OPTICS: REFLECTIONS

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Ray Tracing Reflections

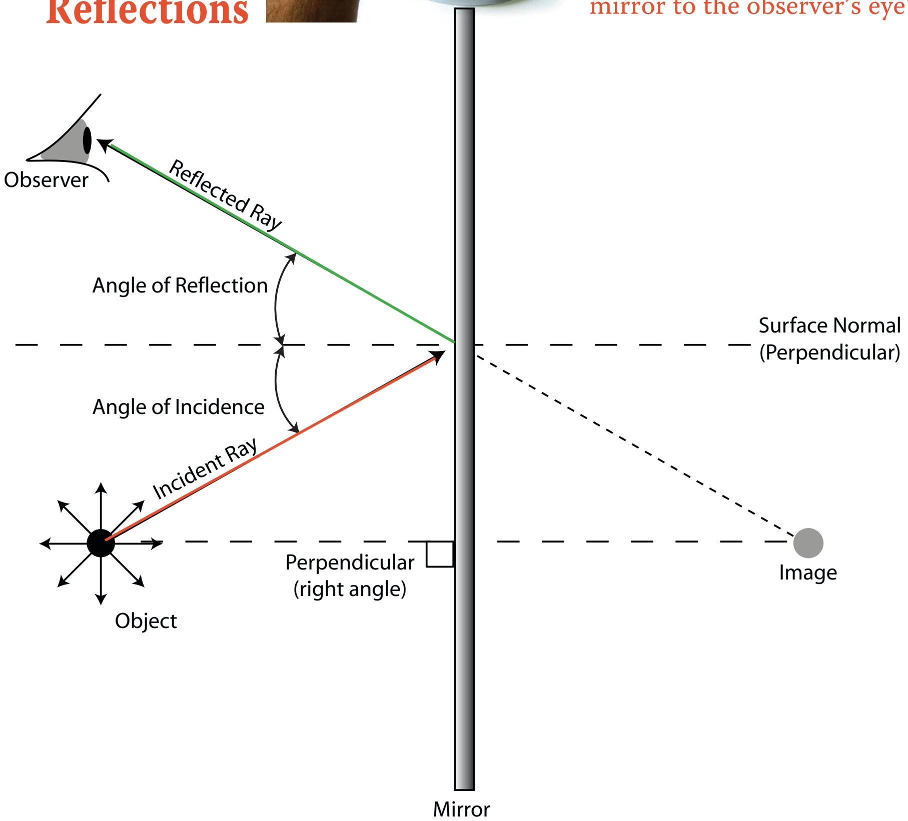
We are all familiar with our reflection in different objects: pots and pans, car hoods, puddles of water. The smoother the reflecting surface, the better the reflection. Humans have been perfecting mirrors for thousands of years—we've always been interested in the way we look.

But how does reflection work?

To get a handle on how reflection works, scientists draw something called a ray tracing diagram. *A ray tracing diagram is just a map of the path taken by a beam of light (a ray) from an object to the eye of an observer.*

If we start with an object—for simplicity, let's make it a dot—in front of a mirror, we'll be able to see its reflection. The reflection will appear to be coming from behind the front surface of the mirror. *Check it out—it's true!*

How can we trace the light ray's path from the dot to its reflection in the mirror to the observer's eye?



In a ray trace diagram of an object reflecting in a mirror, the incident ray travels from the object, bounces off the mirror and travels into the observer's eye.

A perpendicular line—surface normal—from the point where the ray bounces off the mirror forms an angle with each of the two rays. The angle that each ray makes with the surface normal must be equal.

There's an important rule for reflection: the angle of incidence equals the angle of reflection.

1. Light reflects from the dot in all directions. Some of that light will hit the mirror. Only a little of that will also bounce off the mirror and travel into the eye of the observer. We want to find the path of just those rays. Although there's really no such thing as a single ray of light, for the sake of simplicity, we represent a bunch of rays with just one. The math works!
2. We have to find the surface normal for the mirror. Since this is just a flat mirror, the *surface normal* is a line which is at a 90 degree angle to the mirror's surface. A line that's 90 degrees to a surface is said to be *perpendicular* to the surface.
3. A ray from the object to the mirror is called the *incident ray*. If you draw a perpendicular line from the point where the incident ray touches the mirror, then the angle between the perpendicular line and the incident ray is called the *angle of incidence*. There's also a *reflected ray*. That's the ray which bounces off the mirror. The angle between the perpendicular and the reflected ray is called the *angle of reflection*.

