OPTIX Module 1 – Basic (Optics Basics - I)

Introduction to optics and optical elements

Michaela Kleinert

1 Objectives:

In this module you will learn about

- the proper use and handling of *research-grade* optics equipment;
- how to use mirrors properly and how to align laser beams;
- various lenses and their applications.

Use this manual as you work through the module to keep track of your notes and thoughts. In addition, you will have to add a few printouts or refer to data tables or additional notes in your lab notebook. You will *not* write a separate lab report after this module, because we want to give you enough time to thoroughly familiarize yourself and *play* with the equipment, but you will be graded on how well you complete this manual.

2 Tests and assessment:

In preparation for this module, read through the whole manual and answer the questions that are marked with a *. You should also watch the `VIDEOs` that are posted on our website (`www.willamette.edu/cla/physics/info/NSF-OPTIX`). They are meant to accompany this manual and will show you some critical steps of the module. When you come to lab, be prepared to discuss your answers to these questions with your classmates and your instructor.

You will also take a short test ("Laser Safety Test") before you begin working on this module to ensure that you have watched, read, and understood the *Laser Safety Material*.

Lastly, in order to assess the success of this module, you will take a short assessment test before you start ("pre-assessment"), and another one after you have successfully completed this module ("post-assessment"). At this point you will also have the opportunity to provide us with feedback about the module that we will use to improve it for the next student generation. Thank you for your support!

3 Equipment:

For this module you will need the following equipment. You can find everything that is specific to this module only in the box labeled "Module 1 demos" that is located in one of the cabinets in the OPTIX lab. In addition, you will use equipment that is shared by several other modules; you can find it in the drawers and cabinets in the OPTIX lab (all of which are labeled). Lastly, equipment for the lasers is in the box labeled 'HeNe Laser'. Please feel free to ask your instructor for help.

- Optical cleaning tissue ('Optics Paper'), hemostats/forceps, isopropyl alcohol, compressor, DEMO 1 (flat mirror)
- HeNe laser, lightbulb, piece of paper and detector card
- DEMO 2 (spherical mirror), glass slide, power meter, DEMO 3 and 4 (mirrors with reflective and dielectric coating)
- Several mirror mounts, mirrors, posts, post holders, table screws, dogs, two irises
- DEMO 5 and 6 (converging and diverging lens)
- DEMO 9 (optics with burned dielectric coating)
- Several research-grade diverging and converging lenses, cylindrical lenses, aspheres, achromats, and lens mounts
- LED with power supply

4 Required background knowledge and things you need to do before starting this module:

This is the very first OPTIX module, so relax, you don't need to know much coming into this lab. A few basics will do, and this manual and the associated module will teach you most of them. **Make sure to read through the *whole* manual before coming into the OPTIX lab, and mark everything that you find difficult to understand.** Note that this module is longer and more text-heavy than the following modules since it is your first introduction to optics and we assume that you know pretty much nothing :).

During your lab time, you can work through parts of the manual with your lab group and instructor, and you will get a lot of hands-on experience. The main purpose of this very first module is to make sure that you are safe, and that the equipment does not get damaged. You will learn how to handle research-grade optics equipment correctly, and how to protect yourself from laser radiation in particular. So for now, here are just a few pointers for **good general lab behavior**. Please initial each item to show that you have read *and understood* it. You can always ask your instructor if you have questions before initializing an item.

- This is a research lab, so leave your food and your drinks outside. A good place to store everything, especially if you are working as part of a large group, is the Physics Lounge next door (Collins 104). You are allowed to bring bottles that are tightly sealed (for example water bottles or travel mugs with a screw-on top) into the lab, but keep them on the counter top next to the door. You are not allowed to place them on the optics table!

  *** Any idea why? Hint: Look at the screw holes and imagine what would happen if you spilled milk or soda.**

- Optics equipment should be kept clean. Imagine viewing the world through very dirty glasses all the time. While this is rather unpleasant for you, it can be even worse for optics and lasers: Dirty optics can get permanently damaged if high-intensity laser light is directed onto them. So please take off dirty shoes (for example if you just walked to campus and they are wet) and leave them in one of the cubby holes in the Physics Lounge. **Please also bring a pair of simple, cheap, clean shoes that you keep in the cubby holes and that you only wear in the OPTIX lab or our other research labs.** In addition, please try to avoid dust and other dirt as much as possible.

- In this lab you will use lasers. Watch the video and read the additional *Laser Safety Materials* before coming to lab. There will be a test about laser safety before you begin this module, and **you must pass it** before you will be allowed to work in the lab.

- Most of the laser beams are a few cm above the optics table, which puts them pretty much at eye height for someone who is sitting down. So, **no chairs and no sitting in this lab**. When you want to analyze your data, or if you need a break, please go to the Lounge.

- Fingerprints can easily damage optics. Always think carefully about which part(s) of an optical piece of equipment you can touch safely and which one(s) you should never touch. **Please wear gloves** whenever you handle research-grade equipment, for example when you mount mirrors or lenses. You can find them in the cabinet next to the door. Please note that we recycle these gloves, so collect them in the appropriate box after you are done using them.

- **Read through the whole manual before coming to the OPTIX lab. Work through the boxes in sections 1 through 6 of this module, as well as all the boxes marked with a *, and complete them before coming to the lab. Be prepared to discuss your results with your group members and your instructor. This counts as your pre-lab.**

- **If you damage anything, please tell your instructor *immediately*.** While we of course try to avoid damaging the equipment, accidents can happen. Please don't try to cover up any damage; that only makes life harder for us as we try to figure out why something is no longer working. Tell us exactly what happened, and we can either fix it or replace the equipment quickly.

