# Waves & Optics

Phy 211 Course Text, Exercises, and Laboratories

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# Part I

# Geometric Optics

# Chapter 1

# The Rectilinear Propagation of Light

## 1.1 A Demonstration of Shadows

We have a bright lamp, with an object that casts a shadow on the screen. A representation of the setup from class is drawn in Figure 1.1.

The lamp and the object can both be moved. How can they be moved in order to make the shadow grow larger? How can they be moved in order to make the shadow grow smaller? Why is the edge of the shadow indistinct, and not sharp?

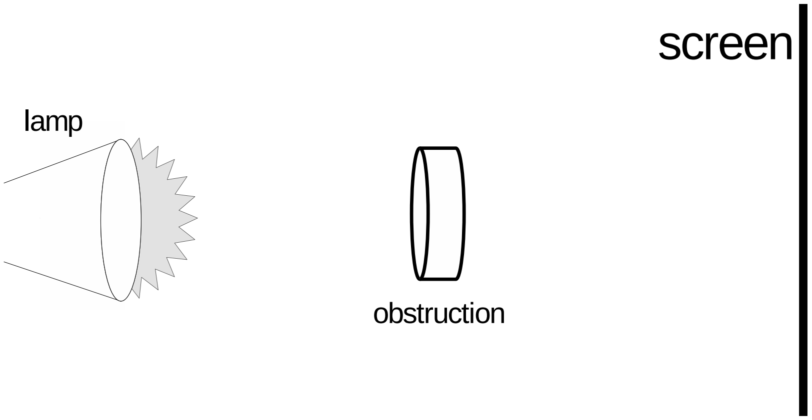

Figure 1.1: Demonstration of a shadow being cast by an object in front of a lamp.

## 1.2 Huygens' Principle

To understand how shadows are made, we must first understand how light propagates, *i.e.*, moves through empty space when there are no objects to obstruct it. We begin by discussing wave fronts.

### 1.2.1 Wave fronts

Let us draw a wave front propagating from a light bulb in Figure 1.2. Every point on this wave front is the source of an infinitesimal wavelet, which propagates outwards from its source on the wave front. When all of these little wavelets are added together, they form a new wave front. This continues so that all of the wave fronts form a series of embedded arcs around the light bulb.

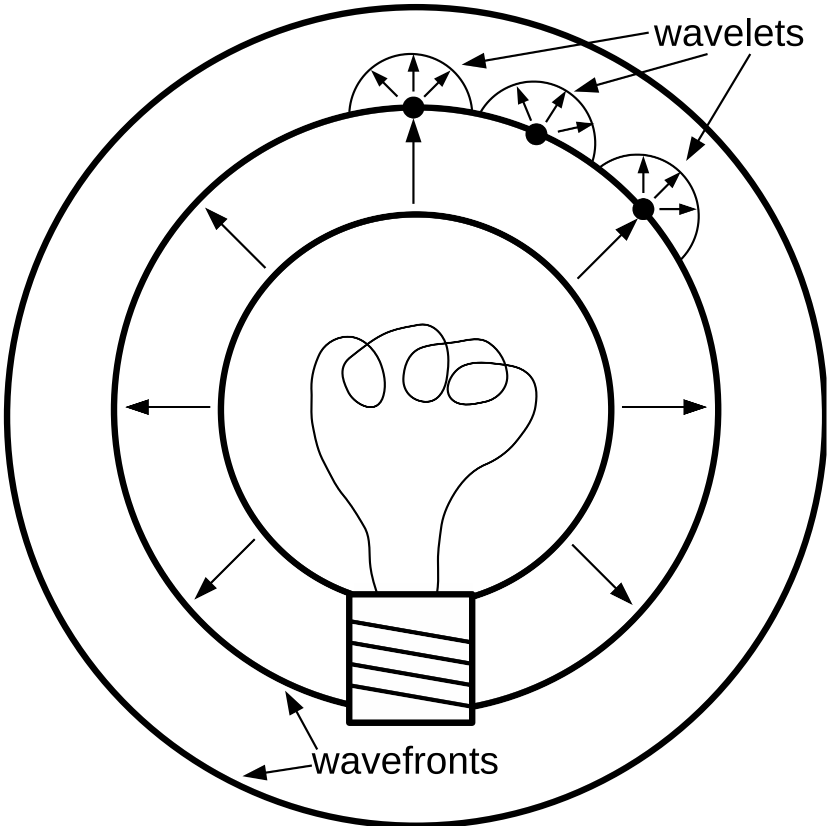

Figure 1.2: Wave fronts propagating from a light bulb.

