Part B: Movement of Sound

Chapter 5. Speed

One of the easiest facts to observe about sound is that it moves. Sounds clearly have sources, from which the sound emanates. And one doesn't have to look too far to find situations where it is clear that this movement doesn't happen instantaneously; sound takes some time to travel from one place to another. Watch from a significant distance while some event makes a sound, and it is immediately apparent that you can see events before you hear them.

Distance

Of all the types of quantities in physics, distance is the one that is represented by the widest variety of letters, each with some connotations. You might often see *d* for distance, or *l* or *L* or ℓ for length, or *h* for height. An *x* often implies a horizontal distance, while *y* and *z* often imply vertical distances. The letters *a*, *b*, and *r* are often used to represent dimensions of objects, with *r* a very common choice for the radius of circular or spherical shapes. You might even see *s* used for distance traveled along a curving path, although in this book *s* will be reserved for speed.

The SI root unit for distance is meter, which is also a base unit for SI. Millimeter and centimeters are also very commonly used for small distances, while a kilometer is about $5/8$ of a mile.

Notice that in order to measure the distance something travels, you need to know the entire path that it took. Often, sound travels in a straight line, so that this isn't a difficulty. But any time that the travel involves a change in direction, the distance along the path will be different from the distance between start and finish points.

Time

Time, on the other hand, is rarely represented by any letter other than lower case *t*. Even when capital *T* and τ (the Greek letter tau) are used for time, they are usually reserved for very specific types of time. The SI root unit for time is the second, which is another SI base unit. For the study of sound, milliseconds and microseconds are particularly important.

English uses the word "time" for two slightly different concepts: clock time, meaning the time at which an event occurs, and elapsed time, meaning the duration of some process or event. Fundamental physical equations rarely deal with clock time, especially in hours, minutes, and AM/PM. But whenever time is measured from an origin, such as on a time axis in a graph, that is effectively clock time.

Elapsed time can be thought of as the difference, or subtraction, of two clock times. If I start my commute at $t_1 = 8{:}15$ AM and end it at $t_2 = 8{:}23$ AM, then the elapsed time for my commute is

$$t_2 - t_1 = 8 \text{ min} \quad . \tag{5.1}$$

Since physical equations nearly always involve elapsed time, if you are working a question where you have clock time information, don't forget this subtraction!

When physicists want to emphasize that a variable is the difference between two other quantities, it is common to prefix the variable letter with a Δ (capital Greek delta). There is a pattern to the subtraction which is very general in physics: "value of interest, minus a reference value." Such a difference may, or may not, refer to a change in the quantity (that is, a variation over time). But if it is a change, then this pattern is equivalent to "later value minus earlier value," or "final minus initial," or "ending minus beginning." When you know the values numerically, as with Eq. 5.1 , this may be second nature. But when you are working algebraically with unknown variables, this pattern usually requires a little attention because the parts are in reverse chronological order.

Because an elapsed time is always a difference between two clock times, Δt would be a sensible symbol for elapsed time. On the other hand, since physical equations hardly ever contain clock time, it's overkill to use a Δ every time. In the end there is no hard-and-fast rule. In each equation you read, you must be aware of what the symbols represent.

Speed

As discussed in Section 4d, if something is moving so that distance traveled is proportional to the corresponding time of travel, then we define its speed as the ratio

$$s = \frac{d}{t} \quad , \tag{5.2}$$

where t is specifically the *elapsed* time required to travel the distance d. In this book, speed is represented with the algebraic symbol s. Elsewhere, you may often see speed represented by v, which comes from the word velocity. Another choice is c, primarily used for the speed of waves. The derived unit (in terms of root units) is m/s.

This type of motion, with distance and time proportional, is said to have **constant speed** or **uniform speed,** and it means that the speed can be calculated by using *any* two positions along the path of motion. It is not necessary to use the distance (and time) from the beginning to the end of the motion. All that is required is that the elapsed time and the distance used in the equation correspond to each other.

