Tues. 10/18 Wed. 10/19 Thurs 10/20	**O1&2:** Light & Mirrors **L7:** Mirrors & analysis, (**O3**) **O3:** Lenses	**RE-O1&2;** Lab Notebook, Abstract & Conclusions sects. **PL7; Quiz 5:** Q10, Q11 **RE-O3**
Mon.10/24 Tues. 10/25 Wed.10/26 Thurs. 10/27	 ***Review*** **Exam 1** **O4** Opt Systems	**HW7:** O1: 4; O2: 7, 8 **HW Redos** **RE-O4**

- **Equipment**
  - Ppt.
  - Graph paper
  - HW to hand back
  - Echo-Chamber Ray Tracing Program
  - Odeon
  - Board Laser Optics set?
  - Rulers
  - Handheld laser and plexi-glass tube or cylinder
- **Reflection**
  - **In water:** Wave tank simulation http://www.falstad.com/ripple/ set for setup:refraction.
  - **In light:** Arbor Scientific optics kit & power supply
- **Plane & Spherical mirrors –** big concave Mirror
  - Laser & smoke in a can
  - Asymmetric object, like my tea-pot.
  -
-
- Go over Homework Rules

O1 The Nature Of Light
O1.1 Intro
O1.2 Light Moves in Straight Lines
O1.3 Objects Give Off Light
O1.4 Plane Mirrors
O1.5 Refraction at Plane Surfaces
O1.6 Total Internal Reflection

O2 Reflection and Mirrors
O2.2 Images – Virtual and Real
O2.3 Ray Tracing
O2.4 Formulas and Sign Convention
O2.5 Convex Mirrors- Virtual Images
O2.6 Concave Mirrors – Virtual and Real Images
O2.7 Plane Mirros – Virtual Images

Questions?

O1 The Nature Of Light
O1.1 Intro
Transition

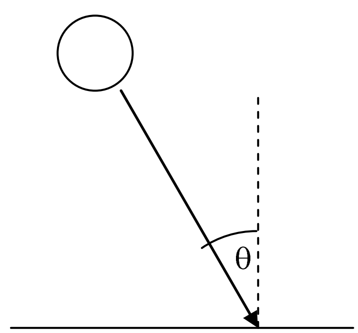
- On one or two occasions in Physics 231, I pointed out that there are two complementary/contradictory endevours in theoretical physics
  - **Fundamental theory.** To develop an explanatory model that relates observations to the fewest and most *fundamental* facts / ideas.
  - **Good-enough approximate theory.** For a given question, to develop the simplest model necessary – strip out all extraneous details.
- For example, Newtonian mechanics is 'good-enough' approximate model for most everyday situations, but if things are moving too quickly, you do have to refine your definitions of momentum and energy. As we've just learned in unit Q, if an object's wavefunction's wavelength is larger than the object itself or things it'll interact with, you'll need to consider it's wave-like behavior in those interactions, if not, Newton's good enough.
- Similarly, the four "Maxwell Laws" that you encountered in Electricity and Magnetism reflect a rather *fundamental* model of electric and magnetic field's behaviors. They predict wavish behavior for light; however, just as with the wave's we've just been dealing with – if the object's the light interacts with is smooth on the scale of the wavelength, a 'good enough' model is rather Newtonian.
- I won't theoretically derive this sufficiency, but I'll motivate / demonstrate it with a simulation.

O1.2 Light Moves in Straight Lines

Transition from Wave to Ray optics.

Long before there was wave-particle duality for photons and electrons, there was ray-wave duality for classical light. Near the end of Electricity and Magnetism, you learned how oscillations in electric and magnetic fields constitute light. In Unit O, we'll use the fact that, in spite of the inherent wavyness of light, we can often describe its propagation in much the same way as we would a particle.

Say you were playing air hockey, and you knocked the puck like so:

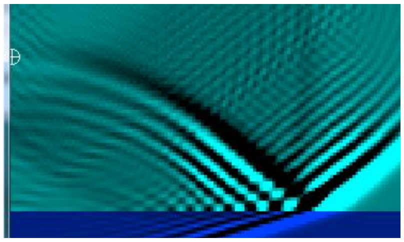


When it bounces back off the bumper, what will be the angle of its reflection relative to the normal?