### 1.2.2 The Law of Rectilinear Propagation

Follow a path from the light bulb through each wave front, connecting similar wavelets in each wave front, and we produce straight lines, which we can illustrate in Figure 1.3. These straight lines are called **light rays**. The fact that light will follow a straight path, in the absence of anything getting in the way, is called the law of rectilinear propagation (meaning that light moves in straight paths).

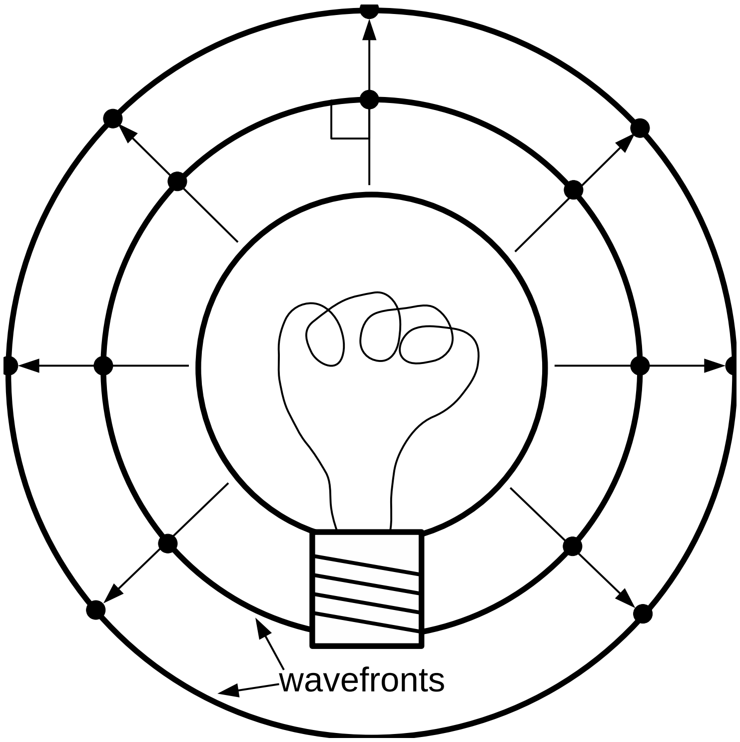

Figure 1.3: The formation of light rays.

Light rays have a couple of geometric properties. The first and most obvious is that they are orthogonal to the wave fronts and therefore indicate the directions in which the wave front is propagating. In the case of the light bulb, the light rays appear radial and point away from the light bulb in all directions.

The second and more subtle property is that, being straight, then in the Cartesian coordinate system in which the light bulb exists the light rays follow the path of shortest time between two points. We'll get back to this property in Chapter 2.

### 1.2.3 Physical Evidence

How do we know that light rays offer a true description of how light actually moves? We can observe the rectilinear propagation of light in nature, as illustrated in Figure 1.4. Light from the Sun propagates through a forest, blocked by branches and trunks, forming narrow bands that always follow straight paths. This image illustrates that the law of rectilinear propagation is an apt description of how light moves.

Figure 1.4: Sunlight shining through a forest. Image credit: Niki Pike, https://nikipike.com/wp-content/uploads/2016/02/IMG_7708.jpg

### 1.2.4 Light Rays and the Anatomy of a Shadow

Now that we have an idea for how light propagates, we can use light rays to draw shadows cast by an object and then use those light rays to relate the object and light source distances to the size of the shadow. Figure 1.5 on the next page sketches the shadow cast in our demonstration (Fig. 1.1) in detail. The variables we will use are:

- $S$: The height of the light source
- $O$: The height of the object
- $U$: The height of the umbra
- $P$: The height of the penumbra (partial shadow)

- $x$: The distance from light source to object
- $L$: The distance from light source to screen

