Light and Optics:

We just learned that light is a wave (an "electromagnetic wave", with *very* small wavelength).
But in many cases, you can safely *ignore* the wave nature of light!

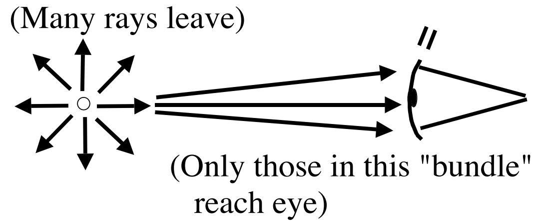
Light was studied for a long time (obviously), long before Mr. Maxwell, and very well understood. People thought about light as sort of like a stream of "particles" that travel in straight lines (called "**light rays**"). Unlike particles, waves behave in funny ways - e.g. they bend around corners. (Think of sound coming through a doorway.) But, the smaller the λ is, the weaker these funny effects are, so for light (*tiny* λ), no one noticed the "wave nature" at all, for a long time. λ of light is 100 x's smaller than the diameter of a human hair!

We'll come back to the (subtle) wave nature of light in Ch. 24.
But for now, we'll study the more "classical" aspects, called **GEOMETRICAL OPTICS** - the study of how light travels, and how we perceive and manipulate it with mirrors and lenses.
We'll also be incorporating parts of CH. 25 into this as we go along, because Ch. 25 is about lenses, glasses, telescopes, etc.

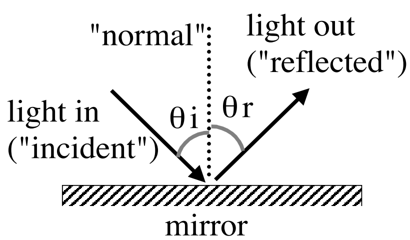
- We will ignore time oscillations/variations (10^14 Hz is too fast to notice!)
- We'll assume light travels in straight lines (c=3E8 m/s, super fast)
- Light can then change directions in 3 main ways:

i) Bouncing off objects = **reflection**
ii) Entering objects (e.g. glass) and bending = **refraction**
iii) Getting caught, and heating the object = **absorption**
(iv) Bending around objects = **diffraction** is a subject for Ch. 24)

How do you know where objects are? How do you *see* them? You deduce the location (distance and direction) in complicated physiological/ psychological ways, but it arises from the angle and intensity of the little "bundle" of light rays that make it into your eye.



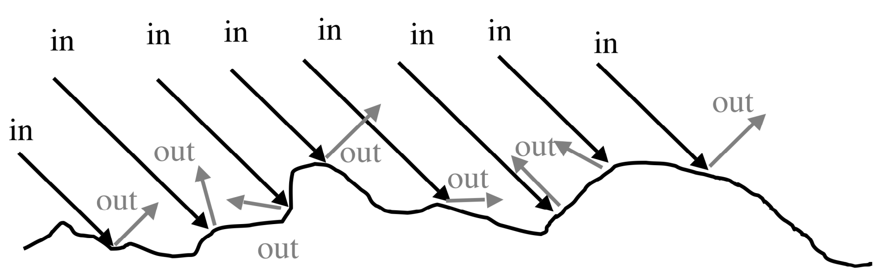
If light bounces off a smooth surface (like a mirror, or a lake), it's called "**specular reflection**", and it is always true that



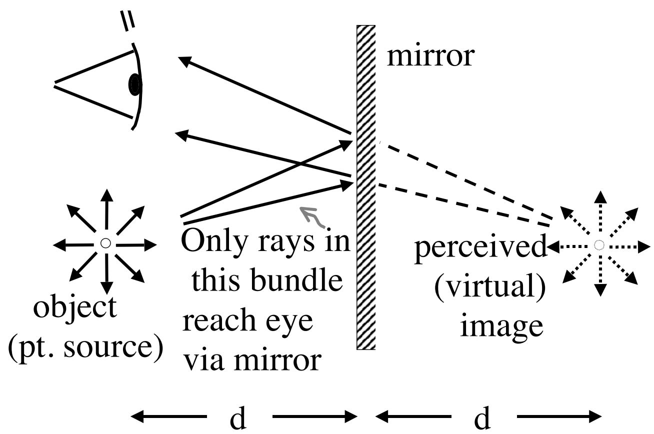
Θ(i) = Θ(r), "angle of incidence"="angle of reflection"

(See sketch for the precise *definition* of which angles those are!)

If light bounces off a *dull* surface (like e.g. white paper, or a wall), it's called "diffuse reflection", and the light comes out every which way. (Microscopically, "dull" means that the surface is not smooth on the scale of the wavelength of light)



If rays come from a "point source" (a small bulb, the tip of my nose, the end of an arrow, ...a particular *point* on an object) and then reflect off a mirror, they will *appear* to come from behind the mirror (to an observer properly located):



My eye sees (some of) the rays leaving the object.
My brain *assumes* they rays must have travelled straight, so my brain "draws the dashed lines" and deduces the object must be located at the "***image point***" shown on the right.

This image is called **virtual**. The rays *appear* (to me) to come from that point in space, but they were never really there! (If you put a piece of paper somewhere back there blocking the dashed lines, it has no effect on the image. The paper is *behind* the mirror, after all!)