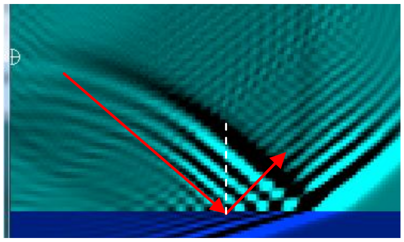
Assuming a perfectly elastic collision, and that the wall doesn't go anywhere, then the puck reflects with equal and opposite angle – that's the only way for it to maintain energy and keep its horizontal component of momentum constant.

Now, consider a wave, say in the surface of water, rippling toward a wall, like so

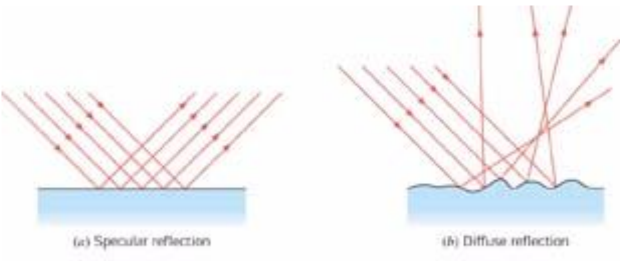
How will it reflect?, let's see
Demo: http://www.falstad.com/ripple/ set for setup:refraction.



If you could surf on a wavecrest, you'd follow the same trajectory as the ball thrown at the wall. One way to think about why this is: the initial wave incident at an angle could be thought of as a superposition of two waves, one going straight down with its wavelength and one going straight across with its wavelength, as you're familiar, the straight down one would reflect back straight up while the across one would be unchanged. So the new supper position results in a wave propagating just as much over as before, but up instead of down.



This kind of behavior allows us to visualize the propagation and reflection of waves the same way as you would a rain of balls bouncing off a surface. By following the paths of individual balls, you can learn and predict much about the whole wave's behavior.



Seeing an object.

- When we ‘see’ an object, some of the light bouncing off it from the overhead lamps, the sun,… is bouncing into our eyes.
- **Shiney & Smooth**
  - If the surface is smooth compared to the light’s wavelength, then the light that’s incident on it reflects in a way the preserves its order – a plane wave in reflects to a plane wave out, light tracing the outline of a jackolantern’s smile in traces one out; we see these surfaces as shiney. That’s the kind of surface we’ll consider most.
- **Dull & Rough**
  - Alternatively, if the surface is bumpy on order of the wavelength, then the reflected light gets all jumbled and we see the surface as dull. Mind you, it’s still true that, for each individual ray, the angle of incidence is equal to that of reflection, it’s just that the surface against which those angles are measured is tipped differently for each ray. For that matter, we’d also need to worry about the real wave behavior – interference, diffraction…

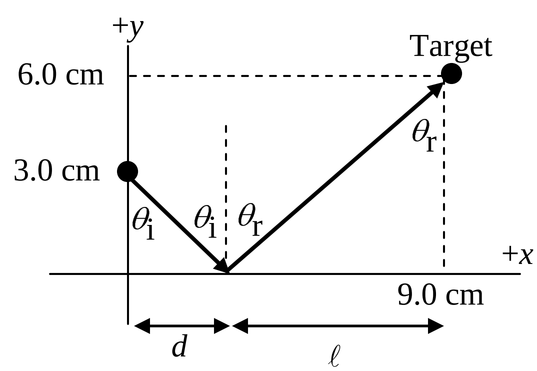
O1.3 Objects Give Off Light

O1.4 Plane Mirrors

Example 1. A laser mounted 3 cm above a horizontal mirror should be aimed at the mirror so that it bounces off and hits a target that is 9 cm over and 6 cm above the mirror. How far over should the laser hit the mirror?

6. ***REASONING*** The drawing shows the situation described. The law of reflection indicates that the angle of incidence θ_i is equal to the angle of reflection θ_r.

SOLUTION For the incident and reflected light, we have



$$\underbrace{\tan\theta_i = \frac{d}{3.0\text{ cm}}}_{\text{Incident light}} \quad \text{and} \quad \underbrace{\tan\theta_r = \frac{\ell}{6.0\text{ cm}}}_{\text{Reflected light}}$$

But $\theta_i = \theta_r$, according to the law of reflection, so that tan θ_i = tan θ_r, and we have

$$\frac{d}{3.0\text{ cm}} = \frac{\ell}{6.0\text{ cm}} \quad \text{or} \quad \ell = 2d$$