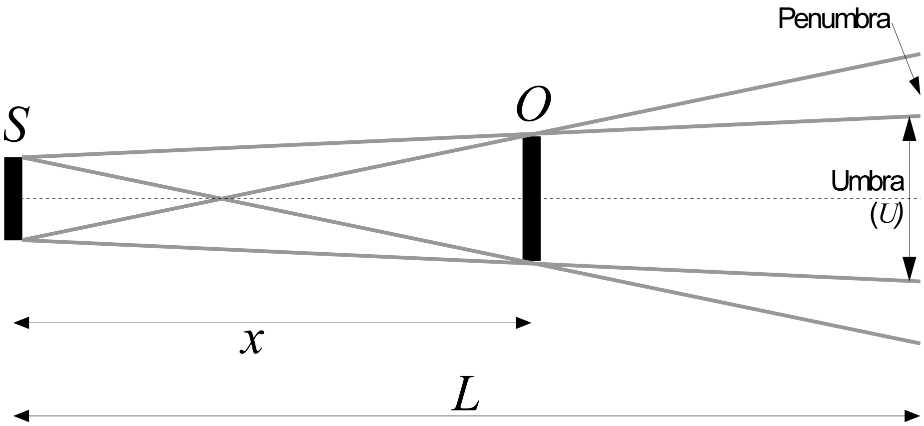

Figure 1.5: Relating source and object distances to the size and appearance of the shadow cast.

We will make measurements from the center line, so that $S/2$ represents the height of the light source above the center line, and so forth.

The technique we are going to employ relies on finding similar triangles, *i.e.* those triangles that share the same angles, even if their sides are different lengths. For example, the height of the object *above* the light source appears to be proportional to the height of the umbra above the light source. We can therefore equate the ratio of the vertical height and horizontal length for each of those triangles, since that ratio equals the tangent of the apex angle of the two similar triangles:

$$\frac{O/2 - S/2}{x} = \frac{U/2 - S/2}{L} \tag{1.1}$$

Carrying down the 2, this becomes

$$\frac{O - S}{2x} = \frac{U - S}{2L} \tag{1.2}$$

This equation can be simplified using cross multiplication and removing a common factor from both sides:

$$(O - S)L = (U - S)x \tag{1.3}$$

Since we wish to discover a relationship between shadow size and object/light source distances, we should now solve for $U$ in the above equation.

$$U = \frac{OL - SL + Sx}{x} \tag{1.4}$$

We will rearrange this slightly so that $L$, $x$, and $L - x$ all appear separately:

$$U = \frac{OL - S(L - x)}{x} \tag{1.5}$$

so that now we can use this equation to show how each of the distances are responsible for the size of the umbra. More than any other single variable, $x$ decides the size of the umbra. $U$ and $x$ are inversely proportional, so that if the object is very close to the light source, then the umbra is very large. There is a second important relationship that is easy to observe: as $x$ approaches $L$, then $U$ approaches $O$.

Now let us take a look at the size of the penumbra, which is oftentimes harder to measure than the umbra because it is not as dark. We will use the light ray starting from the bottom of the source and leading all the way to the top of the penumbra. This can be difficult to see, so take time discerning the following similar triangles equation:

$$\frac{O - (O - S)/2}{x} = \frac{P/2 + S/2}{L} \tag{1.6}$$

We will carry down the two as before, plus check our algebra to ensure that

$$\frac{O + S}{2x} = \frac{P + S}{2L} \tag{1.7}$$

Then we cross-multiply and remove the common factor from both sides to get

$$(O + S)L = (P + S)x \tag{1.8}$$

Solving for P, the size of the penumbra, we find

$$P = \frac{OL + SL - Sx}{x} \tag{1.9}$$

which can be re-written as

$$P = \frac{OL + S(L - x)}{x} \tag{1.10}$$

That looks pretty similar to our equation for the umbra, except that the two terms in the numerator are added instead of subtracted. In essence, however, what this shows is that the size of the penumbra has the same basic dependencies as does the size of the umbra: It becomes larger when $x$ is smaller, and in the limiting case of $L$ and $x$ being similar then $P$ becomes the size of the object itself.

Of course, what we actually see of the penumbra is an annulus around the umbra. How thick that annulus appears can be shown by subtracting our equation for the umbra from our equation for the penumbra.

$$P - U = \frac{OL + S(L-x)}{x} - \frac{OL - S(L-x)}{x} = 2S\frac{L-x}{x} \tag{1.11}$$

Then, the thickness of the penumbral annulus can be written by dividing both sides of the above equation by 2:

$$\frac{P-U}{2} = S\frac{L-x}{x} \tag{1.12}$$

The penumbra will appear large when the source is physically large. The size of the penumbra can be further enhanced if the distance from object to screen is large compared to the distance between the object and light source.

We will explore these relationships more in this chapter's laboratory: *Using Shadows to Measure the Sizes of the Earth, Sun, and Moon.*