We'll encounter "**real images**" soon like the image projected onto a movie screen. But you don't get that with a simple flat mirror - as you can see above, the image is virtual.

- Note: *many rays* go from the object "o" to the eye. You can show (see Giancoli P. 686) that they all appear to come from the same image point. I only drew 2 of those rays, to keep the picture as simple as possible. (All you need is two lines, in general, to trace back to a unique point origin)

- The distance "d" in the picture above is the same for both object and image. If an object is 2 m in front of the mirror, I will perceive it to be 2 m behind the mirror (a total of 4 m horizontally away from the object)

- *Curved* mirrors can play nice tricks on you! ("Object in mirror is farther than it appears") Depending on the shape, images can appear closer, farther, bigger, smaller... (Giancoli section 23-3 is about this: it's fun, but optional reading)

Any transparent medium (air, H20, glass,...) that lets light through will have a number n, the "**index of refraction**", associated with it. n is determined by how *fast* light travels through the material. (Light only travels at c, the "speed of light", in vacuum. In materials, it is always slowed down.) The bigger n, the slower the light travels:

$\boxed{n = c/v}$ = speed of light (in vacuum) / speed of light (in medium)
= 3E8 m/s / v (in medium)

n >1 always. (another way to say this: light never goes faster than c!)

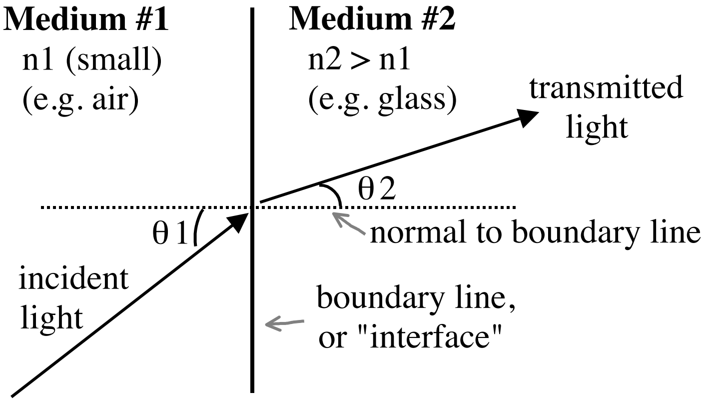
Examples:
- air: n= 1.0003
- water: n=1.33
- glass: n=1.5
- diamond: n=2.4 (light travels less than half the normal speed in diamond!)

Over in the JILA labs, there are experiments with materials that have n (at one special frequency, anyway) about 1E7, so large that the speed of light is about as slow as a person on a bike!

<u>If light goes from one medium into another, it will (in general) bend</u>, i.e. change it direction. This is called **refraction.**

This fact is explained way back in Giancoli 11-13: it is a property of waves. Nevertheless, the description of the effect doesn't need to refer to the wavelength, or wave nature, of light, so this topic still belongs in this geometrical optics chapter.

The math involved is fairly straightforward (one equation to learn), and there are many important consequences/applications, ragning from simple eyeglass lenses, to fancy telescopoes, to medical imaging equipment, optical fibers for phone lines, etc...



• Light is SLOWER on the right side, where n2 is large.

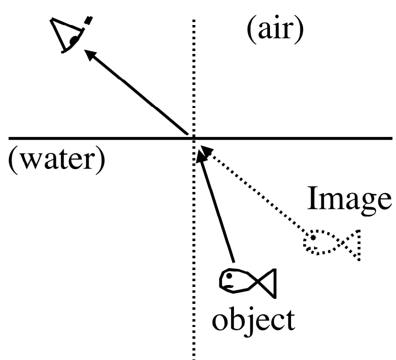
• θ1 is larger, θ2 is smaller: Light gets bent "towards the normal" as it goes from low index (like air) into higher index (like glass)
(And vice versa = you can always *reverse* a ray diagram like this)

There is a formula for the refraction of light (as shown in this figure) derivable from Maxwell's Equations, called **Snell's Law:**

$$n1 \sin(\theta 1) = n2 \sin(\theta 2).$$

(See fig for definitions of symbols)

Example: You are looking into water at a little fish.



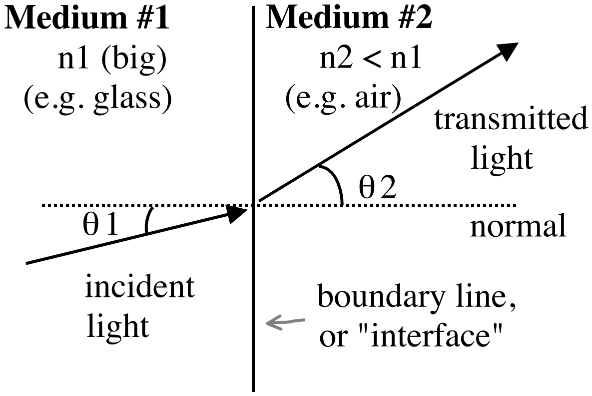
• Your eye draws "straight lines" (dashed, in the fig) and deduces that the fish is located at the *image* point in the figure.