*** Lastly, as preparation for this module, write down everything optics-related you remember from the optics unit in Intro Physics II or from previous classes, for example in high school. Any relations, sketches, key words that pop into your head. If you can connect them in a meaningful way, even better! And now - have fun in the lab!**

5 Introduction:

> "...[O]ptics and photonics are technologies central to modern life. An understanding of integrated circuits, displays, fiber communication, medical tools, and solar power all require a deep understand of underlying optical principles, as outlined in the 2012 report of the National Research Council [*Optics and Photonics. Essential Technologies for Our Nation.* Committee on Harnessing Light, National Research Council (2012)]. Lasers in particular are used in almost every aspect of research and everyday life, ranging from powerful yet precise drills in industry to applications in medicine for noninvasive diagnostics and faster, safer, more localized treatment. Lasers are used in Internet and GPS communication, in LIDAR (Light Detection and Ranging) to detect pollution in the atmosphere, and in bar code scanners and CD/DVD readers. They become more relevant in a world that relies on online data storage to provide safer means of encrypting data (quantum cryptography), and they help us understand more about the world we live in, from the universe (e.g. through the use of laser guide stars and spectroscopy of astronomical objects) to chemical reactions (by freezing them in time with ultrafast pulsed lasers) [*Atoms, Molecules, and Light: AMO science Enabling the Future.* Committee for an Updated Assessment of Atomic, Molecular, and Optical Science. National Research Council. ISBN 0-309-08613-2 (2002)]. At the same time, optics is highly accessible to students of all ages, making it an ideal topic to capture and cultivate scientific interest and curiosity. In fact, UNESCO has declared 2015 the "International Year of Light and Light-based Technologies" [UNESCO: `http://www.light2015.org/Home.html`]." [NSF IAP grant #1505919, OPTIX]

In this module you will learn the basics that are necessary to successfully complete more advanced modules, and to succeed in our research labs and in a career in a STEM (Science, Technology, Engineering, Math) field after graduating from Willamette. We will begin with a brief section on how to properly handle research-grade optical equipment, which is more delicate than the teaching equipment you have used so far. We will then talk about lasers and other light sources, dive into mirrors and optical alignment, and lastly lenses, which find applications in all sorts of optical instruments (think for example of a telescope or a microscope). Lenses are used to collimate laser beams or to focus them. But even in everyday life they find numerous applications, like in your glasses or contact lenses.

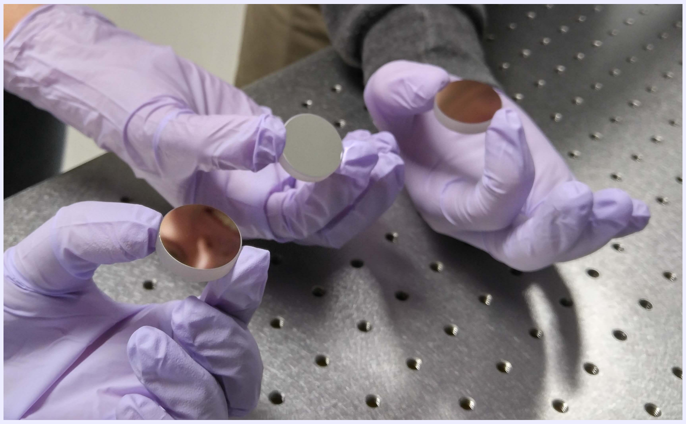
6 How to handle research-grade optical equipment:

The golden rule of optics is: Don't touch it with your bare hands. Research-grade optical elements like lenses or mirrors very often come with special coatings that reduce the reflection of light of a certain wavelength (so-called *Anti-Reflection Coatings*), which allows you to send a laser beam over multiple elements without losing significant amounts of power. When you touch such a coated element with your fingers you deposit some of the oils that your fingers produce naturally onto the element - or in other words, you leave a fingerprint. And fingerprints can be surprisingly difficult to remove, especially if they have been on the element for a while since the oils "etch" their way into the coating and destroy it. Sometimes you can save the optical element if you clean it quickly (we'll tell you in a moment how), but in some cases even that is not possible because the element is so delicate; an example of this would be a diffraction grating (you will encounter them in the *Intermediate* version of this module).

Note: You will see several boxes throughout this manual. **Blue boxes** contain tips and tricks, while **yellow boxes** are (mostly) empty and are meant for your own notes, and **green boxes** encourage you to play with and explore the equipment. Even if you print this manual with a black-and-white printer you will be able to easily distinguish the boxes: Yellow boxes typically have no header, while blue boxes always have the header "How to..." and green boxes have the header "Let's play with it".

How to hold optical elements safely:

Put on gloves. You can find them in the upper cabinet next to the door. Keep in mind that we recycle them, so please place them in the labeled box once you are done using them. Grab the optical element *gently* from the outside, touching only the unpolished part of the glass, just as shown in the photo below.



If you press down too hard it is very likely that some part of your fingers touch the outside of the actual optical element, and even with gloves that can leave some marks.

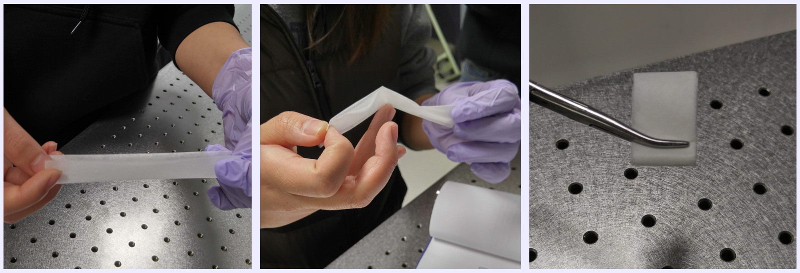
If, despite your best efforts, you leave a fingerprint on an optical element, please ask your instructor for help; they will show you how to clean that particular optical element (if possible). You can find general cleaning instructions below and on the next page. Please also watch the `VIDEO` called `HOW TO CLEAN AN OPTICAL ELEMENT`.

