# Doppler Effect and Sonic Booms*

OpenStax HS Physics



## 1

: By the end of this section, you will be able to:

- Describe the Doppler effect of sound waves
- Explain a sonic boom
- Calculate the frequency shift of sound from a moving object by the Doppler shift formula, and calculate the speed of an object by the Doppler shift formula

Teacher Support: The Learning Objectives in this section will help your students master the following TEKS:

- (7) Science concepts. The student knows the characteristics and behavior of waves. The student is expected to:
  - (7D):investigate behaviors of waves, including reflection, refraction, diffraction, interference, resonance, and the Doppler effect

**Section Key Terms**

| | |
|---|---|
| Doppler effect | sonic boom |

**Table 1**

Teacher Support: [BL]Before the start of this section, it would be useful to review the properties of sound waves and how they are related to each other.

## 2 The Doppler Effect of Sound Waves

The **Doppler effect** is a change in the observed pitch of a sound, due to relative motion between the source and the observer. An example of the Doppler effect due to the motion of a source occurs when you are standing still, and the sound of a siren coming from an ambulance shifts from high-pitch to low-pitch as it passes by. The closer the ambulance is to you, the more sudden the shift. The faster the ambulance moves, the greater the shift. We also hear this shift in frequency for passing race cars, airplanes, and trains. An example of the Doppler effect with a stationary source and moving observer is if you ride a train past a stationary warning bell, you will hear the bell's frequency shift from high to low as you pass by.

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TEACHER SUPPORT: [BL][OL][AL]Ask students if they have ever experienced the phenomenon where a car horn or siren appears to change its pitch as the vehicle passes them by. If so, when did it appear to be higher? And when was it lower? You can do a demonstration of the Doppler effect in class using a buzzer and a string. Tie the buzzer to one end of a string. A buzzer produces a monotonous sound. However, when you swing it around your head, its pitch appears to change. Ask students how they think this happens. What could be the reason for the changing pitch?

Safety warning: Make sure the buzzer is secured tightly to the string before swinging.

What causes the Doppler effect? Let's compare three different scenarios: Sound waves emitted by a stationary source (Figure 1), sound waves emitted by a moving source (Figure 2), and sound waves emitted by a stationary source but heard by moving observers (Figure 3). In each case, the sound spreads out from the point where it was emitted.

If the source and observers are stationary, then observers on either side see the same wavelength and frequency as emitted by the source. But if the source is moving and continues to emit sound as it travels, then the air compressions (crests) become closer together in the direction in which it's traveling and farther apart in the direction it's traveling away from. Therefore, the wavelength is shorter in the direction the source is moving (on the right in Figure 2), and longer in the opposite direction (on the left in Figure 2).

Finally, if the observers move, as in Figure 3, the frequency at which they receive the compressions changes. The observer moving toward the source receives them at a higher frequency (and therefore shorter wavelength), and the person moving away from the source receives them at a lower frequency (and therefore longer wavelength).

MISCONCEPTION ALERT: Be sure to point out that the Doppler effect is only experienced due to the *relative* motion between the source and the observer and does not depend on the actual speed of either.

Students might think that the Doppler effect occurs only with sound waves. This is not the case. It can occur with any kind of waves. In fact, we see it in the light waves that reach us from distant stars. Here, the effect is observed in the form of color change.


**Figure 1:** Sounds emitted by a source spread out in spherical waves. Because the source, observers, and air are stationary, the wavelength and frequency are the same in all directions and to all observers.

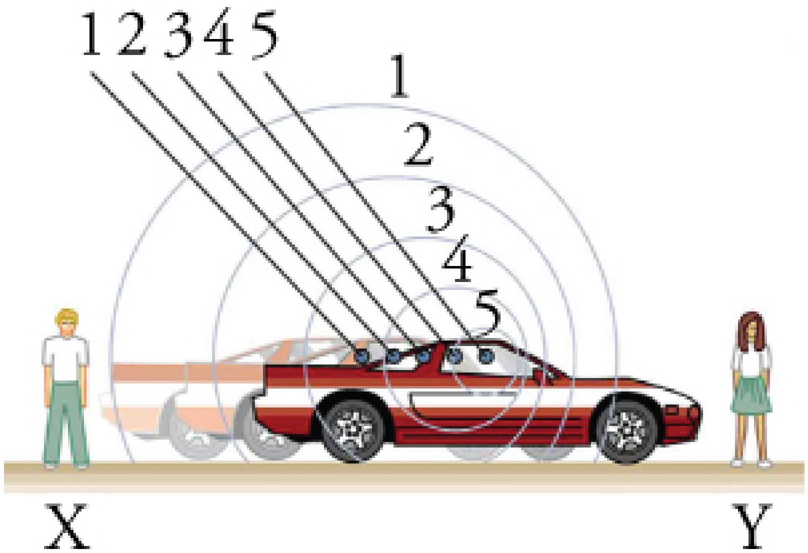


**Figure 2:** Sounds emitted by a source moving to the right spread out from the points at which they were emitted. The wavelength is reduced and, consequently, the frequency is increased in the direction of motion, so that the observer on the right hears a higher-pitch sound. The opposite is true for the observer on the left, where the wavelength is increased and the frequency is reduced.