• The image you see is *virtual*, the light rays do NOT physically pass through the spot where they appear to originate from.
(If you placed a black card right in front of the spot where you perceive the fish to be, you will still see the fish, the rays don't pass through the card's location.)

• The image appears to be slightly *less deep* (you have to think about that one, it requires that you carefully draw more than one ray, because you can't figure out "depth" or "distance" with only one light ray.

• Light rays are always reversible. That means the fish perceives you in another place too - higher than you really are. (Can you see why?)

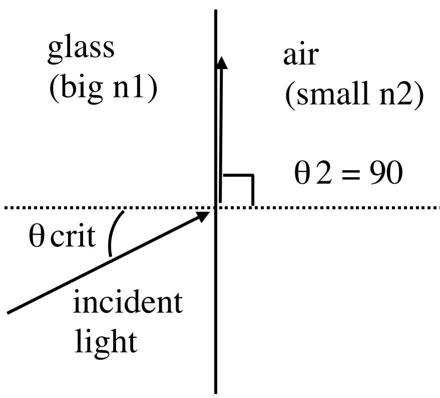
Consider when the rays go from *bigger* n1 to *smaller n2*, i.e. n1 >n2.
(Like light going from water into air, as in the fish example)



Light is *faster* on the right side. (Notice that now θ2>θ1)

The bigger θ1 gets, the bigger θ2 gets.

But... θ2 can never get bigger than 90°.
There is a **critical incident angle** θ1 for which θ2=90°



At this critical angle, Snell's law says n1 sin(θcrit) = n2 sin(90) = n2

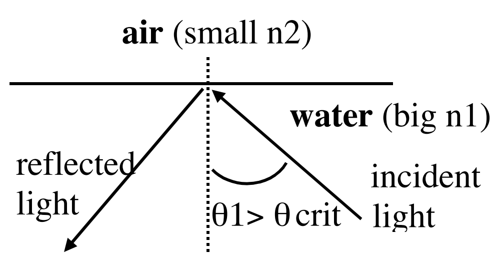
or $\boxed{\sin(\theta crit) = n2/n1}$

The light is no longer really "escaping" the glass.

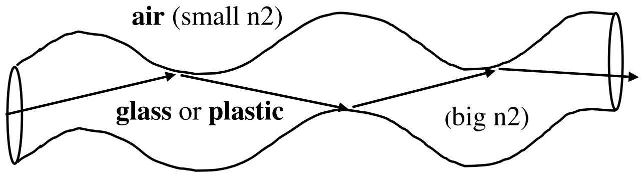
If θ1 gets any *larger* than this critical value, you cannot solve Snell's law any more for θ2: sin(θ2)>1 is not mathematically possible.
Light incident at (or greater than) the critical angle cannot escape. It will have to reflect, and this is called "**total internal reflection**".

You get very nearly 100% reflection in this case - much better than normal mirrors, which generally absorb some incident light.

For water (n=1.33) going to air, sin(θcrit) = 1/1.33, and my calculator gives θcrit = $\sin^{-1}(1/1.33) = 48.8°$.
(I drew this picture "rotated" to give a different geometric example - make sure you understand it.)



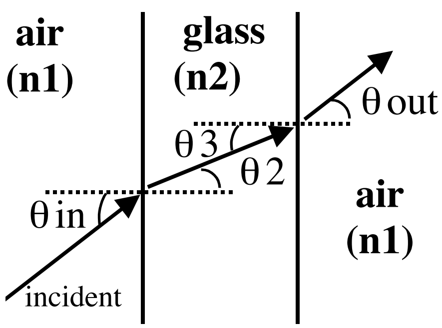
Example of total internal reflection: "optical fibers", used e.g. as an "endoscope" (a medical tool to look inside of bodies)



You take a thin, flexible fiber of glass (or really a whole bundle of them), which can be threaded into a body.

Light enters at one end inside the body, but the light rays are all bouncing at a shallow angle (θ greater than θcrit, do you see this?) against the glass/air boundary, and totally reflect, bouncing their way along never getting out till they reach the end, outside the body.

Light rays can pass through several boundaries. For example, you might have a *sheet* of glass - a light ray will enter (going from small n1 to larger n2) and then exit (large n2 -> small n1)



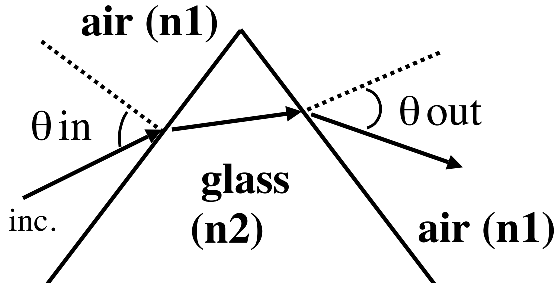
At *each boundary*, Snell's law will hold. At the left boundary we have n1 sin(θin) = n2 sin(θ2)
(light bends *toward* the normal - convince yourself of the equation and the physics)

At the right boundary we have n2 sin(θ3) = n1 sin(θout)
(light bends away from the normal - again, convince yourself)

But geometry tells us (if the walls are parallel) that θ2 = θ3
(do you see why?) Which means sin(θ2) = sin(θ3).
So n1 sin(θin) = n2 sin(θ2) = n2 sin(θ3) = n1 sin(θout)
(can you follow all the steps required to write that last line down?)
That means (compare the *far left* with the *far right* of that eqn)
sin(θin) = sin(θout), which says θin = θout.