How to correctly clean (some) optical elements:

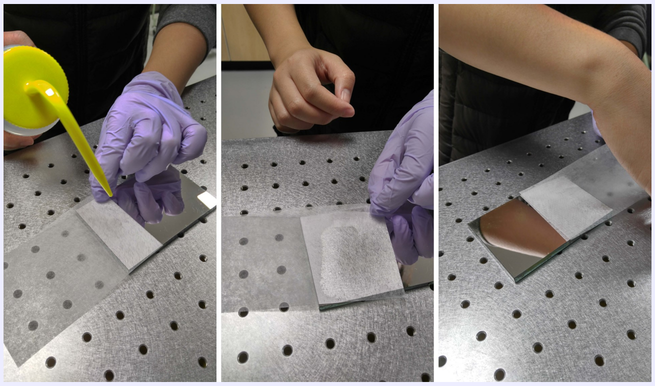
- To clean optical elements, you need clean compressed air; special optical cleaning paper, which is very fine, clean paper; a pair of small pliers (hemostats work great!); and methanol or isopropyl alcohol of high optical grade. Both alcohols are relatively safe unless you drink them or inhale large amounts of the vapor. You should avoid getting them on your skin as they dissolve the oils in your skin and dry it out quickly. For more information please read the *Material Safety Data Sheet* (MSDS), that you can find in the cabinet in which the optics cleaning supplies are stored. In most cases, isopropyl alcohol is preferred over methanol since it leaves less residue on the optical element.

How to correctly clean (some) optical elements, cont'd:

- Gently blow dust off the optics using clean compressed air. We have a special oil-free compressor that is stored in the lower cabinet next to the door for exactly that purpose. Please ask your instructor for help before you use if for the first time. Make sure to hold the nozzle close to the optics without touching it, at an angle of approximately 45°, and gently blow down onto the surface. This removes any big dust pieces that could scratch the surface before you use the paper and the alcohol to clean it further, and by blowing *down* on the optics, you avoid adding significant amounts of dust to the air above the table.
- Fold the optics paper twice in half along the short side (creating a "hot dog"), taking care that your fingers don't touch the middle part of the paper; you will use this part to clean your optics, and you want to avoid leaving fingerprints on it. Then fold it in half twice along the long axis ("hamburger style"). Again, make sure that your fingers don't touch the middle part. Lastly, grab the folded paper with the hemostat such that about 2-3 mm of the middle edge are on one side of the hemostat as shown in the photo sequence below.



- Add a few drops of isopropyl alcohol to the optics paper and, in one quick smooth motion, gently drag it over the optical element you want to clean. If the optical element is not as clean as you would like, discard the optics paper and use a new one, folding it following the method outlined above.
- In some cases, when the optical element is extremely delicate like a diffraction grating, you want to use a slightly modified method: Gently blow off the optical element with compressed air as described above. Then place a piece of optics paper onto one end of the optical element and add a drop of isopropyl alcohol onto the paper as shown in the left photo below. Gently drag the paper across the optical element. That way, you first distribute the alcohol across the full surface of the optical element, and then dry it off as you reach the drier part of the paper.



You can practice both methods on the mirror labeled `'DEMO 1'`.

Ask your instructor for help, and record any additional observations, problems, concerns, or comments in the following box.

Please note that these two methods should really only be used if you see fingerprints or something similar on an optical element. Dust will be much more common, and in that case just use the compressed air to gently blow the dust off the element as described on page 5.

Summarize how to correctly handle research-grade optics equipment, and list a few things that you should avoid at all cost.

7 Lasers and other light sources

Danger: You must have watched, read, and understood the *Laser Safety Materials* before proceeding. Lasers can permanently damage your eyes and/or your skin if handled incorrectly!

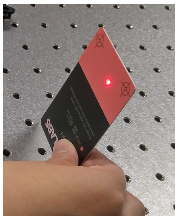
In most of the modules we will use lasers as our light source because they are convenient and by now relatively inexpensive, highly collimated, and coherent sources of light that come with a very narrowly determined wavelength, power, and polarization. Only occasionally will we use a white-light source such as a lightbulb or an LED.

7.1 Task: Comparing a laser and a lightbulb

Before we worry about alignment, let's first compare the output from a laser and from a regular lightbulb. Confirm that your laser safety goggles will protect you from light at 633 nm. You can check this by checking the 'OD' value that is printed for each wavelength range listed on the goggles. 'OD' stands for 'optical density', and that tells you how strongly the goggles block light within a certain wavelength range. For example, and OD of +7 means that the incoming light is attenuated by a factor of 10^7 after passing through the goggles. That's quite a bit! However, these goggles are only designed to protect you from stray light. You should never look directly into a laser beam with them!

Put on the goggles and mount the HeNe laser securely to the table by putting one of the small *T-nuts*(located in the screw box) into the bottom of the laser and attaching a post using a set screw as shown in the photo below.

Plug the HeNe laser into the outlet and turn it on (there's a switch at the back of the laser). Because the goggles are working correctly you will not see the laser beam. But you can make it visible, even while wearing goggles, by using one of the detector cards.



The HeNe laser is a class IIIa laser, which means it can damage your eyes. In addition, there are also other student groups working in the same lab, so you **must wear your safety goggles at all times**. However, a few of the tasks in this module will ask you to take off the goggles to peek at the projection of the laser beam on the wall or on a piece of paper. Note that this is safe as long as you ensure that

1. the laser beam is level with the table and follows a straight path;
2. the laser beam is either hitting the wall directly or is being blocked by a piece of paper at the edge of the table, so that it does not proceed all the way across the room;
3. you have removed all jewelry and other reflective items from your hands and wrists and you are not reaching into the beam with reflective tools like screw drivers;
4. you don't bend down and look into the laser beam.

Please always check with your instructor first to confirm that it is safe to take off the goggles, and announce to the other students in the lab that you will take off your goggles.