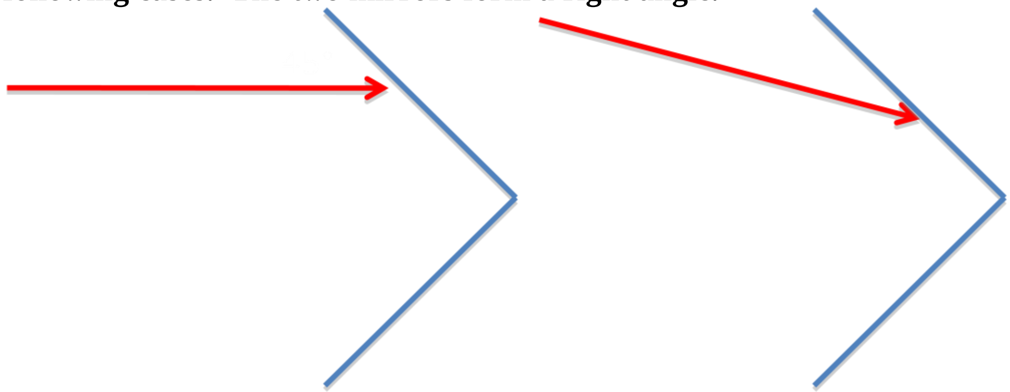
From the drawing we can see that $d + \ell = 9.0$ cm, and using the fact that $\ell = 2.0d$, we obtain

$$d + \ell = d + 2.0d = 9.0\text{ cm} \quad \text{or} \quad d = 3.0\text{ cm}$$

Therefore, the laser should be aimed at the point at $\boxed{x = +3.0\text{ cm}}$.

Ppt slide 1

In what direction does the light beam reflect from the second mirror in each of the following cases. The two mirrors form a right angle.

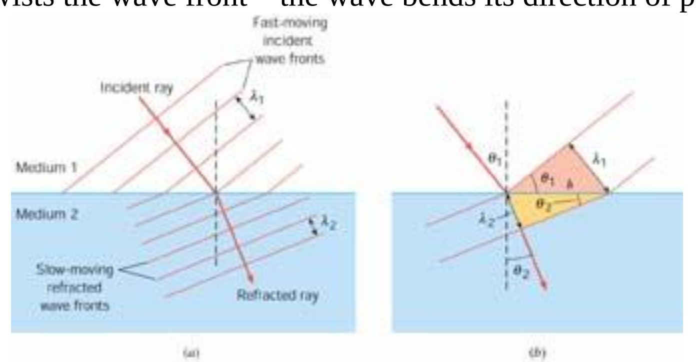


O1.5 Refraction at Plane Surfaces

Refraction.

Of course, looking at this simulation, you see the waves don't just reflect, they also penetrate into the new medium, but they *do* change their direction a little. That's known as refraction. For waterwaves, you can make this happen by changing the *depth* of the water – a surface water wave's speed depends upon the depth of the water (why is the subject of an advanced waves course). Of course, for any wave,

- **Water refraction**
- **Demo: Ripple Tank Demo** set for Refraction, but with the source frequency turned up enough to see a few consecutive wave fronts at once.
- Waves cross deep-shallow interface at different angles. The segment of the wave in the fast runs ahead and the segment in the slow lags behind. This twists the wave front – the wave bends its direction of propagation.



$$\sin\theta_1 = \frac{\lambda_1}{h} \Longrightarrow \frac{\sin\theta_1}{\lambda_1} = \frac{1}{h}$$

- $\sin\theta_2 = \frac{\lambda_2}{h} \Rightarrow \frac{\sin\theta_2}{\lambda_2} = \frac{1}{h}$

$$\frac{\sin\theta_1}{\lambda_1} = \frac{1}{h} = \frac{\sin\theta_2}{\lambda_2}$$

- This equation can be rewritten in terms of wave speeds if we make the observation that the frequencies of the waves must be the same in the two media. This necessity follows from conservation of wave fronts. If ten wave fronts approached an interface from one side in, say one second. Then an equal number must cross over the interface into the other medium in one second. If only 8 crossed over showed up on the other side, then where did the other 2 go? If 14 appeared on the other side, then where did the extra 4 come from?
- So,
  - $v_1 = \lambda_1 f \Rightarrow \lambda_1 = v_1 / f$ and $v_2 = \lambda_2 f \Rightarrow \lambda_2 = v_2 / f$

$$\frac{\sin\theta_1}{\lambda_1} = \frac{\sin\theta_2}{\lambda_2}$$

- $\frac{\sin\theta_1}{v_1 / f} = \frac{\sin\theta_2}{v_2 / f}$

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$$

- **Refraction and Sound.** The exact same thing happens for sound traveling through regions of air with different temperatures. On nights when the air cools off much faster than the ground, the air near the ground remains warmer than that further up so sound waves from, say, a distant train, refract away from the ground, making it quieter down here.