Since the dot is scattering rays of light in every direction, how do we know which rays will bounce into the eyes of the observer?

4. There's an important rule for reflection: *the angle of incidence equals the angle of reflection***.** In a flat picture like our ray tracing diagram, that means that there can only be one point on the mirror from which our ray can bounce and go into the eye.
5. The observer will see the dot as floating somewhere behind the front surface of the mirror. We can see exactly where by using our ray tracing diagram. We need to extend the reflection ray backwards and then draw another line perpendicular to the mirror which goes through the original dot. The point where this perpendicular and the extended reflected ray intersect is where the object appears to be floating behind the mirror.

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Mirror, Mirror on the Wall

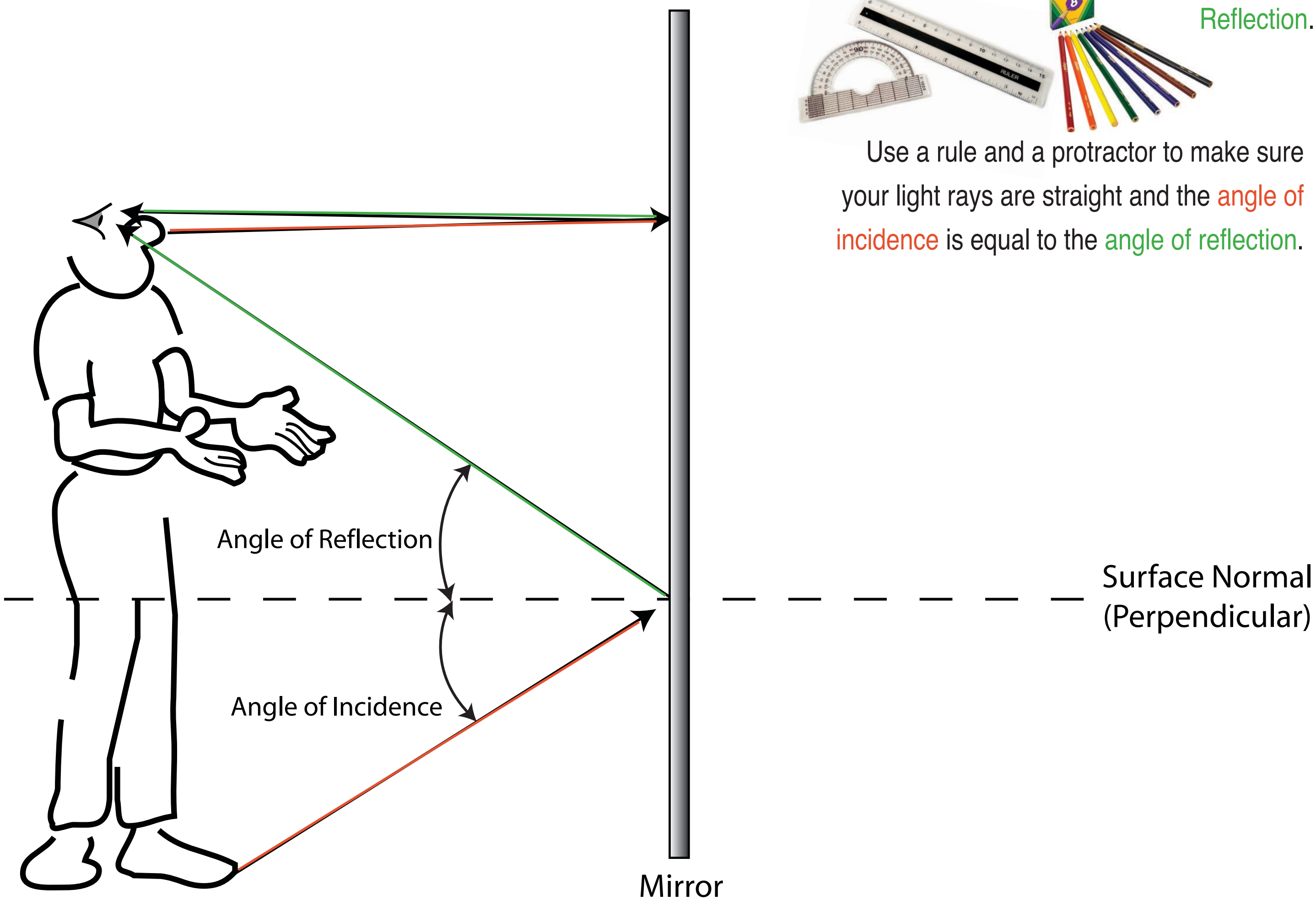
While ray tracing diagrams for dots are relatively simple, what happens if we want to create a ray tracing diagram of a more complicated object? Say we want to create a ray tracing diagram of a person being reflected. Well, we can think of any complicated object as a collection of simple dots and do ray tracing diagrams for the most important, defining dots of the object.