How do you know if a motion has constant speed? Calculate the speed using a variety of time intervals; if you keep getting the same result, then the speed is constant. This may sound like a circular definition, but actually it's not because it makes reference to the objective reality. More precisely, if we obtain the same speed from several of different calculations, then we introduce a physical model that the motion has constant speed. The more often that model works, the greater our confidence in it becomes. (This is not the only way to increase our confidence in a model. Another would be to connect it to other successful models through a derivation.)

Chapter 6. Average Speed

What if you are dealing with a motion that does not have a constant speed? For any particular choice of two positions along the motion, you can still apply Eq. 5.2. The result would be called an **average speed.** However, notice that the average speed will change depending on your choice for the beginning and end of your calculation.

Warning

> The most familiar type of average, appropriate to a list of several values, is calculated by adding the values together and then dividing by the number of values in the list. The technical name for that is the **arithmetic mean**. But average speed is a more advanced type of average, and usually cannot be calculated in that way.

For instance, suppose that an object moves at a constant speed over a distance of 1 m during 1 s, and then suddenly speeds up to a new constant speed, covering a distance of 4 m during 2 s. Those two constant speeds are 1 m/s and 2 m/s, but the average speed for the entire motion is

$$s = \frac{(1\ \mathrm{m} + 4\ \mathrm{m})}{(1\ \mathrm{s} + 2\ \mathrm{s})} = 1.667\,\frac{\mathrm{m}}{\mathrm{s}} \quad , \tag{6.1}$$

not 1.5 m/s.

Both average speed and the arithmetic mean result in numbers that are qualitatively in the middle. And there is a special case in which the average speed is equal to the arithmetic mean of a list of speeds.

However, that special case has no particular significance. So, it's best to consider average speed to be an entirely new idea, and to calculate it by first finding the total distance traveled and the total time elapsed.

Chapter 7. Speed of Sound

7a. Speed of Sound

For sound, the constant speed model works very well, as long as the sound medium is the same everywhere. This means not only the material itself is the same (air, water, wood, etc.), but also that its properties are the same (temperature, saltiness, direction of wood grain, etc.). Not only is sound speed then constant, but it is also normally the same for all different kinds of sounds (high or low pitch, loud or soft, harsh or pleasant).

> The speed at which sound travels depends only on the medium through which it travels.

But the sound speed can be very different in different media. The most striking distinctions depend on the phase of matter. Generally speaking, sound speeds through other gasses are similar to the speed in air. Sound speeds in liquids are several times higher, and sound speeds in solids are several times higher still. An Internet search will easily return numerous web sites with measured speeds of sound in various materials. One good example can be found in *HyperPhysics*.[3]

Sometimes it is sufficient to simply know the medium. But for some substances, it is also necessary to specify certain conditions, such as the temperature, before one can predict the speed of sound through them. Other considerations can arise as well. In wood, for instance, the direction of sound travel relative to the direction of the wood grain can alter the sounds speed significantly.

Of greatest interest to humans is the speed of sound in air, which is approximately $s_{\text{sound}} = 340\,\text{m/s}$. But this is one of the situations where temperature makes a difference. This book chooses to use $14.5℃ = 58.1°\text{F}$, which gives the speed of sound the nice round number above and which is quite close to the global average temperature for the Earth. But if you look in other references, you may see other values used. For example, scientists like to use $20.0°\text{C} = 68.0°\text{F}$ as a standard "room temperature," which results in a sound speed of $343.3\,\text{m/s}$, which in turn is often rounded to $343\,\text{m/s}$.

To get an intuitive feeling for that speed, notice that it moves a bit further than one foot during each millisecond. Under optimal conditions, with two sharp clicks sounded close together, the smallest time difference that can be perceived is a few milliseconds. But when something is seen and then heard, the smallest delay that can be reliably identified is closer to 100 ms.[4] So when observing a distant sound source, it needs to be roughly 100 feet away in order to notice that the sound that you hear is out of sync with what you see.