Place the lightbulb next to the laser and turn it on as well. Place a piece of paper behind the laser and the light bulb, **stand behind the laser**, and **take off your goggles**.

Observe the light from the laser and the lightbulb on the paper; do not look directly into either of them! Record your observations in the box on the next page. Comment on things like color, divergence of the light, what the light looks like on a piece of paper, etc.

8 Mirrors and basic alignment procedures

In this section we will introduce you to mirrors and how to use them to modify the path of a laser beam.

8.1 How to pick the right mirror

There are two different basic types of mirrors: **Plane mirrors** and **spherical (or other curved) mirrors**. Let's first look at plane mirrors: Imagine that a plane mirror is attached to the table, and that you shine a laser beam directly perpendicular onto the mirror.

*** Where does the reflected beam end up?**

This is a situation you typically want to avoid.

*** Can you imagine why? Hint: Think about what happens when the reflected beam makes it all the way back to the laser.**

Now imagine you have an angle θ between the incident laser beam and the *normal* to the surface of the mirror. What happens now? Do the experiment by placing one of the big rectangular mirrors labeled as `‘DEMO 1’` onto the table (don’t just hold it in your hand!) and sliding it into the path of the laser beam. Making sure that the laser beam does not move up or down, change the angle under which the laser beam hits the mirror.

Record your observations, including a small sketch.

This, of course, is the famous **Law of Reflection:** “The angle of incidence is the same as the angle of reflection (as measured with respect to the normal to the surface).” The last part in parentheses is actually very important: While here, in the case of simple reflection, it doesn’t matter whether you pick the angle between the surface and the laser beam, or the one between the normal and the laser beam, because the incident and the reflected angles are identical and thus either of these two pairs of angles will be equal, the choice of angles matters significantly once you consider *refraction* into a material (like a lens; we’ll come to this in a moment). So make it a habit to *always* use the angle between the laser beam and the normal to the surface.

Now that you’ve seen plane mirrors in action, let’s look at some curved mirrors, in particular **spherical mirrors**. There are also parabolic or elliptical mirrors, which are just other types of curved mirrors. They follow the same principles we’ll derive here in a moment, so we won’t discuss them separately. If you are interested in what they do, check out for example Thorlabs’ website at `www.thorlabs.com`. You can find them under ‘Products Home’ → ‘Optics’ → ‘Optical Elements’ → ‘Mirrors’. Spherical mirrors come in two versions: as **converging (‘concave’)** and **diverging (‘convex’)**.

Let’s play with it!

Take the big mirror labeled as `‘DEMO 2’` and hold it a few cm away from your face with the mirror curving away from you, and then slowly move it away until it is at arm’s length.

Describe what you see.

Now turn it around so that the mirror is curving toward you and repeat.

Describe what you see.

Spherical mirrors can act as lenses: An ideal converging or concave mirror focuses parallel rays of light to a single point, just like an ideal lens. This point is related to the curvature of the mirror: If you picture the spherical mirror as part of a circle, then the point onto which the light is focused is the center of that circle. Therefore, spherical mirrors are often characterized by their *Radius of Curvature* R, and as you may remember from the optics unit in Intro Physics II or from highschool physics, R is related to the focal length of a lens f through $f = R/2$. Similarly, an ideal diverging or convex mirror "defocuses" the light, just like a diverging lens does. It, too, can be characterized by the radius of curvature (which for diverging mirrors is negative). If you again picture the mirror as part of a circle, then in this case you are looking from the *outside* at the circle, and the radius of curvature is still the radius of that circle. Diverging mirrors are often used in cases where it is important to "see around the corner", for example on street crossings with poor visibility, since they allow you to gather light from a larger angle.

Another thing to consider is a mirror's **reflectivity** at a given wavelength. Take a thick glass slide and attach it to a mount or post using double sided sticky tape. Make sure that it is perpendicular to the table and angled at about 45° with respect to the incoming laser beam. You should observe that the majority of the laser beam passes through the glass slide, but that a small fraction is reflected.

What angle of reflection do you expect? Thus, where, relative to the laser beam, do you expect to see the reflected beam? Draw a sketch.

$\theta_R =$

Now use a power meter to measure the power of the beam before it hits the glass slide (call this P_0), the power of the beam that is transmitted (P_t), and the power of the beam that is reflected (P_r). To use the power meter correctly, turn it on and make sure that the wavelength is set to 633 nm, the wavelength of your laser.

Record your values, including an estimate for their uncertainties, in the space below. Is $P_0 = P_r + P_t$? If not, why not?

$P_0 =$ $P_r =$ $P_t =$

$P_r + P_t =$

Imagine what happens to your laser beam when you reflect only a few percent of the incident light; it gets very weak very quickly. Or in other words: a glass slide is a really poor mirror. So, to improve the reflectivity and thus reduce the losses when reflecting off a mirror, companies add a coating to the mirror. There are two types of coatings, **metal** and **dielectric** ones. Carefully take out the two mirrors labeled as `'DEMO 3'` and `'DEMO 4'` if you want to see an example of each.Metal mirrors are perfect for a wide range of applications, and in fact, you will use silver-coated mirrors throughout this module.

Another type of coating is a dielectric coating. Here, instead of increasing the reflectivity of the mirror using a metallic coating, similar to your bathroom mirror, a thin layer (or several) of a transparent material is deposited. The key is that this material has a different *index of refraction* compared to both air and the glass substrate. You can think of the index of refraction (or refractive index) as a measure of how 'easy' it is for light to travel through a given material. Air has a refractive index of (very close to) one, and light travels at the speed of light, c, through it. As the refractive index increases, the speed of light decreases. It's kind of like entering molasses - the more viscous the molasses (the higher the refractive index), the more difficult it is to move through it, and thus the slower you have to go (the speed of light decreases). The index of refraction also plays a key role when light enters from one medium into another. In other words, when it refracts at a boundary. Consider a beam of light coming from the left under some angle θ_1 with respect to the normal and entering another material. Let's say the index of refraction of the first material is n_1, and of the second material n_2.