▪ **The marching Band Analogy**
  - The reading gives a good analogy for a few lines of a marching band, if everyone marches with the same beat, but those at one end take *longer* steps, then they'll get farther, and the whole line will bend.

▪ **Constant "Speed of Light" but slowing of light's "wave speed."**
  - Here's another instance of "fundamental vs. Good enough."
  - The text makes one extremely common simplification which is 'good enough' for ray optics but not 'fundamental' and leads to conceptual difficulties if you try applying it to other situations.
  - **Superposition Principle for E field and conductors.** I expect that you learned the principle of superposition in Physics 232, and how it applies to electric and magnetic fields. For example, if you have a hollow conducting sphere and a source of electric field outside it, the field inside the sphere is 0 *not* because the charges on the sphere's surface "absorb" the external field, but because

they arrange themselves on the surface in response to it and produce their *own* field which, inside the conductor, is equal and opposite to that of the external source.

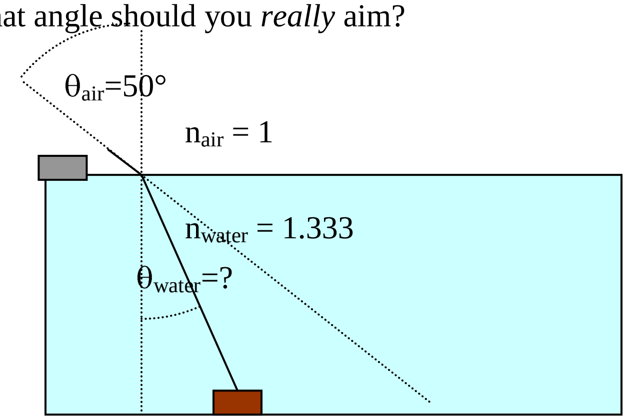
- **Propagation of each source's field vs. propagation of whole pattern.** With that refresher, think of what *really* happens when the electric field associated with light comes to a surface. *That* field just keeps on going, at the speed of light. *Meanwhile*, the charges in the material rearrange themselves in response to it and are then responsible for an additional field. The mechanical responses of those massive charged particles is sluggish, and thus there's a delay in the production of this new field. *That* is what is slow – not the propagation of a field once created, but the process of charges moving to create new fields by charges responding to the existing fields. The original electric field, and the subsequent contribution of each charged particle in the material travels at the same old speed c, but the composite effect is that the *overall wave pattern* ripples more slowly.
- So, to simply say that the speed of *light* is different in different media is misleading – fields from each individual source propagate at the same speed as always, *c*, but the composite wave pattern, ripples slower, thanks to the sluggish charged particles.

▪ **A**ll this said, the *wave speed* is most certainly slowed, and that's what we're concerned about with refraction. Defining "Index of Refraction" for a material as the ratio of the speed of light to *wave speed* in a given medium: $n_1 \equiv \frac{c}{v_1}$

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} \qquad \textbf{Snell's Law}$$

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

○ **Example1:** You're playing the dive-for-the-brick-game in a friend's pool. The brick is tossed out into the deep end. Laying one your raft it looks like you should aim for 50° below straight down. Given that the refractive index of air is ~ 1, and that of water is about 1 1/3, at what angle should you *really* aim?



▪ **Quantities**
- θair = 50°
- n_{air} = 1
- n_{water} = 1.333
- θwater = ?

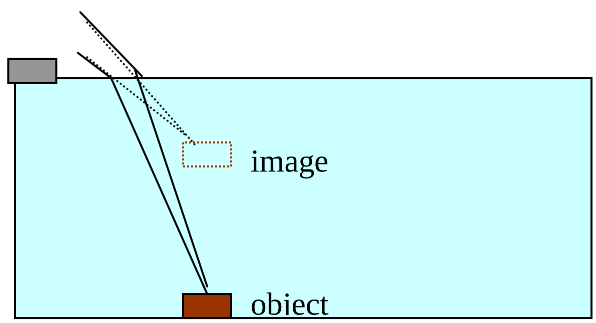
▪ **Relations / Math**

- $n_1 \sin\theta_1 = n_2 \sin\theta_2$;

  $$n_{air} \sin\theta_{air} = n_{water} \sin\theta_{water} \Rightarrow \theta_{water} = \sin^{-1}\left(\frac{n_{air} \sin\theta_{air}}{n_{water}}\right)$$

  $$\theta_{water} = \sin^{-1}\left(\frac{1 \cdot \sin 50°}{1.33}\right) = \boxed{35°}$$