7b. Extra: Speed of Sound in Air

If a more exact value for the speed of sound in air is needed, a more accurate model taking air temperature into account is

$$\begin{aligned} s_{\text{sound}} &= 331.3\,\frac{\text{m}}{\text{s}} + \left(0.6\,\frac{\text{m}}{\text{s}}\right) T[℃] \\ s_{\text{sound}} &= 331.3\,\frac{\text{m}}{\text{s}} + \left(0.6\,\frac{\text{m}}{\text{s}\cdot℃}\right) T \quad . \end{aligned} \tag{7.1}$$

[3] C.R. Nave, "Speed of Sound in Various Bulk Media," *HyperPhysics*, n.d., http://hyperphysics.phy-astr.gsu.edu/hbase/tables/soundv.html (June 2013).
[4] W. James, *The Principles of Psychology* (New York: Henry Holt & Co, 1923), 1:615.

This model has an error of less than 1% for temperatures from $-63°C$ to $97°C$. A model with even wider applicability is presented in Chapter 120. The speed of sound in air is also slightly affected by other factors, such as the humidity.

The two lines of Eq. 7.1 are actually exactly the same, except for the way that they tell you what units to use. The first line uses "$T[°C]$" to indicate that the air temperature must be measured in degrees Celsius in order for the equation to work. This method, having equations that require specific units, is centuries old, and still favored by some engineering disciplines. However, there is no standard notational convention. The square brackets to specify units is specific to this book.

The second line is a more elegant notation, and it is therefore preferred in physics. Because units combine algebraically, the °C in the denominator of the coefficient indicates that it would be very convenient to express the variable T with the unit °C, because the units would cancel. Expressing the temperature with a different unit would not exactly be wrong. It would just result in an unmanageable tangle of units.

7c. Extra: Speed of Sound Not in Air

Sounds in gasses besides air also depend on temperature, and for the same reason from the perspective of physics. Compared at the same temperature, gasses made of smaller molecules have significantly higher sound speeds than gasses of larger molecules. Many people are familiar with the odd effect that helium has on speaking, and these effects trace back to this higher speed of sound. The details are described in Chapter 120.

Liquid sound speeds generally depend on temperature to about the same degree as sound speeds in gasses. They also depend on the pressure in the liquid. Pressure is explained in Chapter 125.

Sound speeds in solids have a much smaller dependence on temperature, so that a single-speed model works well if conditions are not extreme. However, other complications can arise in solids. The most notable is that a second, fundamentally different kind of traveling disturbance is possible. Some people consider this disturbance to be a kind of sound, while others consider it only to be something very similar to sound. This type of disturbance travels significantly slower through solids than ordinary sound, although still usually faster than liquid sound speeds.

Chapter 8. Traveling Sound

When working with questions involving the motion of sound, one needs a general idea of the directions in which it moves. More details will be covered in later chapters; here just the basics are introduced. None of these should be surprising, but they are worth reflecting on for a moment.

Sound emanates from sources, often spreading out as it leaves. You might say that a single clap of hands creates a single sound, in the sense of a single event. But you might equally well say that the single clap produces multiple sounds (in the sense of disturbances traveling through the air) that travel away in many different directions. Figure 8.1 shows those many sounds as the various arrows pointing away from the hands. The path traveled by one sound, in this sense, is called a **ray.**

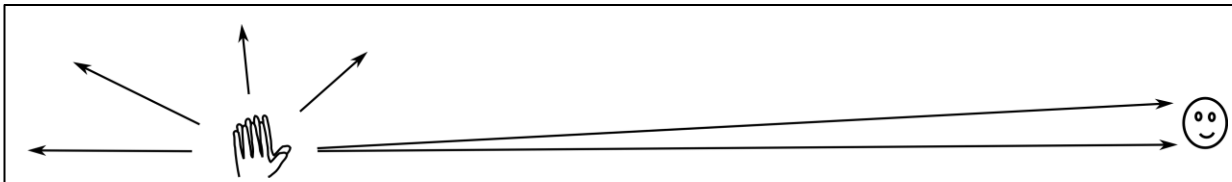


Figure 8.1

Sound diverges as it radiates from a source, but far away sounds are moving almost parallel.