*** In the space below, draw what happens for the three cases $n_1 < n_2$, $n_1 = n_2$, and $n_1 > n_2$.**

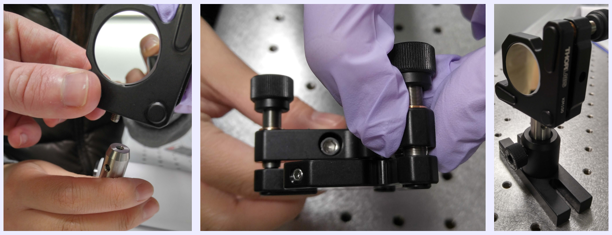
$n_1 < n_2$: $n_1 = n_2$: $n_1 > n_2$:

The relation between the incident and the refracted angle is of course given by **Snell's Law**, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. You will learn how exactly this dielectric coating works in the *Intermediate* version of this module that you will take in ATEP.

Now that you have a better understanding of a what a mirror is and what it does, let's get hands-on again and learn how to mount and use it in an actual optics lab. Since mirrors and other optical elements are quite delicate and need to be aligned precisely, we use mounts to hold them in place and aid us in the general alignment procedures outlined below. Most mirrors will sit in so-called kinematic mounts. These mounts consist of five pieces: The actual mount, a black anodized aluminum structure with a 1-inch hole and two or three screws at the back; a small set screw at the top of this mount that allows us to hold the mirror in the mount securely; a half-inch diameter aluminum post of some length; a black post holder of some length; and a black base that looks either like the letter C or H, see the photo below.

How to mount a mirror in a kinematic mirror mount:

- You can find a `VIDEO` tutorial called `HOW TO MOUNT A MIRROR` on our website.
- To insert the mirror, loosen the set screw with an Allen wrench.
- Wearing gloves, gently drop the mirror into the mount until its back is flush against the back of the mount.
- Tighten the set screw until the mirror is held securely.
- Slide a small screw from the top into the hole on one side of the mount and screw the screw into the post (you have to remove the small set screw first). Make sure to tighten this screw.



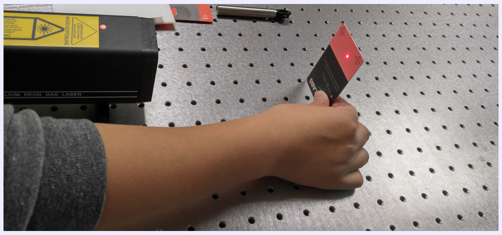
- Connect the base to the post holder by inserting a 1/4-20 table screw into the countersink hole of the base and screwing it into the bottom of the post holder. Again, make sure to tighten this screw. Insert the post into the post holder. The big thumb screw on the post holder is spring loaded, which means that it will hold the post in place nicely even if it is only tightened slightly.
- Adjust the big thumb screws at the back of the mirror mount to their mid-range; that gives you the most flexibility when using them to align the mirror.

Speaking of alignment - what do these screws do? Rotate them, one by one, and record your observations below. A sketch in which you indicate which screw you are talking about might be helpful.

Now that the mirror is safely mounted in the mirror mount you can attach it to the table using a 1/4-20 screw. Always make sure to lock all optical elements down securely, and **never just place them on the table since it is very easy to knock them over, potentially damaging them, or ruining your careful alignment**. Always make sure to double check that all the screws that hold the base, mount, post, and mirror mount together are securely tightened. As you read earlier, it is important to keep the beams as parallel to the optics table as possible, and align them in straight lines. You'll now learn how to do that. Please also watch the `VIDEO` called `HOW TO STRAIGHTEN AND LEVEL A LASER BEAM`.

How to ensure that laser beams follow a straight and level path:

- **To ensure that a laser beam is level with the surface of the table:** Place a piece of paper, one of the detector cards, or an iris onto the table close to the laser and mark the height of the laser beam on it. Then move the paper/card/iris backwards. If the beam moves away from your mark, up or down, adjust the mirrors until you hit the mark again. You will learn how to adjust mirrors and practice this in just a moment in the following section.
- **To ensure that the laser beam follows a straight path:** You can use the rows of screw holes as a guide. Gently lean over the table and look down onto the rows of screw holes. Then move the detector card or piece of paper backwards, thus tracing out the path of the laser beam. Looking from above you can easily see if the laser beam veers to the left or right. Again, use mirrors to correct the path of the beam.



Keeping the laser beams straight and level with the table surface does more than just make the beam path look tidy; it is an essential safety measure to ensure that the beam can't get into anyone's eye. Keeping the beams straight also serves another purpose: Aligned this way, a laser beam will always make 90° turns when it hits a mirror. That is good, because most mirrors tend to do weird things with the polarization of a laser beam unless the laser beam reflects off the mirror at either 45° or 90°.

8.2 Task: Learn how to align a laser beam

We'll now put your alignment skills to the test. Attach the HeNe laser safely to one corner of the table, **put on your goggles**, and then turn on the laser. Confirm that it is going straight and approximately level with the table. Insert one mirror a few cm after the laser and make the beam turn 90°. Make sure that the beam hits the mirror roughly in its center, and ensure that it stays parallel to the table after bouncing off the mirror. Lock the mirror down and tighten all screws. Then insert a second mirror, again after a few cm, and turn the beam another 90° such that it is now parallel to the original beam. Lock both mirrors down tightly. Again, ensure that the beam is aligned straight and stays level with the table.

Check with your instructor when you are done and record any observations, tips/tricks, or concerns below. Take a photo of your final setup and attach it to your report. Also sketch it (bird's eye view).