- **Apparent Depth**
  - Here we just followed one ray of light form the object. If we trace out a few rays, we can explain another interesting phenomena: things in water always appear nearer than they are.
  - For example, say you're looking into a fish tank, viewed from the front you get one impression of how far back they are and how far to the left they are; but then you walk around to the left side and now they don't seem nearly as close to the front, and they seem much closer to the left. Similarly if you go from looking down to looking in the side. Or maybe you are just reaching or diving into the water to pick something up, and it turns out being deeper than you expected.
  - Here's how that works. Recall that when you see an object you expect that the light arriving at your eye radiated from the object in *straight* lines the whole way from it to you. Let's compare what some rays of light from the sunken brick do, vs. what you expect them to do; this will show us the difference between where the *object* actually is and where you *imagine* it to be.



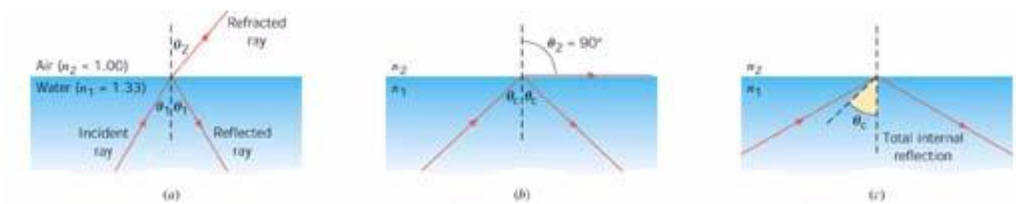
Two-minute problem
The index of refraction for air is approximately 1.0 and for water it is about 1.33. You are at the bottom of a 6-ft deep pool and a light is 12 ft. to your right and 12 ft. above you. The light will *appear* to be at

A. Less than 45° from vertical
B. 45° from vertical
C. More than 45° from vertical
D. You won't be able to see it

O1.6 Total Internal Reflection

Total Internal Reflection

- In general, when light hits an interface, some fraction of it reflects, obeying
  - $\theta_i = -\theta_r$
- and some fraction transmits, obeying
  - $n_1 \sin\theta_1 = n_2 \sin\theta_2$
- When light comes to the interface of media from the high index side, i.e. the side with the slow speed of light, the transmitted light gets bent down from the normal, toward the interface. Increasing the angle of incidence, the transmitted beam can be brought right down to parallel to the interface, or 90° off the normal!
- **Demo: Ripple Tank demo** internal Reflection setup, but switch source to first be at low angle, so there *is* transmission, then slowly make it sharper and sharper until there isn't.

- **Q:** What happens when the incident angle is any larger?
  - **A: Demo:** Shine light through a Plexiglas triangle and see that the transmitted beam dies & the reflected beam grows more intense.
  - If the incident angle is increased any more, no light gets transmitted: it is completely reflected!
- 

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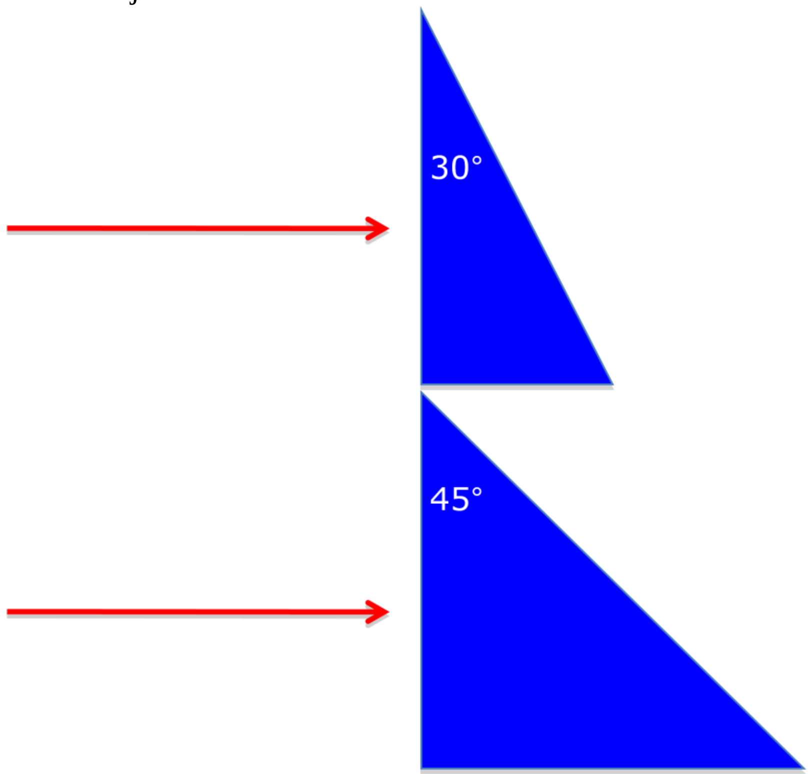
- **Example3:** For what angle of incidence would light cease to transmit from glass into air, i.e., what is this interface's *critical angle*?
  - **Quantities**
    - $n_{air} = 1$
    - $n_{glass} = 1.52$
    - $\theta_{air} = 90°$
    - $\theta_{glass} = \theta_{glass\text{-}air\text{-}crittical} = ?$
  - **Relations / Math**
    - $n_1 \sin\theta_1 = n_2 \sin\theta_2$; $n_{glass} \sin\theta_{glass} = n_{air} \sin\theta_{air}$
    - $\sin\theta_{glass} = \dfrac{n_{air}\sin\theta_{air}}{n_{glass}} = \dfrac{n_{air}\sin 90°}{n_{glass}} = \dfrac{n_{air}}{n_{glass}}$