Usually, sounds will move in straight lines through a medium, making straight rays. This is true as long as the sound medium**,** and in particular the sound speed in the medium, is the same everywhere. This model might cease to work, though, if the medium is not uniform, such as air that is hotter in some places than in others. Curving rays are described in Chapter 163.

Once the sounds have traveled very far from the source, the divergence of the sounds may be so small that it is a good model to say that they are moving parallel to each other, such as near the observer in Figure 8.1. Very near a large sound source, especially a flat source like the giant speaker in Figure 8.2, it can also be a good model to say that the sound rays are nearly parallel.

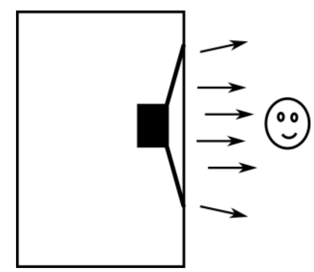


Figure 8.2
Very close to a large flat source of sound, sounds move nearly in parallel.

Closer to the source, it may be important to recognize that the different sound paths are diverging. But if we are not *too* close to the source, such as halfway across Figure 8.1, it may be a good approximation to say that the sounds are all coming from a single point in space. This is the **point source** model. This model best applies when the distance from the source to the observer is greater than the longest dimension of the source.

(When deciding whether a model applies to a given situation, physicists often check whether something is "much greater" than something else. Exactly what this means is not actually well defined, and it may depend on the situation. As a rule of thumb, though, "much greater" typically means "at least 10 times larger.")

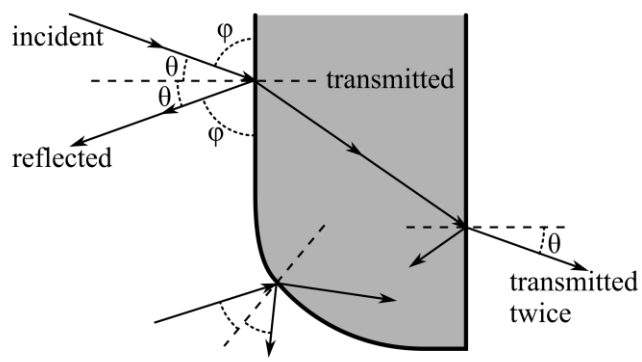


Figure 8.3
Sound reflecting off and transmitting through boundaries between media.

When a sound arrives at an abrupt boundary in the medium (either a change in the medium properties, or a change from one medium to another), it will likely split into a part that is reflected and a part that is transmitted. The original sound, before it reaches the boundary, is called the **incident** sound. The **reflected** sound travels back into the original medium, and thus travels at the same speed as the incident sound. The reflected sound ray makes the same angle with the boundary as the incident sound did, as shown in Figure 8.3. This is true of the angle between the sound ray and the medium boundary (labeled φ in the figure), and also of the angle between the sound path and the line perpendicular to the boundary (dashed line in the figure, angle labeled θ). That line is called the **normal to the surface,** and although it is more abstract, it may be easier to work with when the boundary is curved, as seen in the lower part of Figure 8.3.

The part of the sound that is **transmitted** across the boundary into the new medium will *not* continue to travel in the same direction—more about that in Chapter 161. However, if the sound passes through a new medium and back into the old (as on the right of Figure 8.3), through two parallel boundaries, then the final direction of travel will match the original. So, if sound passes through a thin plate, such as a windowpane, the transmitted part travels nearly along the same path that it would have without the plate.