8.3 Task: Learn how to change the height of a laser beam

In reality, you sometimes have to slightly raise or lower the height of the laser beam, for example when you send the laser from one piece of equipment to another. Let's practice this. Your goal is to modify your current setup such that the final beam is about 5 mm higher than the original laser beam, but is still traveling in a straight line and parallel to the surface of the table.

Discuss this with your neighbor and record your battle plan, including a quick sketch of the setup, in the box below.

Then put your plan to the test! Align the mirrors and confirm that your planned setup indeed produces the desired result. Note: If you reach the end of the thumb screw that rotates the mirror mount think about how you can modify the spacing of your mirrors to avoid that.

If you had to modify your setup, make sure to write down any chances and reasons for these changes here. Lastly, record any open questions or comments that you have about mirrors here as well.

9 Lenses

A lens is essentially just a piece of glass that is thicker on one end and thinner on another. There are two basic types of lenses: Converging (or convex) lenses that are thicker in the middle and thinner toward the edge, and diverging (or concave) lenses that are thinner in the middle and thicker toward the edges. 'Converging' and 'diverging' are names that are easy to memorize once you know what a beam of light does when it hits these lenses, but 'concave' and 'convex' are a bit more difficult to remember. This might help you: "My neighbor's dog Rex loves food and is convex." That dog clearly is thicker in the middle and thinner toward the edge! Alternatively, you can picture the opening of a cave, which has the same shape as a concave lens.

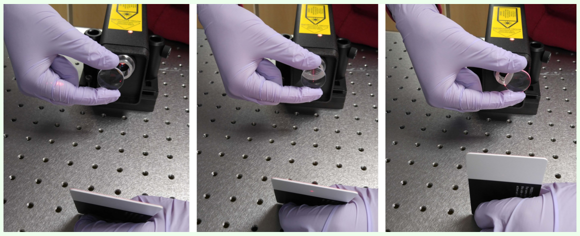
Your first task is to figure out what each of these lens types does. **Put on your goggles** and ensure that your laser beam either directly hits a wall or that you have attached a piece of paper at the edge of the table that blocks the beam. Insert the beam expander directly after the laser. You will learn later how it works; for now, all you need to know is that it widens the laser beam by a factor of 20. That'll make the following experiments easier. If you don't have a beam expander, place a +50-mm lens directly after the laser and place a +1000-mm lens a distance of 1050 mm away from the first lens. Make sure that the beam hits both lenses in the center (you will learn later how to do this correctly. For now, please ask your instructor for help.)

Let's play with it!

Use the two lenses labeled as `'DEMO 5'` and `'DEMO 6'` and figure out which one is converging and which is diverging. Note: You are allowed to touch these lenses while wearing gloves (but *only* these lenses). Then hold them in the path of your laser beam such that the beam hits the lens pretty much in the center. Observe the beam on a detector card across the full length of the table, starting directly behind the lens.

Describe what happens when it passes through a diverging compared to passing through a converging lens. Also rotate each of the lenses in your hands about an axis parallel to the laser beam (no tilting) and describe what you observe.

Place the `'DEMO 5'` lens in front of the wide beam. Then move it perpendicular to the laser beam such that the beam hits the lens off-center, either further to the left or further to the right and no longer in the middle as shown in the photos below. If you find it too difficult to hold the lens in your hands, you may mount it in a lens holder (look for the 'How to mount a lens' box below).



Observe the laser beam on the detector card at a distance close to the focal point of the lens and describe what happens when you move the lens left and right.

In particular, compare the location of the focal point (i.e. its distance from the lens) when the beam hits the lens further to the left, directly in the middle, and further to the right of the lens. A sketch may help. Note: This is a pretty subtle effect!

The distortions you see are called **lens aberrations**, and there are several different types. The particular one you observe here is called 'spherical aberration', and it appears when a laser beam is not going through the center of a lens. In that case, rays that hit the lens farther away from the center are bent more strongly and come to a focus closer to the lens compared to rays that hit the lens in the center. This leads to a smeared-out focus and an overall distorted beam. Wikipedia actually has a nice article on lens aberrations. Search for 'Optical Aberration' to find it. [Note: This article is a pretty reliable source of information because lens aberrations are important for photographers, and there are many competent amateur photographers out there. And that means that the article has been checked repeatedly by many people who know their craft.] In this article you can also learn about other types of lens aberrations, like chromatic aberration or coma.

Spherical aberration can become very noticeable when you use a wide laser beam and a small lens. In order to avoid spherical aberrations, use lenses with a diameter that is at least twice as large as the diameter of the laser beam.

Remove the lenses `'DEMO 5'` and `'DEMO 6'` and put them back in their respective containers. Then find the lens labeled as `'DEMO 8'`. This is a so-called **cylindrical lens**.

Let's play with it!

Explore its properties by placing it into the laser beam (center it nicely) and observing the beam at a few distances after the lens.

Record your observations. Again, rotate the lens in your hand about an axis parallel to the laser beam and comment on the shape of the laser beam while you do this. Compare this observation to what you found for the converging and diverging lens. Record your observations.

Now that you have gained some intuitive understanding and hands-on experience with lenses, let us dive a little deeper. While lenses have many applications, their main purpose is to **alter the collimation** of a laser beam. A beam of light is called *collimated* when its rays are perfectly parallel. Unless you place an optical element into the path of such a perfectly collimated beam, it will stay collimated forever, meaning that rays of a collimated beam will never come to or diverge away from a single point. This is an over-simplification; there are no perfectly collimated laser beams in real life. You'll learn more about these real-life laser beams in **`MODULE 5 - INTERMEDIATE.`** However, we can produce laser beams that are fairly well collimated. For example, observe the light from the HeNe laser over a large distance of several meters.

Would you call this laser beam collimated? If not, why not? If so, over which distance would you call it collimated?