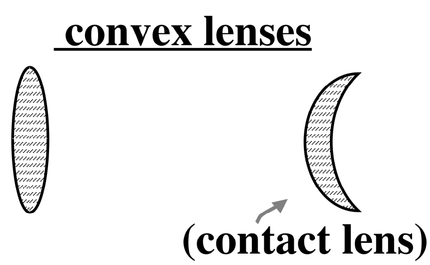
Conclusion: the light ray is displaced sideways a tiny bit, but it is not bent, overall. (Glass over paintings doesn't distort the image like looking into a fishbowl does)

What if you have glass with walls that are *not* parallel?



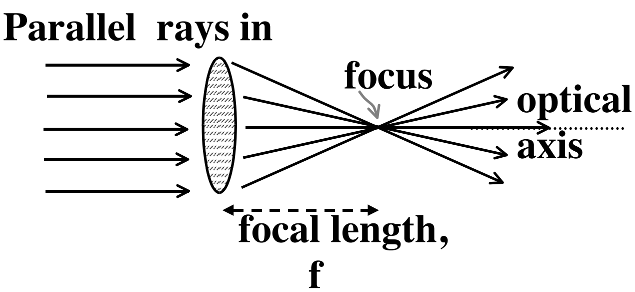
The incoming ray is now bent. You have to think about this a bit, but it will always be bent *away* from the thinner part of the glass...

This is the ideas behind **lenses**.
As light enters, it is bent. and rays come out different depending on where and how they strike.



The geometry looks complicated (and it is!) but for thin lenses, the result is relatively simple.

First consider a bundle of parallel, horizontal rays entering a convex lens from the left, as shown below.



The central ray sees two parallel edges, so it is not deflected at all. It goes straight on through.

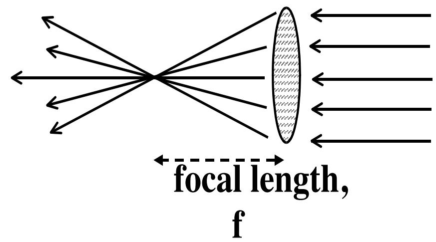
The rays striking the edges bend *away* from the thinnest part, as shown.

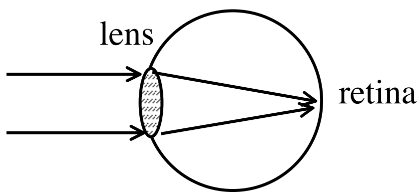
This (convex) lens is called a "converging lens". All the parallel incoming rays are bent towards a common point, the focus, or focal point. (Of course, the incoming rays don't *have* to be parallel - in which case we'll have to think about what happens! We'll get to that soon)

How could you produce parallel incoming rays like that? Lots of ways. Simplest example: having a small "pointlike" source very far away... Although the source sends out rays in *all* directions, the only rays that will make it to you are those that happened to be going in YOUR direction to start with. You will see only those rays, which are nearly parallel... (you need to think about that a little - draw a picture for yourself)

Lenses have *two* focal points, because they work just as well if the light goes the other way. (Remember, ray diagrams are always reversible)

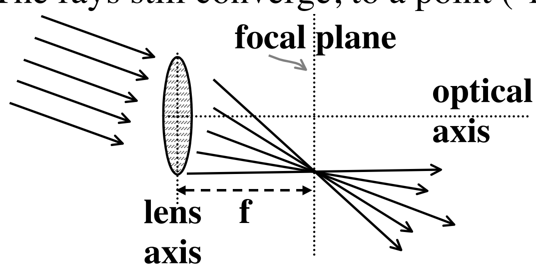
The focal length wll be the same on both sides. Interestingly, this is true even if the lens has a funny shape, like that "contact lens" on the previous page!



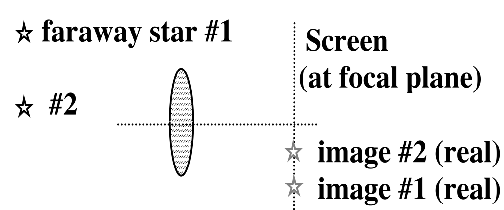


Your eyeball has a lens. The retina is like a screen.
(Images of objects form on the retina.)

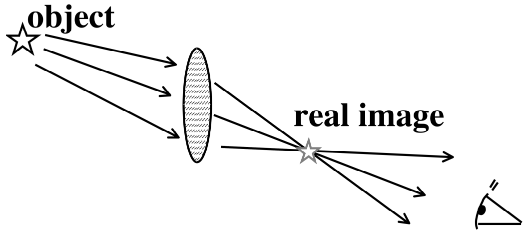
What if the rays come in parallel, but "off axis" (not parallel to the optical axis)?
The rays still converge, to a point ("f" away from the lens axis), in what is called the "focal plane" of the lens. But, they converge to a point off the optical axis.



