders combine to form an image? They interfere! From the diagram,
you can see that the three beams (the central, zero order diffraction beam, and the two 1st order
beams) will combine to give a spatially varying intensity. At points labeled "a", the beams all
have their peaks and troughs aligned (in phase), and so the intensity there will be quite high.
At points labeled "b", the first order beams are out of phase with the zero order, so there is
cancellation and the intensity is very low. The variation in intensity across the interference
pattern **is the image of the grating**! Notice that the image from these three beams won't
look much like the grating: it's sinusoidal, not square. But if we add in the higher diffraction
orders, the image will be a better and better representation of the original square wave grating.
We are simply adding the higher spatial frequency **Fourier components** to the image. How
many orders would you have to collect to get a perfect square wave image?
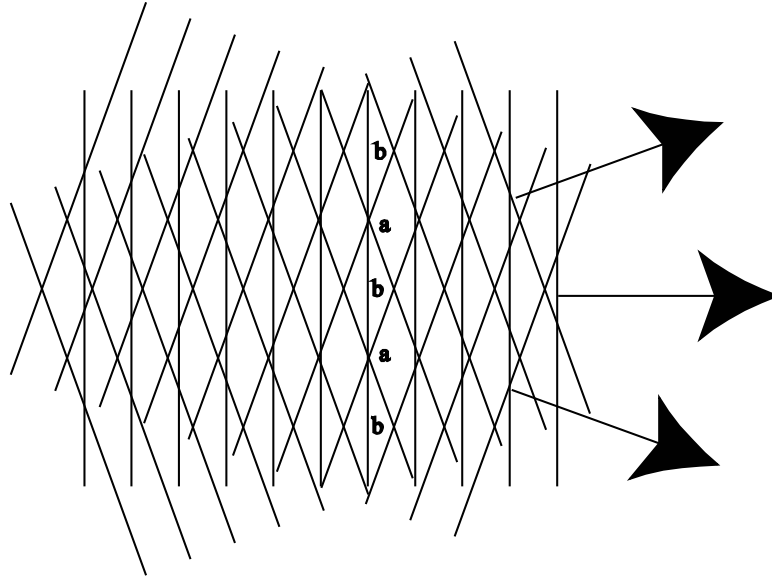
Suppose your lens is too small (in diameter) to collect and focus even the first order diffraction spots. In that case, there is only one beam going through the lens, and there is nothing to interfere with it. There will be **no spatial variation** (smaller than the spot size) in the image at all... no indication that the object is even a grating at all. We say that the optical system cannot **resolve** the grating.

Experimental:
To demonstrate the loss of resolution, you can take the 100 grating, shine the HeNe through it, and use an $f = +50$ lens to focus (combine) the spots. To see the image of the grating, you will need to make the image distance very large. You can project the image onto a piece of paper taped to a far wall.

When you can see the image of the grating, block all of the diffraction orders except for the central order. Can you still see the grating image?

One measure of the **resolution** of an optical system is the size of the smallest grating that can be imaged. If the lens captures more diffraction spots ("orders"), then it can make a better image. A lens must capture at least the zero and first order diffraction spots to make any image of the grating.

For a given grating and wavelength of illumination, calculate the size of the lens (in terms of $\sin\theta$, the sine of the half angle subtended by the lens at the object) needed to form an image. Are your measurements of lens size in accord with your calculation?

The combination $n\sin\theta$ is called the "numerical aperture" of a lens. (n is the index of refraction of the intervening medium, air in this case.) The expression for minimum lens size you just calculated can be inverted to give the resolution of a lens as a function of the numerical aperture. Do this in your report.

6   EXPERIMENT V - Magnifiers Microscopes, and Telescopes

A magnifying glass is useful for examining small objects. The proper use of a magnifying glass is to hold it close (a few cm) to your eye, and then bring the sample up behind it.

Experimental:
Observe the effects of the magnifying lenses of different focal lengths ($f = +50, +100$). Is the image from a magnifying glass real or virtual? Is the image distance larger or smaller than the focal length?

The human eye cannot comfortably focus closer than about 20 cm. However, with a magnifying glass, you can bring objects much closer than that. Use a ray diagram to explain the operation of the magnifying glass. Does a magnifying glass increase the angular (or apparent) size of the object? How would you define magnification for this optical arrangement?