Below is a diagram of a person in front of a mirror. In this case, the observer is the person we are reflecting—the position of the person's eye is the position of the observation. The tip of the nose and the tips of the toes have already been traced. Do the ray tracing for the belt and the knees.

What You Need:

Use a red pencil for Incident Ray and a green pencil for Reflection.

Use a rule and a protractor to make sure your light rays are straight and the angle of incidence is equal to the angle of reflection.



So what makes a good mirror? Think smooth and large!

Does the mirror have to be as tall as the person to reflect the whole person?

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Good Mirror, Bad Mirror

Silver mirror on a bronze stand, Roman, 200 BCE

What Makes a Good Mirror?

If an incident ray falls upon a polished steel surface—like a pot above—there will be a well-defined reflected ray. That's called specular reflection (or mirror-like reflection). But a sheet of paper reflects light more or less in all directions. That's called diffuse reflection. Surfaces which reflect diffuse light make lousy mirrors—you wouldn't want to check your hair in the wooden spoon above, but the shiny surface of the pot might point our if your coiffure is off. In fact, early mirrors were just highly polished silver disks.

The difference between diffuse and specular reflection is surface roughness—a reflected ray is formed only if the average depth of the surface irregularities is substantially less than the wavelength of the incident ray. Basically, this means the smoother the surface, the better the mirror.

A surface can make a good reflector for long wavelength incident rays, but the same surface could be a poor reflector for shorter wavelengths. The bottom of a cast-iron pot, for example, makes a crummy mirror for short wavelength visible light but is an admirable surface for reflecting long wavelength microwaves.

Beyond smoothness, a surface also has to be substantially larger than the wavelength of the incident ray. If the surface is too small, light will scatter instead of forming a reflected ray. That scattering is called diffraction.

Why do you think a still pond makes a good reflection but an ocean in a storm does not?

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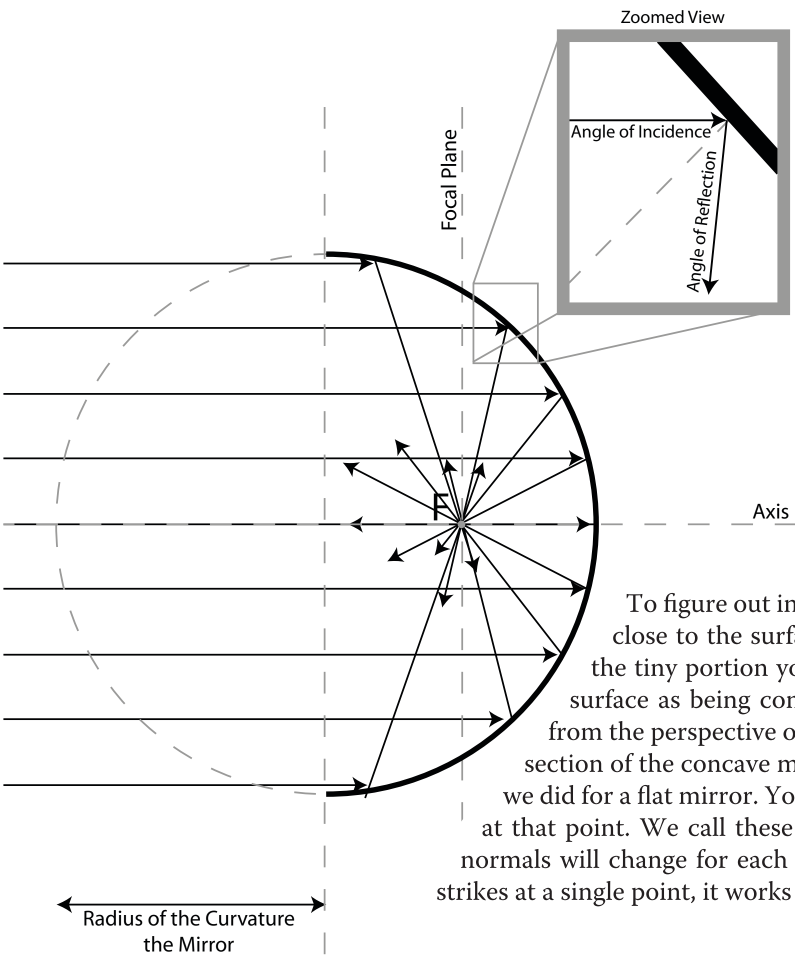
Curvaceous!