A consequence of this last diagram is the imaging of distant objects, like stars, on a piece of film at the focal plane of a camera.



The images formed by these simple converging lenses are **real,** the light rays really do pass through that point!



If you stand as shown, you perceive the light to be coming from the "image" spot. And they really ARE coming from that spot! The image is real.

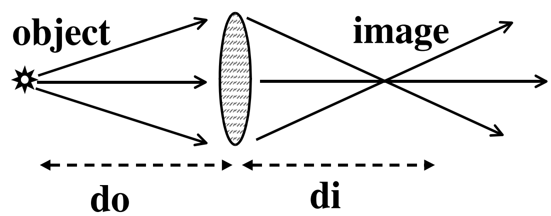
Optometrists define P = 1/f = "power of lens". (It's a poor name - it has nothing to do with power as in "watts". The units of P are m^-1, and are quoted as "diopters".)
1 D = 1 diopter = 1 m^-1.
A "5 D lens" means f = 1/P = 1/5 m^{-1} = 0.2 m, or 20 cm focal length.

What if the object is <u>not</u> at "infinity", so incoming rays are <u>not</u> parallel?

- Image <u>is</u> still formed
- No longer in "focal plane"
- May be real, or virtual: Depends on lens, and how close object is.

The **<u>Lens Equation</u>** tells you all sorts of useful info:

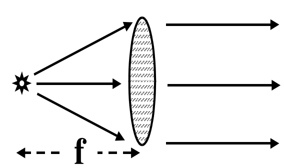
$$\frac{1}{f} = \frac{1}{do} + \frac{1}{di}$$ where



do = "object distance"
di = "image distance"
f = "focal length".
(The equation is proven in Giancoli, if you are interested. It's basically just geometry. See the figure for definitions of symbols.)

<u>Comments and examples:</u>

• if do=f (i.e. an object at the focus on the left), then 1/f = 1/f + 1/di.
The only solution to that is di=∞ (think about it)
We've seen the picture for this case before: (notes p.8) There is no image, or if you like, the image is "off at infinity".



• If do = ∞ (i.e. if object is very far away) then 1/f = 1/∞ + 1/di which says di = f. We already knew this: image of faraway sources is in the *focal plane,* a distance f from the lens.

• If do = 2f, then we have 1/f = 1/(2f) + 1/di, solving for di gives di = 2f. (check for yourself) There is something pleasingly symmetric about this result: an object at twice the focal distance focuses at twice f on the other side.

As do decreases from ∞, the formula says di *increases* (from f). Why? You can think about the *math* yourself (maybe try some numbers), but the *physics can be seen from sketches:*

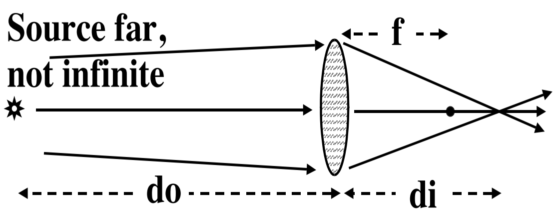
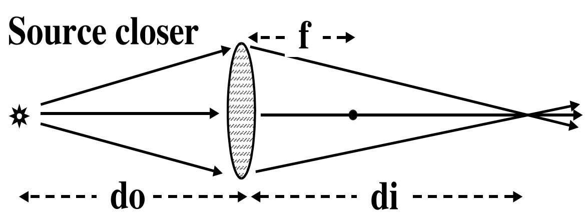


Image is *barely* past f, the focal point.

A given lens can only bend light so much. If the rays are coming in not quite parallel, as shown, the lens can't bend them as far "inward" as it did when they really came in *exactly* parallel.

If the source is nearer still, the rays come into the lens at a yet steeper angle, the lens can’t bend them down to the original focus, it can’t bend that much!



They will focus, but farther away. (That's what the formula gives too)

The lens equation is great, but it is essential that you <u>also</u> be able to make a *sketch* to crudely estimate what’s going on! These sketches are called “**ray diagrams**.” It also helps to see what’s going on when the source is “extended” rather than a *point* source

<u>Ray Diagrams</u>:

1) Draw the object & the lens.

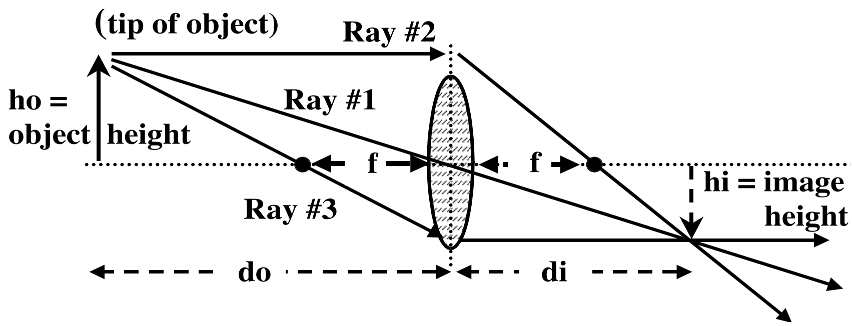
- The lens is drawn as a lens shape, but for the purposes of math *and* sketch, think of it as paper-thin and very tall...
- Draw <u>both</u> foci of lens as points. (heavy dots in my fig)
- You usually just need to pay attention to the extreme point ("tip") of the object, especially if the base is on the optical axis.