A microscope uses a short focal length lens close to the object of study to produce an enlarged, intermediate image. The intermediate image is then viewed with a magnifier (called the eyepiece) to gain further magnification. Set up a microscope as shown. (Note: you can omit the $f = -100$ mm lens; simply adjust the ocular ($f = +200$) appropriately.) Draw a ray diagram to explain image formation in the microscope. Adjust the lens and sample positions to as to produce the largest magnification you can. What is the magnification of the "objective" lens (the lens closest to the specimen?) What is the magnification of the eyepiece or ocular? Replace the $f = +50$ mm objective with an $f = +100$ objective. Where must you place the $+100$ lens to get a good, focused image? How does the magnification of the objective relate to the focal length?
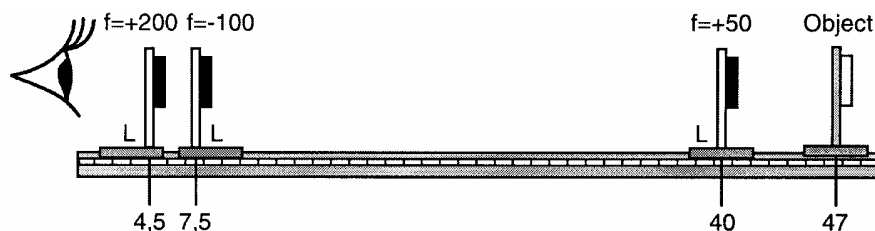

Figure 1: The microscope

The telescope. It is not useful to talk about the size of objects that are at infinity - rather, the angle the object subtends is what we think of as "size". (The moon, for example, is about a half a degree "wide".) Draw a ray diagram that shows how a telescope increases the apparent angle of objects at infinity. What is the angular magnification of the Cornelsen telescope?
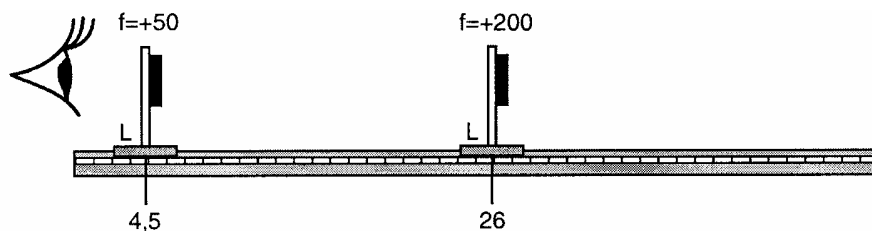

**Figure 2:** The telescope

7 EXPERIMENT VI

7.1 Polarization

Light is electric and magnetic fields, which are vector quantities, oscillating and perpendicular to the direction of propagation. The interaction of light with materials is usually dominated by the electric field interaction. Consequently, the direction in which the electric field oscillates is called the direction of polarization.

Materials can be made that absorb light with a preferred polarization. The perpendicular polarization can pass through. These materials are called polarizers. (If an electric field is at an angle to the "pass" orientation, the vector component along that orientation is passed.)
Experimental:
Set up the optical rail as shown:
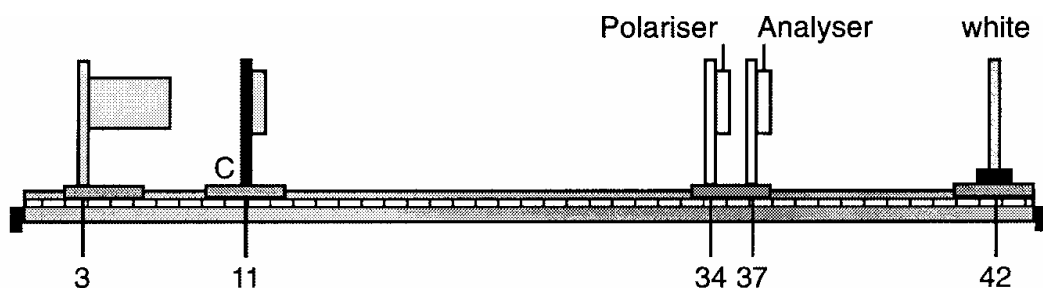
Replace the screen with a photodiode light detector. Measure the intensity of light passing through two polarizers, as you rotate the second polarizer. As a function of θ, the angle of the second polarizer, what should be the light intensity? Fit your data to theory. (You may need to consider the possibility that the polarizers are not "perfect": in other words, they may absorb some light, even if the light is polarized in the "pass" orientation, and they may pass some light that is polarized in the blocking orientation. Include these possibilities in your data analysis!)