Think about going to a County Fair. Do you remember walking through a Mirror Maze? How about a Fun House full of curved mirrors? The shape of our reflection depends on the curvature of the mirror. Sometimes, curved mirrors can make us look short and fat and sometimes they can make us look tall and thin. Sometimes, curved mirrors can turn our reflection completely upside down.



How? Let's ray trace!

Let's start with a concave mirror. A concave mirror (think "cave") is one whose surface is shaped like the inside surface of a hollow sphere. Shine some light on it. The light is represented as the parallel lines coming in from the left.

The dashed circle helps us see the mirror as a full circle and makes it easier to visualize the circle's radius and center. The point F is the focal point of the concave mirror.

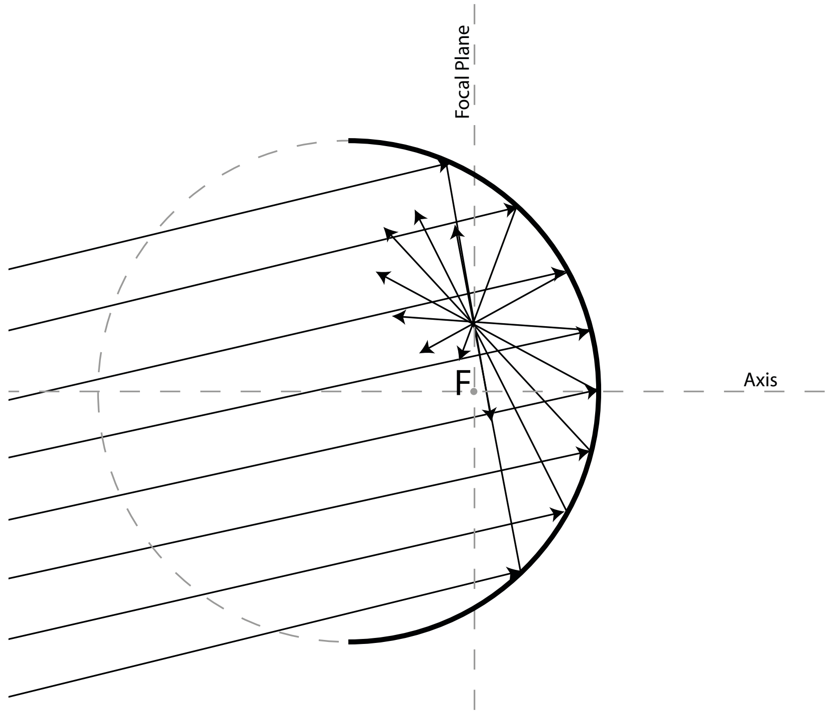
A focal point is where all the reflected rays come together.

The focal length is the length, along the axis, from the focal point to the surface of the mirror. The focal length of a curved mirror is also half the radius of its curvature. While *"radius of curvature"* is a pretty advanced concept, in a circular mirror like the one illustrated, it's just equal to half the radius.