2) Draw exactly 3 special rays*, & trace them through the lens.

3) Deduce where the rays converge (or appear to converge *from*): That's your image!

*Special Rays: Any rays work, but 3 of them are *easier*:
Ray 1: enters through *center* of lens - this ray goes *straight through*.
Ray 2: enters parallel to optical axis - this ray heads to *far* focus
Ray 3: through focus on near side comes out parallel on far side.

<u>Example:</u>



Think about all three of these rays. You should understand (from the last couple of pages) *why* each of those rays does what it does.

The lens formula says 1/do + 1/di = 1/f. The figure will always help you *understand* what is going on! *Both* are useful.

"**Lateral Magnification**" <u>m = hi/ho</u> (that's the *definition)*
Geometry says <u>m = -di/do</u> (see Giancoli for a proof)

The minus sign is a *reminder*. (we'll discuss signs more, soon.)
For now, a negative "m" (or equivalently, a negative "hi", like in the example figure above) means that the image is ***inverted***.
In the example above, "do"> 0, because the *object is real*.
In the example above, "di"> 0, because the *image is real*.

(Can you see that the image is real? If you stand to the far right, you perceive an inverted image at that spot, and yes, the light rays REALLY do emerge from that point in space)

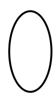
In **cameras** (see Giancoli 25-1) the focal length f is generally fixed. (It just depends on the shape of the lens, and is not variable)

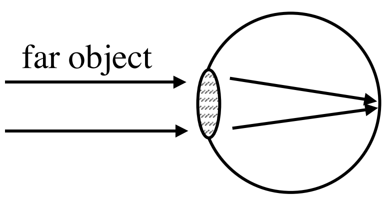
Since (1/f) = (1/do) + (1/di), the "image distance" di depends on do. "di" is where the film needs to be, so you must adjust the distance of film depending on how far away the object is. (this is called "focusing the camera," the lens -> film distance changes)

In **eyeballs** (see Giancoli 25-2) the distance of the retina behind the lens ("di") is *fixed* by the size of your eye. So, your eye adjusts the *shape* of the lens, & thus changes "f"!

Camera examples: A "50 mm lens" means f = 50 mm = 0.05 m. An object at infinity means the film should be .05 m behind the lens. As object gets closer => film should be moved further *back,* away from lens. That's what's happening when you twist-focus an SLR camera. [note: "35mm Camera" refers to the film size, *not* lens size.]

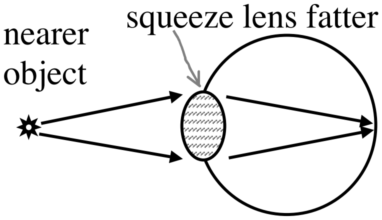
Eyeball examples: In general  thin lens = less bending = *larger* f

 Fat lens =more bending= *smaller* f

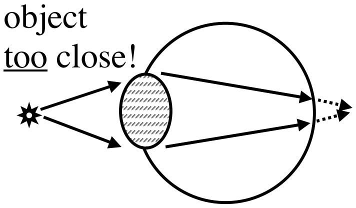


- Object at infinity
- eye relaxed
- lens is thin
- f is the size of the eyeball

- Object is closer = need to bend light more sharply to get it to focus on retina
- need fatter lens (smaller f)



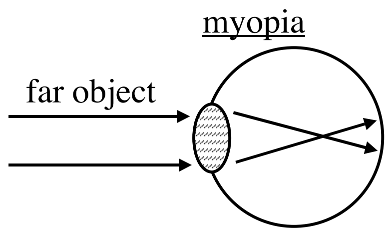
- Muscles squeeze the lens to do this.



- Can't make f small enough, (can't bend rays sharp enough) = can't focus! See fuzz…

Near point ("N") = shortest distance you *can* still focus to. Typically, N~ 25 cm (~10 in) for normal eyes.

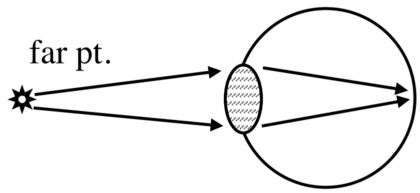
If you are “near sighted” (**myopic**) you can see nearby things, but not far away objects. Your “relaxed” eye lens is *still* too fat, and bends light *too* much:



- Lens is too fat
- Focus is inside the eyeball
- You see “fuzz”

•

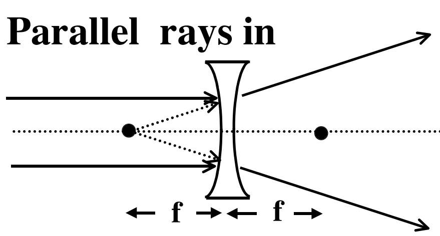
This (myopic) lens has a “far point”, which is the *farthest* it can still focus on.



point

- Relaxed eye
- *Can* focus on this (nearer) object.