$$\theta_{glass} = \sin^{-1}\left(\frac{n_{air}}{n_{glass}}\right) = \sin^{-1}\left(\frac{1}{1.52}\right) = \boxed{41°}$$

  - This is the phenomenon behind fiber optics. The light is shown in one end of a long tube of glass or plastic and instead of radiating out all the sides, it reflects back and forth down the length & out the other end of the tube.
  - **Demo:** Fiber optics tube & Plexiglas cylinder. Board laser set and block

- **Exercise:** Determine the path of the light beam in each of the following cases. The objects shown have an indices of refraction of n =1.5 and are surrounded by air.



O2 Reflection and Mirrors
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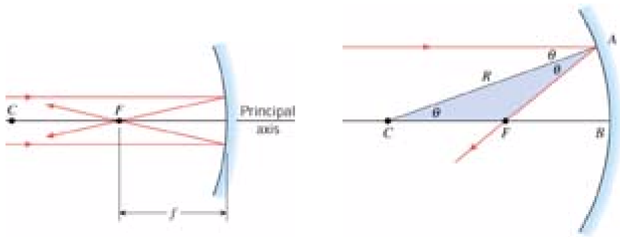
Light Hitting Surfaces – overview.

Spherical Mirrors

- Let's go back to the fundamental rule, $\theta_r = -\theta_I$. These angles are measured off the normal to the reflecting surface. As we saw in the discussion of smooth vs. bumpy surfaces, if different locations on the surface face different directions, then they reflect light in different directions. A bumpy surface is fairly randomly directed, so the reflected light goes in random directions. But what if we got smart about our surface? Say we wanted all light coming in parallel to bounce off into one point. How might we achieve that?
    - Smoothly bend the reflecting surface so that wherever the light hits, it ricochets to your focal point.
- **Demo:** Water waves & circular reflector
    - Produce plane waves and see them focus in.
    - Produce circular waves and see them reflect off to produce plane waves.

- **Focal Point, F**: to which parallel waves reflect and converge, the point from which radiating waves reflect and go parallel.
- For a spherical mirror, that point is located ½ the radius in from the surface. f = ½ r.
  - 

- Note: A circle is not *the perfect* shape for ricocheting *all* parallel light to a focal point. A parabola has the perfect shape, but a circle is much easier to make, and it does well enough for most purposes.

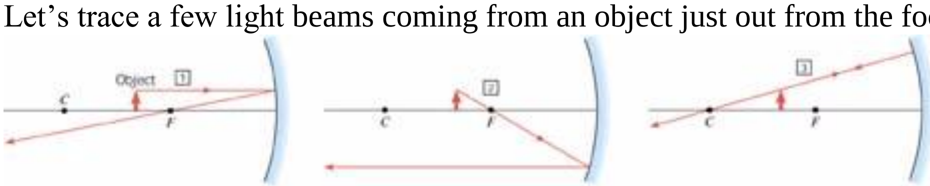
Demo: Beam tracer produce parallel rays and converge.