If a non-collimated laser beam converges to a point, that point is said to be a *focal point.* Give an example of how you can create such a focal point, and demonstrate it experimentally using any of the 'DEMO' lenses you have used so far. Then think about a *perfectly collimated beam.*

At which distance from the laser is the focal point of such a beam?

For the lasers you use in this module, the horizontal and the vertical location of the focus is nearly the same. But for many lasers, in particular diode lasers that you'll encounter in `MODULE 3 - INTERMEDIATE.` the focal point in the horizontal and in the vertical direction are not at the same location. This is another form of aberration called *astigmatism.* You may have heard that term before if you are wearing glasses. Your eye actually can be astigmatic, and your optometrist will prescribe glasses that use cylindrical lenses to compensate for that effect.

One last comment before we move on: A common mistake is to use 'collimated' and 'focused' interchangeably. Be very careful about that: Collimated means that a beam has the same width everywhere, whereas focused means that it comes to a focus somewhere. Thus, they are pretty much exact opposites of one another!

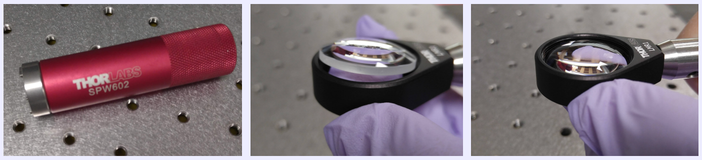
Sketch and label a collimated and a focused laser beam.

9.1 How to align lenses

Next, take out one of the mounted concave and convex lenses and connected them to a lens mount, following the instructions below. Please also watch the `VIDEO` called `HOW TO MOUNT A LENS` that you can find on our website.

How to mount a lens:

- Lenses are not mounted in kinematic mounts because these mounts are quite pricey, and very often it is not necessary to be able to move the lens in quite the same way as a mirror. Instead, we will use simple lens mounts that consists of a 1-inch threaded anodized aluminum ring in which you can place the lens.
- Note that it is very easy to place a fingerprint onto the lens when dropping it into the lens mount, so make sure to wear gloves.
- If you are using an unmounted lens like the `'DEMO 5'` and `'DEMO 6'` lenses, use a smaller 1-inch counter ring and screw it into the first ring to sandwich the lens between the two rings and thus secure it tightly. There is a special tool called 'spanner wrench' that makes tightening the smaller ring a lot easier; it's shown in the photo below (on the left hand side). Just slide it into the bigger ring and rotate it gently until the two notches find the matching grooves on the counter ring. Then rotate the ring until you feel resistance as it hits the lens.
- If you are using a mounted lens, simply screw it into the lens mount and tighten.
- Most of the lenses that you will use in this module have one flat and one curved side. To make it easier to align them correctly (more below), please make it a habit of placing the lens with the flat side down into the lens mount, so that the smaller ring rests on the curved side. That has the added advantage that, for lenses that are strongly curved, the curved part of the lens is protected by the lens mount as shown in the photo below.



As you just saw a few pages ago, sending the beam through the exact center can reduce spherical aberrations significantly! But how can you make sure that you are really going through the exact center and not slightly to the side? There are at least two ways to ensure that. Please also watch the `VIDEO` called `HOW TO ALIGN A LENS` on our website.

How to align a lens using an alignment disk:

- The alignment disk is the small, 1-inch diameter disk that you can find in the same box as the other detector cards. It is covered in the same reddish material that the detector card is coated with, and thus allows you to use it with visible and infrared lasers alike, even while wearing your protective goggles. In contrast to the rectangular detector card, it has a small hole at the center (similar to an iris).
- Slide the disk into the lens mount with the coated side facing the laser.
- Use a mirror or move the lens mount such that the laser beam is passing through the hole in the center.
- Make sure that the lens is aligned perpendicular to the laser beam.
- Lastly, lock the lens down tightly and remove the disk from the lens mount. A little bit of blue tape might help in case it got stuck.

Note that one of the instructions in the last box told you to verify that the lens is *perpendicular* to the laser beam. That is important since a tilted lens (with respect to the laser beam) introduces beam aberrations. Verify this experimentally!

Let's play with it!

Intentionally tilt the lens by a large angle, then follow the alignment procedure described above (minus the "perfectly perpendicular", of course).

Observe the laser beam after the lens and describe what you see. Compare this to a well-aligned lens.

Even without an alignment disk you can ensure that the laser beam passes through the center of the lens.

How to align a lens without an alignment disk:

- Just as before, you have to make sure that the lens is aligned perpendicular to the laser beam.
- Move the lens out of the beam and place a piece of paper or one of the detector cards at least 15 inches away from the position where you want to put the lens. Secure it tightly so that it can't move and mark the position of the laser beam on the card. Note: Please don't use permanent markers or pencils on the card; use blue tape instead.
- Then insert the lens and roughly center it.
- Move the lens left and right until the laser beam hits the same spot as before. Since the lens affects the collimation of the laser beam, the diameter of the beam will no longer be the same, so just make sure that the *center* of the beam that has passed through the lens lines up with the *center* of the spot you marked on the card.
- Lock the lens down tightly and loosen the thumb screw on the post holder. Move the lens up and down until the center of the spot on the paper or card is at the same location as the center of the spot you marked on the paper or card. Lock down the thumb screw.

As we have already mentioned, most of the lenses you will use in this and future modules have one plane and one curved side. They are called 'plano-convex'. We already talked about how to mount them in the lens mounts such that it is obvious which side is the curved side. When inserting lenses into a laser beam, make sure that the curved side always faces to the side of the laser beam that is collimated (or more collimated). This leads to an overall better beam profile, although the effect is too subtle to see with the naked eye.