The myopic eye is "overbending" the light. To correct this problem (like my eyes), you need a lens in front of the eye which should *diverge* the light a little bit. A **diverging** (concave) lens.



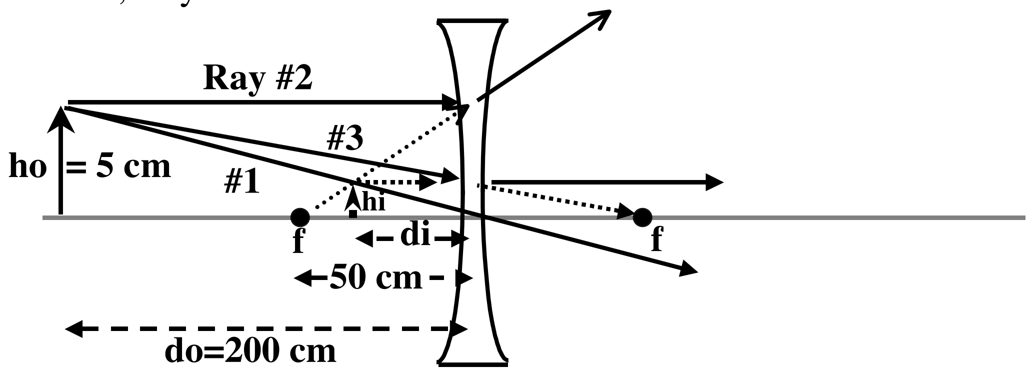
Numerical Convention: “f” for a diverging lens is negative.

Parallel light rays *in* diverge out: They *appear* to be coming from focus on the *back* side, as shown.

So, a far away object on the left will produce a virtual image: The light rays don’t *really* all pass through that point!

Example: Diverging lens, f = -50 cm (Note the - sign.)
5 cm tall object, 200 cm from lens:

Once again, a complicated diagram, but if you think about each ray, one at a time, they all make sense.



For a diverging lens, here are the 3 special rays:

• Ray 1: enters through *center* of lens: this ray goes *straight through*.

• Ray 2: enters parallel to optical axis - this ray heads *away from near focus*. (That's how diverging lenses work - look at the prev. fig: a ray that comes *in* parallel bends away from the center, acting as though it was heading straight away from the near focus)

• Ray 3: The ray that is heading for the far focus reaches the lens, and comes out parallel. (This one is the trickiest to remember, but I like to think of it in reverse, then it's just like Ray #2 backwards)

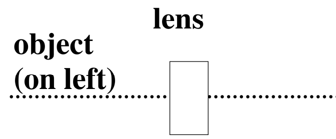
The dashed lines are all just to guide your eye - there are no REAL light rays where the lines are dashed! Stare at this example figure: The image is *small, upright, inside the focus, & virtual*.

Lens formula: (1/f) = (1/do) + (1/di).
Here f = -50 cm (negative, the convention for diverging lenses);
do = +200 cm (given)
So (1/di) = (1/f) - (1/do) = (1/-50 cm) – (1/200 cm) = (-1/40 cm)
which implies di = -40 cm (check the math yourself)

di = -40 cm: That "- sign" tells you image is *virtual*.
The fact that 40<50 tells you image is *inside* focus.
m = -di/do = -(-40)/(200) = +0.2: "+ sign" tells image is *upright*.
The fact that m < 1 tells you image is *small*.

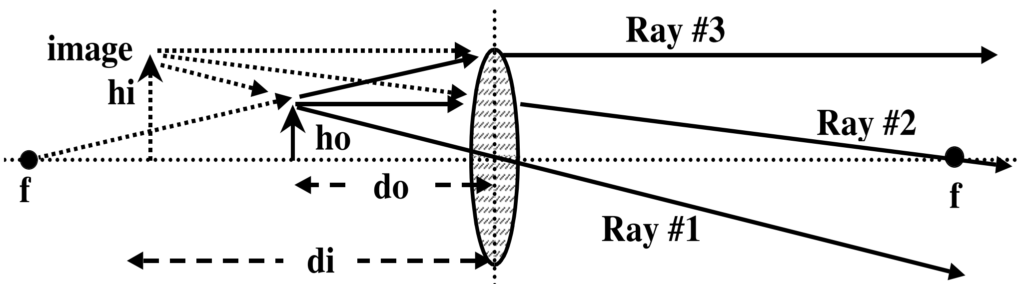
Eqn & sketch both have *same* info: useful checks on each other!

Summary of sign conventions:



Converging lens	$f > 0$
Diverging lens	$f < 0$
Real object	$do > 0$
Real image	$di > 0$
Virtual image	$di < 0$
Upright image	$hi > 0$
Inverted image	$hi < 0$

Example: Object located *inside* of focus of converging lens.
Let f=5 cm, do = 2 cm (object is located 2 cm to left of lens)



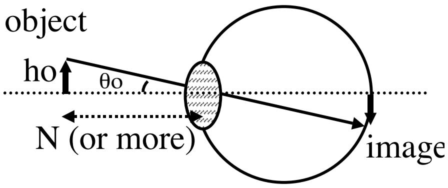
Ray #1 goes straight through.
Ray #2 is parallel on left, then bends towards focus on right.
Ray #3 is on the line *from* the focus on the left, comes out parallel.