Finally, sound can travel around corners. The details of this are quite complicated; see Chapter 164. But on a large scale, where sounds are traveling over meters of distance or more, a reasonably good model is that in the shadow region, where there is no line-of-site to the sound source, the sound appears to be traveling away from the corner itself.

Chapter 9. Working Physics Questions

Putting together several sounds traveling at different speeds or for different times allows for the creation of the first physics questions in this book. For the most part, this book will not present physics questions to be worked. But one example will be shown here, as a way to review steps and tips, to show a good way to approach such questions, and to show a way of keeping the work organized.

Many readers may be able to solve this question with much less organization, possibly even taking a few shortcuts. But, even if you can solve the question without explicitly doing all the steps shown here, you are almost certainly going through the same steps in the back of your mind. It is helpful to be aware of the steps, so that they can be done on paper when you find a question that cannot be done in your head.

The following are generic steps in solving a physics question. Compare them with Figure 9.1 to see how they are implemented.

1. For any question that involves a spatial component, draw a picture. This often helps you to see relationships that were not apparent in a word description of a question. The picture should include not only solid objects, but also things like paths traveled by things over the course of the question. For instance, the picture might show a path traveled by a sound.

   The picture should not be a work of art. It is a schematic, a sketch which clearly represents the situation, but might not even be true to life in some ways. Some parts of the picture may be drawn to a different scale than other parts. In the question some things might retrace their path, which is awkward. When drawing their paths, you should offset those paths a bit. In Figure 9.1 the arrows represent sound traveling perfectly vertically, so the rules from Chapter 8 about equal angles of reflection are not important.

2. Divide your workspace on the paper into three areas: Variables (near the picture), Physical Relationships, and Algebraic Work.

3. Under Variables, start a question by defining some variables that seem likely to be helpful in conceptualizing the situation. It does no harm to define a variable that never gets used. Each variable should refer to a very specific quantity and should be clearly defined. Often, the meaning of a variable can be made clear by labeling something in the picture. Quantities that are known at the outset can be indicated.

4. Under Physical Relationships, record relationships between the variables. The simpler the equations, the better, as you are less likely to make errors. It is *not* necessary to find equations that will instantly solve the question. The equations must involve only variables that are listed in the first area; often, finding equations will help you to think of additional variables that should be added there.

   Notice that these are *not* just the generic equations that are presented in this book. When applying the generic equations to a specific question, it is important to clearly connect all the variables in the equation to the question at hand.

   If you keep a running total of the number of unknown variables in the equations, then when the number of equations gets to be the same as the number of unknown variables, you will know that you are done with the first two areas. At that point, only algebra is required to find an answer. However, in some cases it is possible to arrive at an answer with fewer equations than there are variables. Figure 9.1 shows an example of this happening. If you work the question algebraically, the extra variable cancels out.

   Another possible approach is to supply your own values where they seem to be missing. For example, in the Figure 9.1 question, you might feel like you need the speed of sound through the earth. You could simply guess that it might be $3000\,\mathrm{m/s}$. This approach can simplify the algebra, although it also makes it more difficult to catch math errors. However, be warned: you must be very sure that the variable to which you are giving a value is one that truly does not influence the answer. Otherwise, you will be inserting a value that is incompatible with the given information. Also, if you do this, you are strongly advised to choose values that are physically reasonable.

5. Under Algebraic Work, you combine the equations from Physical Relationships. Of the unknown variables, there is one that you want (the answer to the question), and others that you don't want. The goal in this area is to get rid of the undesired unknowns. The most systematic way to do this is by substitution for the undesired unknowns.

6. Once all the undesired unknowns have been eliminated, you may still need to solve an equation for the desired unknown. Then values for the known variables can be substituted into the equation, and an answer obtained.