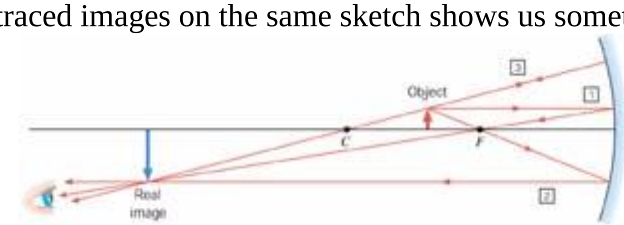
25.1 The Formation of Images by Spherical Mirrors

- We've only considered two very special cases – light originates parallel and is reflected into the focal point, and light originating at the focal point ends up parallel. But what if the light originates somewhere else, not parallel?

Demo: Wave tank – create circular waves somewhere away from the focus point. See it converge elsewhere & then continue on its way. It's as good as if there were a source at this point of convergence – there is an *image* of a source.

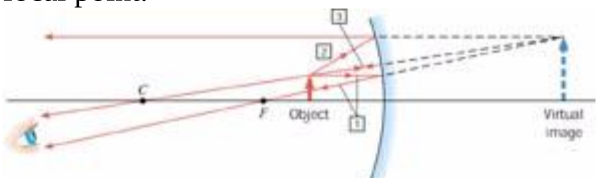
Demo: large spherical (parabolic) mirror and asymmetric object

- **orientation** of the image, - flipped upside-down, east-to-west, north-to-south
- **location** of the image, - in front of the mirror
- **size** - larger
- **Real Image**
  - Let's trace a few light beams coming from an object just out from the focal point.
  - 

  - The three easiest to trace are the ones that have simple rules:
    - 1) Inbound ray parallel to axis will reflect through focal point
    - 2) Inbound ray through focal point will reflect parallel to axis
    - 3) Inbound raw along radial (line from center point) will reflect on itself.
  - Okay, but what's all this ray tracing good for? Where we mentally perceive a point of an object to be is where the light rays entering our eyes appear to be diverging from. For example, if you hold your finger up infront of you, how you mentally judge the distance to your finger is how cross-eyed you have to go to point both eyes at it – the closer the finger, the more cross-eyed. Now, laying all three traced images on the same sketch shows us something:
    - 

- As far as the eye is concerned the light might as well have originated at this second point. In fact, our minds *expect* light to just travel in straight lines, so we are fooled into *imagining* the object to sit there. This is an **image.**
- Notice that we aren't getting *completely* made the fool; the light does *really* converge at image point, just like it does at the real object. Therefore, we distinguish this as a ***real image***.

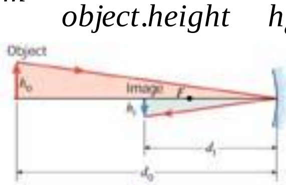
- **Virtual Image**
  - Now let's trace some light rays coming from an object that is just *in* from the focal point.



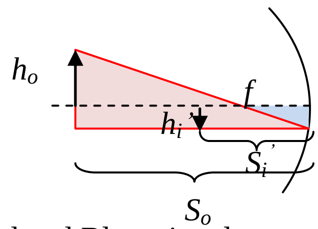
  - Notice that these rays *do not* cross paths again after leaving the image. All the same, the eye expects them to a) be converged on the source and b) follow strictly straight paths. Thus the only way the eye can make sense of the light it receives is to *imagine* the source to be back behind the mirror where the rays received *would* intersect if they went straight.
  - Here we're getting doubly fooled; not only is the object not where we imagine it, neither do the light rays even pass through that point. We call what we see a **virtual image.**
- **Comparing Image and Object**
  - You've probably noticed three basic differences between the image and the object.
    - location
    - size
    - orientation (real is upside down, virtual is right side up.)
  - Given an object's size, orientation, and location and a mirror's radius of curvature, you can trace a few representative rays, obeying $\theta_r = -\theta_I$, and learn the image's location, size, and orientation.
  - You'll be asked in one of your homework problems to do this.

Example 2 Say my tea pot is 4 inches tall, the spherical mirror has a radius of curvature of 2 feet. If I hold the pot 1.5 feet from the mirror, A) where is the image, B) how tall is the image? Find these by drawing the picture to scale and tracing the rays.