Polarization is particularly useful in the study of materials. Some materials are anisotropic, and will refract light differently depending on the polarization direction. Arrange the elements on the optical rail as shown below, omitting the polarizing filter for now. Adjust the lens so that the cross is projected clearly onto the screen. Turn the limespar (calcite) slowly until two crosses appear side by side on the screen. Put the polarizing filter in, and observe the appearance of the crosses as the filter is rotated. In your report, describe your observations and explain.
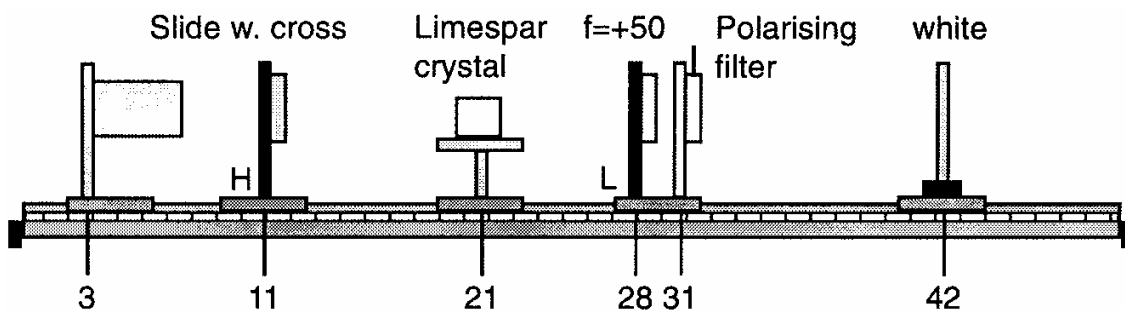
7.2 Chirality and Polarization

Molecules that cannot be superimposed on their mirror images are called chiral. Molecules that look like screws (like DNA) are obviously chiral: there is a real difference between a left-handed and a right-handed screw, as anyone who has tried to loosen a reverse-threaded screw soon learns!

Any molecule with a carbon atom attached to four different substituents is chiral. Most biological molecules are chiral. Chiral molecules can rotate the plane of polarization of plane polarized light. (They will also preferentially absorb either left- or right-circularly polarized light.)

In this experiment, you will use the polarizers and the photodiode to detect the rotation of the plane of polarization by glucose solutions of several different concentrations. (The instructor will provide d-glucose solutions at $0, 20, 40,$ and 60% wt/vol.) Set up the optical rail as shown, but with a photodiode where the screen is. Measure the intensity as a function of analyzer angle.
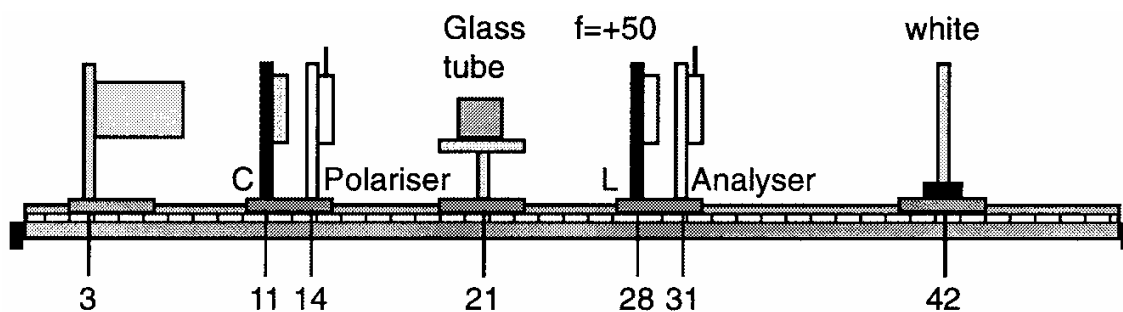
Plot your results (include uncertainties!) **Fit your data** to find the angle at which the transmitted light is at a maximum intensity. (The best procedure is to fit to a sinusoid with an adjustable phase parameter. You could also fit the peak region to a quadratic function.)

Plot the angle through which the polarized light is rotated vs. the concentration of glucose. What functional form should you fit this result to?

In your report, show the chemical structure of d-glucose and indicate all the chiral centers.