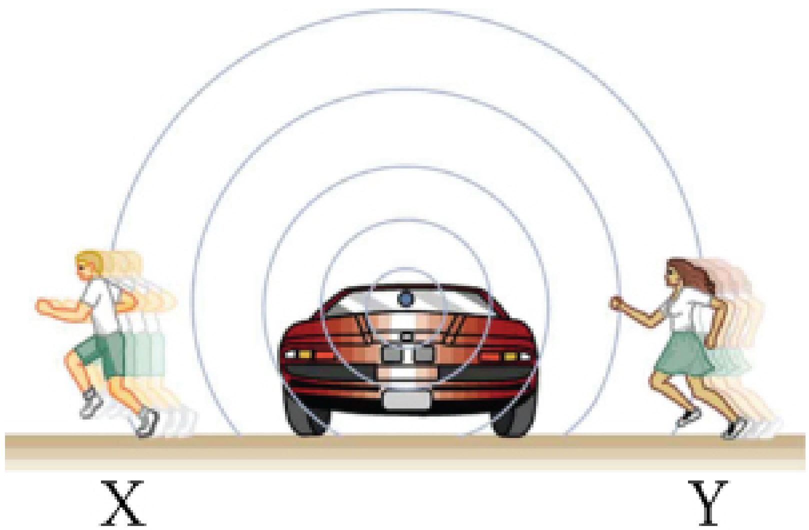


**Figure 3:** The same effect is produced when the observers move relative to the source. Motion toward the source increases frequency as the observer on the right passes through more wave crests than she would if stationary. Motion away from the source decreases frequency as the observer on the left passes through fewer wave crests than he would if stationary.

We know that wavelength and frequency are related by $v = f\lambda$ , where $v$ is the fixed speed of sound. The sound moves in a medium and has the same speed $v$ in that medium whether the source is moving or not. Therefore, $f$ multiplied by $\lambda$ is a constant. Because the observer on the right in Figure 2 receives a shorter wavelength, the frequency she perceives must be higher. Similarly, the observer on the left receives a longer wavelength and therefore perceives a lower frequency.

The same thing happens in Figure 3. A higher frequency is perceived by the observer moving toward the source, and a lower frequency is perceived by an observer moving away from the source. In general, then, relative motion of source and observer toward one another increases the perceived frequency. Relative motion apart decreases the perceived frequency. The greater the relative speed is, the greater the effect.

WATCH PHYSICS: This video explains the Doppler effect visually.

**Grasp Check 1**

[1]

For a stationary observer and a moving source of sound, the frequency ($f_{\text{obs}}$) of sound perceived by the observer is

$$f_{obs} = f_s \left( \frac{v_w}{v_w \pm v_s} \right),$$

where $f_{\text{s}}$ is the frequency of sound from a source, $v_{\text{s}}$ is the speed of the source along a line joining the source and observer, and $v_{\text{w}}$ is the speed of sound. The minus sign is used for motion toward the observer and the plus sign for motion away from the observer.

[1] http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex066

Tips for Success: Rather than just memorizing rules, which are easy to forget, it is better to think about the rules of an equation intuitively. Using a minus sign in $f_{obs} = f_s \left( \frac{v_w}{v_w \pm v_s} \right)$ will decrease the denominator and increase the observed frequency, which is consistent with the expected outcome of the Doppler effect when the source is moving toward the observer. Using a plus sign will increase the denominator and decrease the observed frequency, consistent with what you would expect for the source moving away from the observer. This may be more helpful to keep in mind rather than memorizing the fact that "the minus sign is used for motion toward the observer and the plus sign for motion away from the observer."

Note that the greater the speed of the source, the greater the Doppler effect. Similarly, for a stationary source and moving observer, the frequency perceived by the observer $f_{\text{obs}}$ is given by

$$f_{obs} = f_s \left( \frac{v_w \pm v_{obs}}{v_w} \right),$$

where $v_{\text{obs}}$ is the speed of the observer along a line joining the source and observer. Here the plus sign is for motion toward the source, and the minus sign is for motion away from the source.