Picture says image is *virtual, upright, enlarged, inside* focus.

Or, we can use the formula to get this as well: 1/f = 1/do + 1/di.
Therefore 1/di = 1/f - 1/d0 = 1/(5 cm) - 1/(2 cm) = -0.3 cm^-1
So di = -3.3 cm. Since di is negative => *virtual image*.
di < 5 cm => inside focus,
m = -di/do = +3.3/2 = +1.7, sign says it is upright,
fact that m>1 says it is enlarged.

This is a magnifying glass!

If you want an object to look larger, you bring it *closer* (right?) But you can't bring it closer than "N", 'cause then it gets fuzzy/hard to see. The *max* angle θo an object of height ho can "span" inside your eye is thus tan θo (max)= h0/N

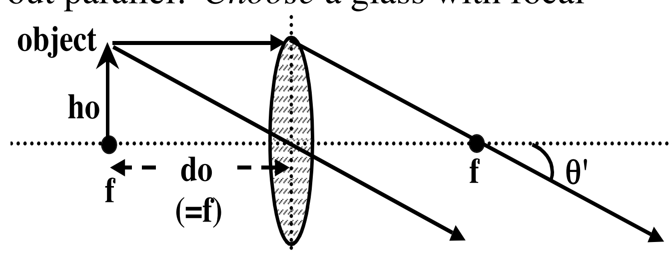


(Look at the figure, convince yourself)

But, what if θo(max) is still too small for you? Magnify θ with a lens!

Magnifying Glass (Giancoli 25-3):
Same principle as the example on the previous page: Usually put object *at* focus, so rays come out parallel. *Choose* a glass with focal length f < N ~ 25 cm (typically)

Object at focus => rays come out parallel.



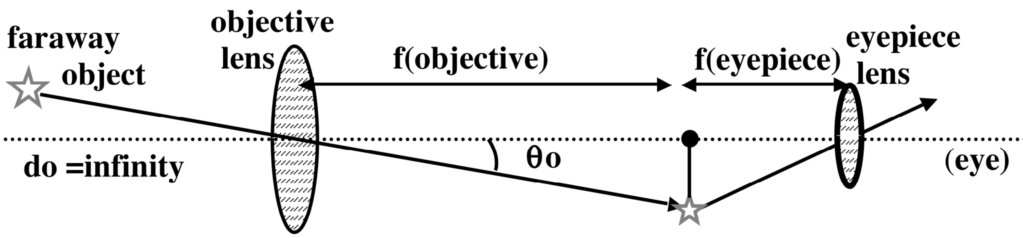
Now, put your eye in front of the lens (on the right.)
Parallel rays come into your eye = you see the tip as a pointlike object at "infinity," tipped up to an angle tan(θ') ≈ ho / f.
• You can always approximate tanθ ≈θ for small θ. (Did you know that? It's true if θ is measured in radians, anyway.)
So what we have here is **Angular Magnification**. The formula is
M = θ'/θo(max) (this defines "angular magnification".)
≈ (h0/f) / (h0/N) = N/f. (from the geometry of the picture, making that small angle approximation)

What's going on is this: the presence of the lens makes the object appear to be farther away (hence, easier to focus on) and *also* subtend a larger angle in your eye (which means it looks bigger) The ratio of the "new angle subtended with the lens" (θ') to the biggest angle you could get by bringing it close (θo(max)) without any lens, is the angular magnification.

E.g: f (lens)=5 cm gives you (if you have a typical near point)
M=N/f~25 cm/5 cm="5X" (5 times angular magnification)

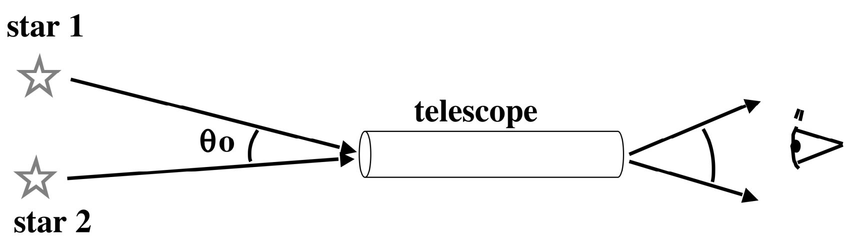
(Note that "M" is different from "m = lateral magnification".)

Telescopes (25-4 in Giancoli)
Sometimes 2 lenses (or more) can be combined to produce useful images. E.g. Astronomical refracting telescopes:
Big (large f): "objective lens"
Small (short f): "eyepiece lens"



Since do = ∞, the objective lens produces a real "intermediate" image at di = f(objective).
Then the eyepiece is f(eyepiece) behind *that* =>
you get an image of that intermediate image (!)

The eyepiece is like a "magnifying lens" in the last example:
With the intermediate image at the focus, your (relaxed) eye sees the *angle* of the image magnified (angular magnification again).



- Geometry gives : $\theta'/\theta_o = f_o / f_e$ = angular magnification.
- Note, the image is inverted.