25.2 The Mirror Equation and the Magnification Equation

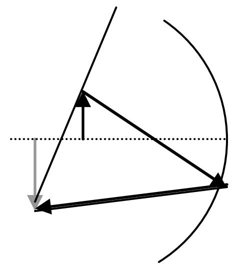
- Alternatively, we can get a little quantitative and come up with two equations: the *mirror equation* and the *magnification equation*.
- **Concave Mirror**
  - **Magnification**, how much bigger or smaller the image is than the object.
    - $m = \dfrac{image.height}{object.height} = \dfrac{h_i}{h_o}$
    - 

- looking at the picture, we can see that we have two similar right triangles – same set of angles, just different lengths of sides. It may sound vaguely familiar from trigonometry that the legs scale, i.e.
    - $\frac{h_i}{h_o} = -\frac{S_i'}{S_o}$ (negative sign comes from the fact one height is measured up and the other down)
    - So magnification can be expressed in terms of *either* heights or distances form the mirror.
    - $m = \frac{h_i}{h_o} = -\frac{S_i'}{S_o}$

- **Mirror Equation**
    - Now, how does the image location depend upon the object location? Drawing a few pictures, you can see that they are strictly related. Here's the easiest picture to use.
    -
    - 

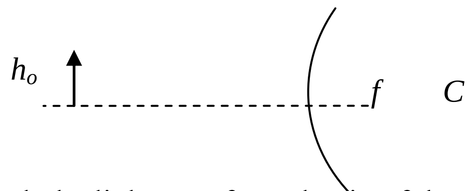
    - The Red and Blue triangles are similar, that is, Again we have similar triangles, so we have
    - $\frac{(-h_i)}{f} = \frac{h_o + (-h_i)}{S_o}$
      $\frac{(-h_i)}{f} = \frac{h_o}{S_o} + \frac{(-h_i)}{S_o}$
    - but, $\frac{h_i}{h_o} = -\frac{S_i'}{S_o}$, so we can replace h_o with $h_o = (-h_i)\frac{S_o}{S_i'}$ so
    - $\frac{(-h_i)}{f} = \frac{(-h_i)}{S_i} + \frac{(-h_i)}{S_o}$
    - since all terms have the same factor of $-h_i$, we can cancel that off and simply have
    - $\frac{1}{f} = \frac{1}{S_i'} + \frac{1}{S_o}$

- **Example3:** A concave mirror has a focal length of 42 cm. The image formed by this mirror is 97 cm in front of the mirror. What is the magnification?
    - **Quantities**
        - f = 42 cm
        - $S_{i'}$ = 97 cm
        - S_o = ?



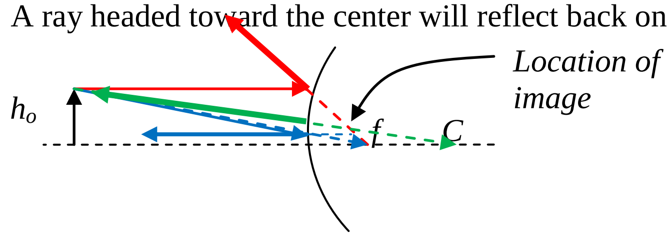
- m = ?
- **Relations**
  - $m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$, $\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{f}$
- **Algebra** (I'll pause along the way to find the object distance).
  - $\frac{1}{d_i} + \frac{1}{d_o} = \frac{1}{f} \Rightarrow \frac{1}{d_o} = \frac{1}{f} - \frac{1}{d_i} = \frac{d_i - f}{d_i \cdot f}$
    $d_o = \frac{d_i \cdot f}{d_i - f} = \frac{97cm \cdot 42cm}{97cm - 42cm} = \boxed{74cm}$
  - $m = -\frac{d_i}{d_o} = -\frac{97\,cm}{74cm} = \boxed{-1.3}$

- **Convex Mirror**
  - Consider this arrangement:



Even though the light rays from the tip of the object can't *actually* penetrate the mirror to go through the focal point or the center, we can still say that

1) A ray *headed* for the focal point will reflect parallel to the axis
2) A ray running parallel to the axis will reflect along the path out from the focal point
3) A ray headed toward the center will reflect back on itself.



Now, the three reflect rays don't *actually* criss-cross at some point but they radiate out *as if* originating at the location behind the mirror. This is a "virtual" image since the light rays don't *really* go there.

- The same mirror / lens equations hold, but different signage. The reading gives some rules on page 13; the "virtual object" seems pretty unphysical *now*, but they'll make sense when we look at compound mirror or lens systems in a later chapter – then the *image* produced by one mirror can be thought of as the *object* that the next mirror images. Should the second mirror itself be in the way, so the rays from the first mirror never actually converge to form the first image, then that unformed image is a 'virtual object' for the second mirror.

Concave	**f>0**
Convex	**f<0**

Real Object / Image (rays *really* go through, in front of mirror)	**S>0 / S'>0**
Virtual Object / Image (rays *don't* really go through, behind mirror)	**S<0 / S'<0**