To figure out in which direction the reflected rays go, imagine zooming in really close to the surface of the mirror. The closer you inspect the mirror, the flatter the tiny portion you are examining will look. At some point, you can imagine the surface as being completely flat, sort of like the surface of the sphere of the Earth from the perspective of a human being standing on it. Now we can treat this very small section of the concave mirror as flat and draw angles of incidence and reflection just like we did for a flat mirror. You can even draw a perpendicular line to the surface of the mirror at that point. We call these perpendicular lines surface normals. These angles and surface normals will change for each point on the surface of the concave mirror, but since each ray strikes at a single point, it works quite well for our ray tracing diagram.

What do you think would happen to a marshmallow if it's put at the focal point of a concave mirror facing the sun?

Up to now, our light has shone on the concave mirror parallel to the axis of the mirror. Let's look at what happens when the light comes in at an angle. Notice that the point where the reflected rays come together has shifted. When we draw a mirror axis and then draw all the lines perpendicular to it at the focal point, we define a plane known as the focal plane. Regardless of the direction of the light rays going into the convex mirror, they will always come together somewhere on the focal plane.



Rays which strike the mirror and which aren't parallel to the axis always converge along the focal plane.

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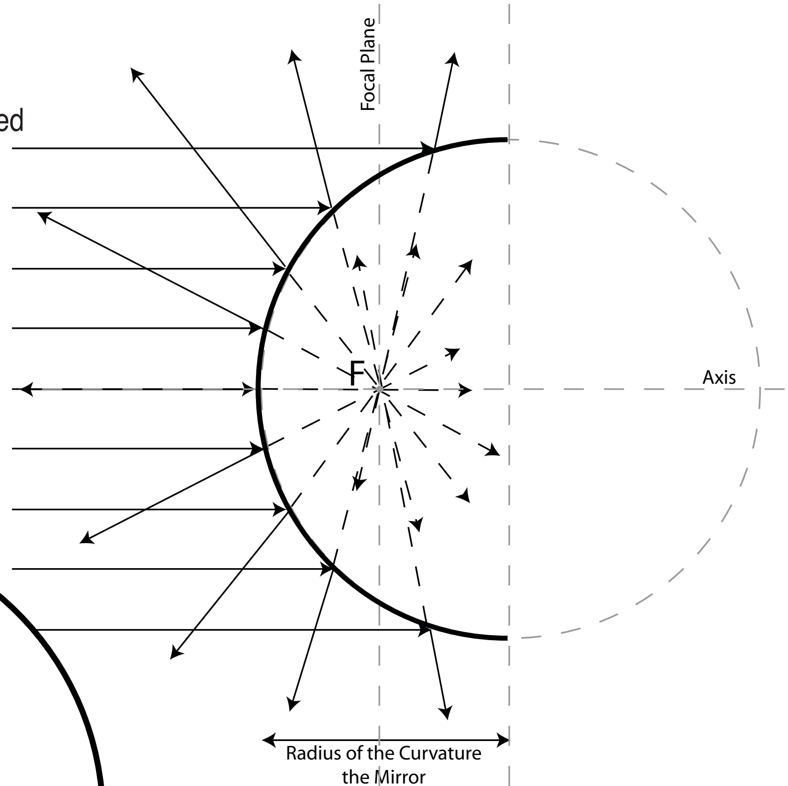
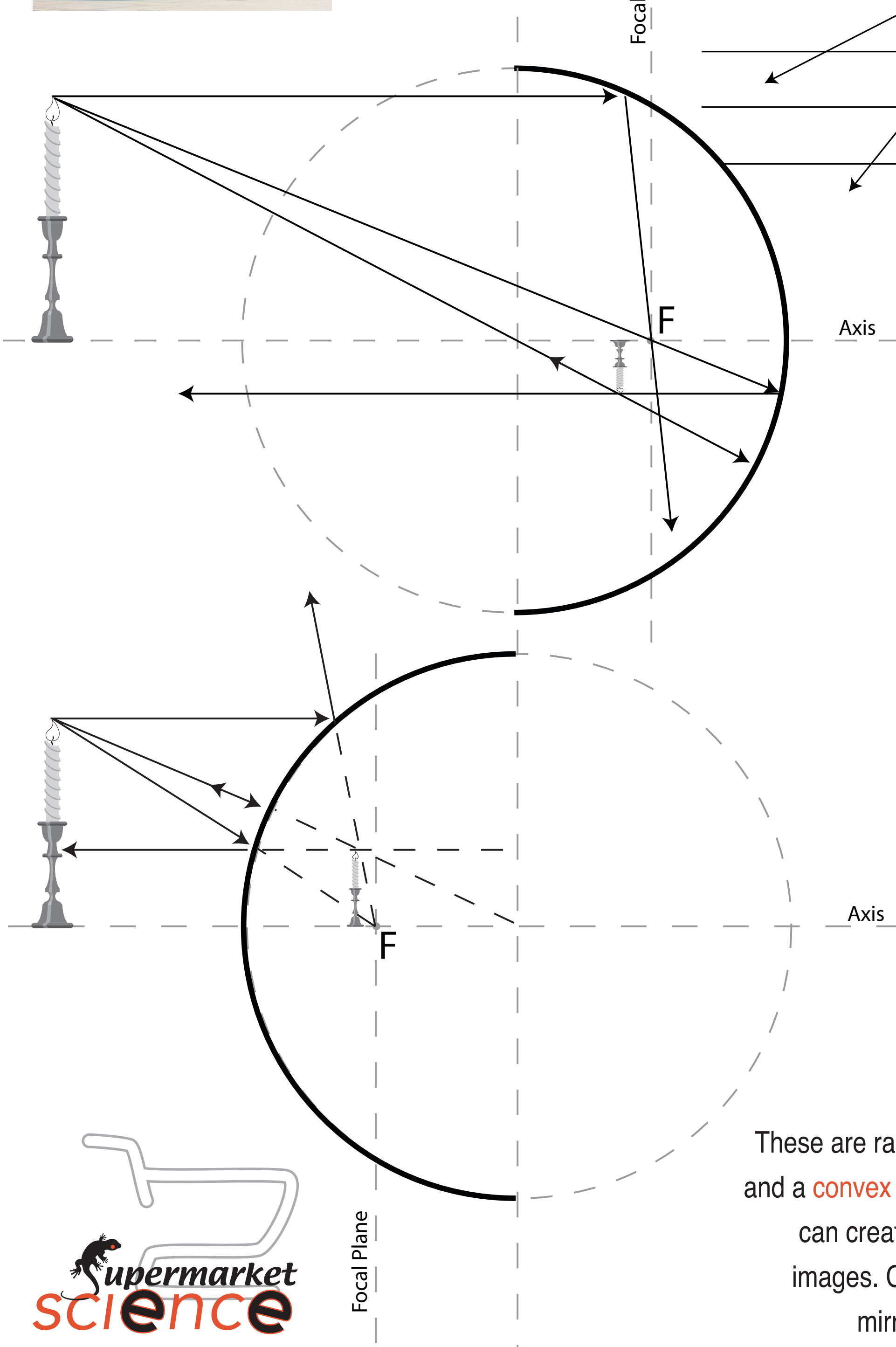
Doubly Curvaceous!