## 3 Sonic Booms

What happens to the sound produced by a moving source, such as a jet airplane, that approaches or even exceeds the speed of sound? Suppose a jet airplane is coming nearly straight at you, emitting a sound of frequency $f_{\text{s}}$. The greater the plane's speed, $v_{\text{s}}$, the greater the Doppler shift and the greater the value of $f_{\text{obs}}$. Now, as $v_{\text{s}}$ approaches the speed of sound, $v_{\text{w}}$, $f_{\text{obs}}$ approaches infinity, because the denominator in $f_{obs} = f_s \left( \frac{v_w}{v_w - v_s} \right)$ approaches zero.

Teacher Support: [BL][OL][AL]The equation shows that a sonic boom is created as the observed frequency approaches infinity. Ask students what happens to the amplitude of the sound wave at this time. The Doppler effect only changes the frequency of the sound. However, when all the waves are superimposed on one another, and their crests match, the amplitude will also tend to infinity. This is what increases the intensity of the wave, creating the "boom".

This result means that at the speed of sound, in front of the source, each wave is superimposed on the previous one because the source moves forward at the speed of sound. The observer gets them all at the same instant, and so the frequency is theoretically infinite. If the source exceeds the speed of sound, no sound is received by the observer until the source has passed, so that the sounds from the source when it was approaching are stacked up with those from it when receding, creating a **sonic boom**. A sonic boom is a constructive interference of sound created by an object moving faster than sound.

An aircraft creates two sonic booms, one from its nose and one from its tail (see Figure 4). During television coverage of space shuttle landings, two distinct booms could often be heard. These were separated by exactly the time it would take the shuttle to pass by a point. Observers on the ground often do not observe the aircraft creating the sonic boom, because it has passed by before the **shock wave** reaches them. If the aircraft flies close by at low altitude, pressures in the sonic boom can be destructive enough to break windows. Because of this, **supersonic** flights are banned over populated areas of the United States.

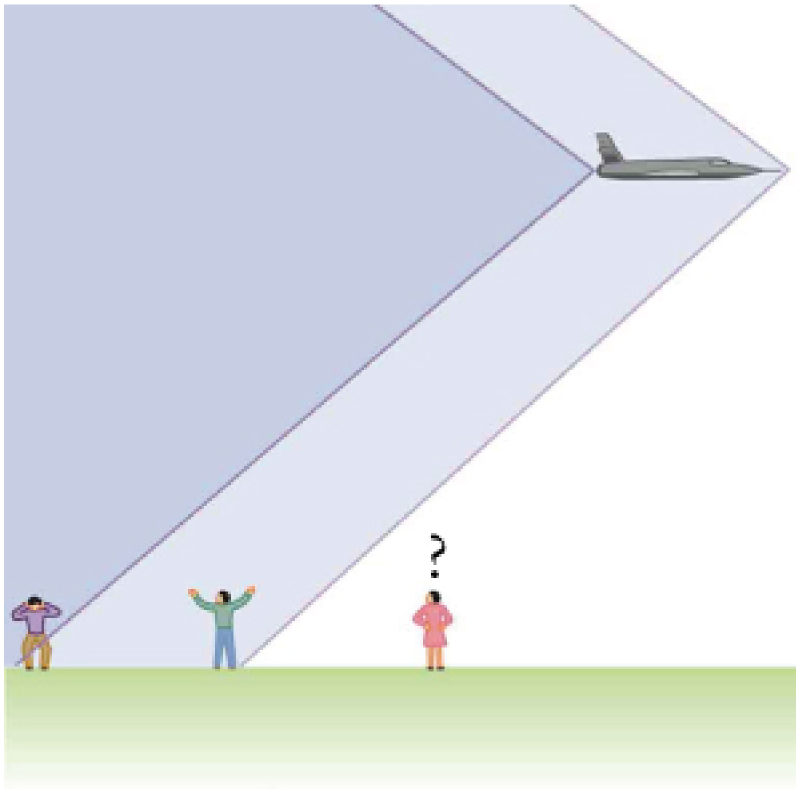


**Figure 4:** Two sonic booms, created by the nose and tail of an aircraft, are observed on the ground after the plane has passed by.

## 4 Solving Problems Using the Doppler Shift Formula

WATCH PHYSICS: This video explains the Doppler effect formula for cases when the source is moving toward the observer.

**Grasp Check 2**

[2]

WATCH PHYSICS: This video explains the Doppler effect formula for cases when the source is moving away from the observer.