Sketch the orientation of a plano-convex lens when you use it to

(a) focus a collimated laser beam:

(b) to collimate a diverging beam:

9.2 The Lens Equation

An important relation that involves the focal length is the **Lens Equation**. It relates the focal length of the lens to the location of the object and of the image that forms when you use this lens. Imagine you want to image an object that is a distance s away from a lens of focal length f. The Lens Equation then tells you that the image will form at a distance s' that is related to s and f via $\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$.

*** Draw a sketch in which you define the two distances and show where the object and the image are located.**

In Intro Physics II you learned how to construct the position and height of the image using the three special rays.

*** Review your knowledge of this, then draw the three special rays for a converging and a diverging lens in the space below. For both lenses, draw the situations $s < f$ and $s > f$ (so there should be a total of four sketches).**

In the next subsections we will focus on predicting the position of the image using the Lens Equation and experimentally verifying it by measuring the focal length and the object distance. Here are three methods of how you can determine the focal length of a lens. Two of them are quick methods that give you a good estimate, while the third one provides a more reliable and accurate result but take longer. You will practice all of them soon, and you will learn about two more methods in the extended version of this module in ATEP.

How to find the focal length of a lens:

- **Method 1: Radius of curvature method:** A very crude way to roughly estimate the focal length of a plano-convex lens, often only in comparison to another lens, is to look at the curvature of the lens surface. A lens with a smaller focal length has a surface that is curved more strongly compared to a lens with a longer focal length. This method works well to distinguish between the 25 mm, 50 mm, and 100 mm lenses, but fails to work well enough for any focal lengths above 200 mm or so. It also only works as long as the lenses you are comparing are made from the same material.
- **Method 2: Infinitely far away light source method:** Another quick method that leads to more accurate results is to project the image of the ceiling lights onto the floor. To do this, position yourself *directly underneath* a ceiling light and lower the lens to the floor until you see a sharp image on the floor. Make sure to look directly at the floor; do not look through the lens! Then measure the distance between the lens and the floor. This distance is roughly equal to the focal length of the lens. This method works well to distinguish between lenses whose focal length differs by a few cm.
- **Method 3: Lens Equation method:** An even more accurate way is to use the Lens Equation by forming an image of an object and measuring s and s'. Then, $1/f = 1/s + 1/s'$, or $f = \frac{ss'}{s+s'}$.

9.3 Task: Measure the focal length of a lens using the three methods

In this subsection you will measure the focal length of a lens using the three methods summarized above. Put on your gloves and select either the mounted 100 mm or 150 mm lens from the lens cabinet (do all of the following with just one of the two lenses, not with both!). Then attach it to a lens mount using the method outlined on page 15. Please also watch the `VIDEO` called `HOW TO MEASURE THE FOCAL LENGTH OF A LENS` on our website.

Method 1: Radius of curvature method: This method only really works well in comparison with another lens. With your gloves on, also pick up the 25 mm and the 50 mm lenses. Hold all three lenses such that you can easily see the radius of curvature of the convex side and note that the 25 mm lens bulges a lot more than your 100 mm [or 150 mm] lens, and that the 50 mm lens is somewhere in between. Note that this method only works for lenses of the same diameter and made from the same material.

Method 2: Infinitely far away light source method: In the blue box above we told you that the distance between the lens and the image of a far-away light source that forms on the floor is about equal to the focal length of the lens.

*** Confirm this mathematically using the Lens Equation. Hint: think about the distances involved in this problem, in particular the distance between lens and ceiling compared to the focal length of the lens and the image distance. Draw a sketch, and then show mathematically that $f \approx s'$.**

Holding your 100 mm [or 150 mm] lens gently, follow the instructions on page 18 to estimate the focal length of this lens using Method 2.

Record the value, including an estimate of its uncertainty:

$f_2 =$

Method 3: Lens Equation method (Note: Don't spend too much time on this method!): Attach the LED to a small breadboard, connect it to a power supply and turn it on; this acts as your object. You may have to turn off the lights (use the green light for some background light) to see the image clearly. Place the lens a distance $s > f$ from the LED and find the image of the LED at a distance s'. Note that the lens has to be at the same height as the LED to get a good image.

Measure both s and s' and record the values, including an estimate for the uncertainty:

$s =$

$s' =$

Sketch the setup.

From your data, calculate the focal length f. Show your work.

Find the uncertainty in f using the uncertainties of s and s' and the method of error propagation. As you may remember, the uncertainty squared of f is given by $\Delta f^2 = \left(\frac{\partial f}{\partial s}\Delta s\right)^2 + \left(\frac{\partial f}{\partial s'}\Delta s'\right)^2$ (this is the method of error propagation). Work this out for $f = \frac{ss'}{s+s'}$.

9.4 Task: Measure the magnification of a single lens

As you know, lenses can be used to magnify objects. Think for example of a simple magnifying glass! You will investigate this now. Your first goal is to derive a theoretical expression for the magnification M of a single lens, assuming that you have an object of height h that is placed a distance s to the left of a converging lens of focal length f. You already know that the image of this object forms at a distance s'. But what is its height h'?

*** Use the Lens Equation together with a sketch that shows the geometry of the problem to derive an expression for h' *that contains only the knowns* h*,* f*, and* s*.* The magnification is defined as the ratio between h' and h: $M = h'/h$.**

Now set up this single lens system. Use two LEDs as your object (the distance between the LEDs is the size h of your object).

Find the position of the image. Measure the size of the image h' (i.e. the distance between the images of the two LEDs) and compare it to the size of the object to find the magnification M.

$h_{meas} =$

$h'_{meas} =$

$M_{meas} =$

Then calculate the magnification using the expression you found in the previous box.

$M_{calc} =$

Compare these two results, including their respective uncertainties. Are they in agreement? If not, why not?

And that's it! You made it successfully through this module and are now qualified to perform the more advanced modules.

Please leave us any comments, suggestions, or concerns in the box below, so that we can optimize this module for future student generations. Thanks!