My recommendation is to keep all equations in terms of variables until the very end. It can be difficult to get used to working with variables instead of numbers. And there may be times when doing so makes the algebraic manipulation more cumbersome. The payoff is that the equations can still be conceptualized in terms of the quantities that the variables represent. Without this, it is easy for the work to become the processing of numbers with no meaning to you, and you are less likely to notice if errors are made.

At each step along the way, you can check your work by testing whether the units make sense. In the final step, the units of the substituted values should combine to give a reasonable unit for the result. Even for intermediate equations, you can imagine how the units would combine if quantities were substituted for variables. For instance, if you see a distance being added to a time, then you will know that an error has been made in the algebraic manipulation.

In practice, the working of a physics question is rarely so neat and tidy, and often some of the details are left off the written page. But it is helpful to be aware of the structure of solving a question, even if you don't follow it precisely. Certainly, if you want others to be able to understand what you are doing, these are the pieces that you need to show—most especially, the variable definitions.

This is an extremely simplified example of a method that is actually used to look for underground reservoirs of oil. Assume that the oil reservoir is a big underground cavity full of oil. An explosion is set off at the surface. Sound from the explosion travels down through the ground. When it reaches the top surface of the cavity, part of the sound reflects back up. The rest of the sound continues through the oil, but at the bottom of the cavity some of the sound is again reflected upwards. A microphone at the surface detects the echoes.

If after setting off the explosion, the microphone detects 2 echoes separated by 40 ms, then what is the height of the cavity? The speed of sound in oil is known to be 1450 m/s.

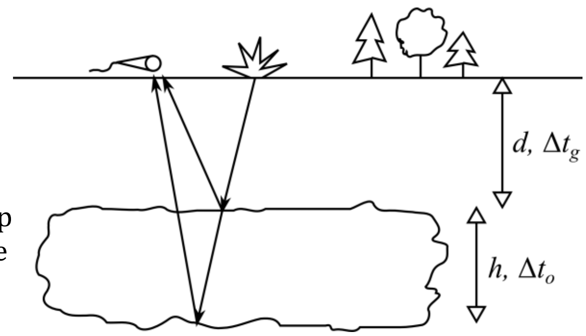
Variables

Given or requested

- s = speed of sound in oil = 1450 m/s
- Δt_e = time interval between echos = 40 ms
- h = reservoir height

Others that look useful

- d = distance from surface to reservoir top
- t_g = time for sound to travel from surface to reservoir top (g for ground)
- t_o = time for sound to travel reservoir height (o for oil)
- t_S = time for short round trip
- t_L = time for long round trip



Physical Relationships

(1) $s = \dfrac{h}{t_o}$ $\left(\text{a specific case of } s = \dfrac{d}{t}\right)$

(2) $t_S = 2t_g$

(3) $t_L = t_g + 2t_o + t_g$

(4) $\Delta t_e = t_L - t_S$

So far, there are 5 unknown variables and 4 equations.

<u>**Algebraic Work**</u>	<u>(comments clarifying the algebra used)</u>
(5) $\Delta t_e = 2t_g + 2t_o - t_S$	substitute (3) into (4), eliminating t_L
(6) $\Delta t_e = 2t_g + 2t_o - 2t_g$	substitute (2) into (5) to eliminate t_S
(7) $\Delta t_e = 2t_o$	simplification! t_g disappears
(8) $\Delta t_e = 2\ h/s$	substitute (1) into (6) to eliminate t_o

Now we have an equation containing only the desired unknown and known quantities.

(9) $h = \frac{1}{2}\, s\, \Delta t_e = \frac{1}{2}\left(1450\,\frac{\text{m}}{\text{s}}\right)(40\text{ ms}) = 29000\text{ m}\,(10^{-3}) = 29.0\text{ m}$

solve (8) for variable h and substitute known values; milli- prefix is converted into a number

Figure 9.1

Detailed example of solving a physics question. Note that variable *d* is defined, but never used. Value of t_g cannot be determined from the given information, but the variable is still useful. Δ is only used in Δt_e because it's a difference in (4). Other approaches are possible.