**Grasp Check 3**

[3]

[2]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex067
[3]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex068

Worked Example:

**4** ***(Solution on p. 11.)***

Suppose a train that has a 150 Hz horn is moving at 35 m/s in still air on a day when the speed of sound is 340 m/s. What frequencies are observed by a stationary person at the side of the tracks as the train approaches and after it passes?

: To find the observed frequency, $f_{obs} = f_s \left( \frac{v_w}{v_w \pm v_s} \right)$ must be used because the source is moving. The minus sign is used for the approaching train, and the plus sign for the receding train.

**Discussion**

The numbers calculated are valid when the train is far enough away that the motion is nearly along the line joining the train and the observer. In both cases, the shift is significant and easily noticed. Note that the shift is approximately 20 Hz for motion toward and approximately 10 Hz for motion away. The shifts are not symmetric.

## 5 Practice Problems

**Exercise 5**
[4]

**Exercise 6**
[5]

## 6 Check Your Understanding

Teacher Support: Use these questions to assess student achievement of the section's Learning Objectives. If students are struggling with a specific objective, these questions will help identify which and direct students to the relevant content.

**Exercise 7**
[6]

**Exercise 8**
[7]

**Exercise 9**
[8]

**Exercise 10**
[9]

[4]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex070
[5]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex071
[6]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex072
[7]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex073
[8]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex074
[9]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex075

## 7 Section Summary

- The Doppler effect is a shift in the observed frequency of a sound due to motion of either the source or the observer.
- The observed frequency is greater than the actual source's frequency when the source and the observer are moving closer together, either by the source moving toward the observer or the observer moving toward the source.
- A sonic boom is constructive interference of sound created by an object moving faster than sound.

## 8 Key Equations

| | |
|---|---|
| **Doppler effect observed frequency (moving source)** | $f_{obs} = f_s \left( \frac{v_w}{v_w \pm v_s} \right)$ |
| **Doppler effect observed frequency (moving observer)** | $\mathrm{f}_{obs} = f_s \left( \frac{v_w \pm v_{obs}}{v_w} \right)$ |

**Table 2**

## 9 Concept Items

**Exercise 11**
[10]

**Exercise 12**
[11]

## 10 Critical Thinking

**Exercise 13**
[12]

**Exercise 14**
[13]

## 11 Problems

**Exercise 15**
[14]

**Exercise 16**
[15]

[10]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex076
[11]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex077
[12]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex078
[13]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex079
[14]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex080
[15]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex081

# 12 Test Prep Multiple Choice

### Exercise 17
[16]

### Exercise 18
[17]

### Exercise 19
[18]

# 13 Test Prep Short Answer

### Exercise 20
[19]

### Exercise 21
[20]

### Exercise 22
[21]

### Exercise 23
[22]

### Exercise 24
[23]

### Exercise 25
[24]

# 14 Test Prep Extended Response

### Exercise 26
[25]

### Exercise 27
[26]

### Exercise 28
[27]

[16]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex082
[17]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex083
[18]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex084
[19]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex085
[20]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex086
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[23]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex089
[24]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex090
[25]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex091
[26]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex092
[27]http://cnx.org/content/m54334/latest/#ost/api/ex/k12phys-ch14-ex093

# Solutions to Exercises in this Module

**to Exercise (p. 8): Solution**

(1) Enter known values into $f_{obs} = f_s \left( \frac{v_w}{v_w - v_s} \right)$ to calculate the frequency observed by a stationary person as the train approaches:

$$f_{obs} = f_s \left( \frac{v_w}{v_w - v_s} \right) = (150 \text{ Hz}) \left( \frac{340 \text{ m/s}}{340 \text{ m/s} - 35 \text{ m/s}} \right)$$

$$= 167 \text{ Hz} \approx 170 \text{ Hz (2 sig. figs.)}$$

(2) Use the same equation but with the plus sign to find the frequency heard by a stationary person as the train recedes.

$$f_{obs} = f_s \left( \frac{v_w}{v_w + v_s} \right) = (150 \text{ Hz}) \left( \frac{340 \text{ m/s}}{340 \text{ m/s} + 35 \text{ m/s}} \right)$$

$$= 136 \text{ Hz} \approx 140 \text{ Hz (2 sig. figs.)}$$

# Glossary

**Definition 4: Doppler effect**
an alteration in the observed frequency of a sound due to relative motion between the source and the observer

**Definition 4: sonic boom**
a constructive interference of sound created by an object moving faster than sound