Even though the rays bounce off the surface of this convex mirror, the reflected rays can be extended into the mirror to find the focal point and plane of the mirror.





We can do the same construction for a convex mirror—a mirror that's shaped like the outside surface of a ball. Notice that the focal point is now on the inside of the mirror—the reflection rays diverge (separate from one another) as they hit the convex mirror. But by extending them backwards into the mirror, we can still construct the focal point and focal plane.

Follow the ray tracing diagram, left, to see how a complicated image is reflected in the concave and convex mirrors. Looking at the convex mirror diagram on the left, note that there are three interesting rules:

1. Rays that go through the center of curvature reflect directly back to the source of the ray.
2. Rays that go through the focal point exit parallel to the axis.
3. Rays that enter parallel to the axis go through the focal point.

These are ray tracing diagrams of a concave mirror (top) and a convex mirror (bottom). Spherical mirrors like these can create highly realistic three-dimensional focused images. Chicago's Cloud Gate sculpture uses curved mirror surface to reflect its visitors and the city..

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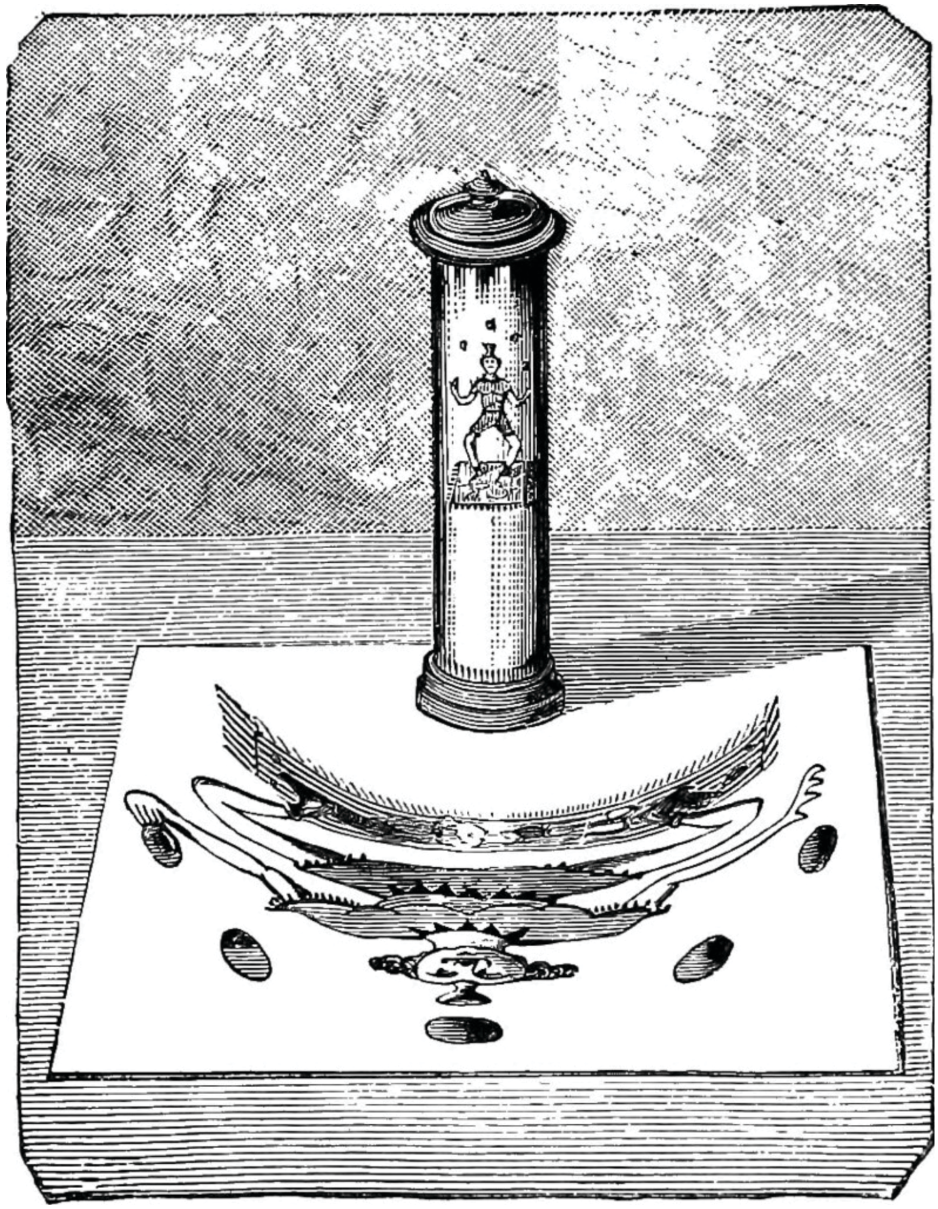
Fun House Portrait



Before the movies, before the Internet, and way before video games and television, people still managed to entertain themselves with optics. On the right is an example of a common toy: a cylindrical mirror placed on top of a grotesquely distorted illustration, reflects back a perfectly fine drawing. It was like a Fun House mirror in reverse.

What You Need:

Take a piece of cardboard and roll into a drum shape. You can use packing rolls or even toilet paper or paper towels hearts. Now cover your cardboard roll with aluminum foil and tape the foil in the back so it wouldn't slip.

Congratulations, you've just made a cylindrical mirror!

To explore how shapes change the way they look in the reflection, draw a triangle, a circle, and a square on a piece of paper and reflect it. Do you notice a pattern of distortion?

Now take a sheet of paper and draw your own portrait in such a way that it looks okay in your cylindrical mirror reflection. It might take a few tries, but don't give up!

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