CNS Institute for Physics Teachers

Title:	**The Doppler Effect**
Original: **Revision:**	27 October 2007 15 February 2009
Authors:	Martin Alderman
Appropriate Level:	Regents, Honors, or AP Level Physics
Abstract:	The Doppler Effect is easily demonstrated qualitatively by spinning a constant frequency oscillator or buzzer on a string, but there are few quantitative labs on the subject. Dr. Kris H. Green of St. John Fisher College suggested a mechanical analog for the Doppler Effect in The Science Teachers Bulletin, Volume 70, Number 2, Spring 2007, STANYS. This activity develops Dr. Green's mechanical analog concept into a student-ready lab with a stable 'wave' velocity. This is a very student centered lab that provides the opportunity for students to independently design and test their experimental methodologies. It also has the potential to include the 'moving source' case of the Doppler Effect.
Time Required:	One double-period for data collection and most analysis
NY Standards Met:	
Special Notes:	**Doppler Effect** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

Center for Nanoscale Systems Institute for Physics Teachers (CIPT)
632 Clark Hall, Cornell University, Ithaca, NY 14853
www.cns.cornell.edu/cipt/
cns_contact@cornell.edu

Behavioral Objectives:
Upon completion of this lab activity, students should be able to:

- Define the Doppler Effect
- List at least 5 examples of the Doppler Effect
- Describe what one observes with sound waves when a source of sound and an observer are stationary, when a source and an observer are getting closer together, and when a source and an observer are getting further apart.
- Use the mechanical analog provided **and his/her own procedure** to obtain quantitative data and use it to demonstrate the Doppler Effect.
- Compare and contrast the optical spectrum of the light from a distant star with that from the sun.
- Solve basic numerical problems involving the Doppler Effect.

Class Time Required:
One double-period for data collection and most of the analysis

Teacher Preparation Time:
Install fresh batteries in each unit

Materials:

- Doppler Effect demonstration oscillator/buzzer
- One motor driven Doppler Effect analog (ideally three student lab team/set-up)
- Stopwatches (at least two per lab team)
- Meter sticks (one per lab team)
- Masking tape (one roll/lab team for temporarily marking positions on the floor)

Optional: One metric measuring tape and/or one metric trundle wheel per lab team
(A trundle wheel is a measuring wheel on a handle. Each rotation is one meter.)
(Plastic trundle wheels are commercially available for ~$18/each or can be made from plans found on the WWW.)

Tips for the Teacher:
This is a very student-centered laboratory. Students are provided with a mechanical system that is an analog to a traveling wave and are asked to devise their own approach to determining the observed frequency of the wave analog. There are several ways to correctly accomplish this task. Some are better than others for a variety of definable reasons, but generally, they are valid. The intention of this activity is to allow the students to explore the possibilities and do real scientific problem solving with minimal teacher interference.

Doing this lab requires a long hall or room space where all the students can work simultaneously. The actual space needed is roughly 1.5 m wide x ~7 m long per lab group.

Instructions to make a Doppler Effect buzzer:

- Purchase a single tone piezoelectric buzzer (Radio Shack Catalog #: 273-060 85dB or the like), one battery clip for a 9 volt battery, one 9 V battery, and a 1.5 m length of <u>sturdy</u>, thin (1-2 mm diameter) string.
- Connect the buzzer wires to the battery clip wires; solder, and insulate the wires with tape or heat shrink tube.
- <u>Securely</u> tie the cord onto the screw hole on one side of the buzzer.
- <u>Securely</u> tape the battery onto the back of the buzzer. It might be necessary to tape over the hole in the buzzer and then cut the hole open again in order to tape the battery securely.
- Test the unit by plugging the battery clip onto the battery. It should produce a very loud, shrill, and steady note.

Other Doppler Effect Demonstrations:

- Doppler Effect Frisbee – This is a common Frisbee with a piezoelectric buzzer and battery securely mounted at the center. The Frisbee can be tossed from student to student (outside!) so they can hear the effect of relative motion.

- Doppler Effect Pennywhistle – This is a pennywhistle mounted into a piece of surgical tubing such that it can be blown while it is spun in a circle overhead.

- Doppler Effect Nerfball – This is a Nerf basketball with a piezoelectric buzzer and battery mounted inside. Students can toss the ball back and forth to get the same Doppler Effect as the Frisbee demo.

- YouTube and TeachTube have numerous videos about the qualitative aspects of the Doppler Effect.

<u>The piezoelectric buzzer</u>:

- The first part of this lab is set up as a demonstration, in part for safety reasons.
- The battery must be very securely attached to the buzzer. Check it before each use.
- Be sure there is plenty of clear space around you and that you have a firm grip on the cord when spinning the buzzer.
- This demonstration works best when you are fairly far in front of the whole class, and you spin the buzzer in an elliptical orbit emphasizing the motion towards and away from the class.

<u>Procedure Check</u>: Teachers are advised not to check the procedures their students are proposing to use. A large part of the value of this activity is for the students to learn by doing. This may cost time, but the point is for the students to design, test, redesign and retest until they find a valid procedure. When students do need help, please try to limit assistance to the bare minimum.

<u>The 'Moving Wave Source' Case</u>: The Mechanical Analog unit could also be placed on a small motorized low constant velocity cart to allow for the study of the 'moving wave source' case of Doppler Effect.

Relative Motion Lab: This lab could be very effectively used in teaching about relative motion with only minor modifications.

Doppler Equation Derivation: As this lab is written, the students do not derive the Doppler Effect equation. It should be possible to have AP students do exactly that, but it is beyond the scope of this lab.

The Dr. Philip Krasicky Doppler Analog -

One way to begin to give students a sense of Doppler Effect came to me by way of Dr. Philip Krasicky at Cornell University.

- Line a group of students up in the hallway, equally spaced, with one hand extended as seen in the photograph.
- Have one student walk slowly down the line at a constant speed clapping her hand against each student's hand as she walks past. (Teacher counting1,2,1,2,… at a steady rate sets the pace for the student's walking.)
- Next have the whole equally spaced line of students march down the hall to the same slow, steady cadence the teacher counts out and have the student from the previous step repeat her hand clapping role as she walks to the same count opposite the motion of the line. Have the class note that the sound of the hand-claps occurs at a higher frequency.
- Finally, repeat the previous step with the student doing the hand clapping while walking backwards at a rate slightly faster than the rate at which the line is marching. Have the class note that the sound of the hand-claps is at a very low frequency.

References:

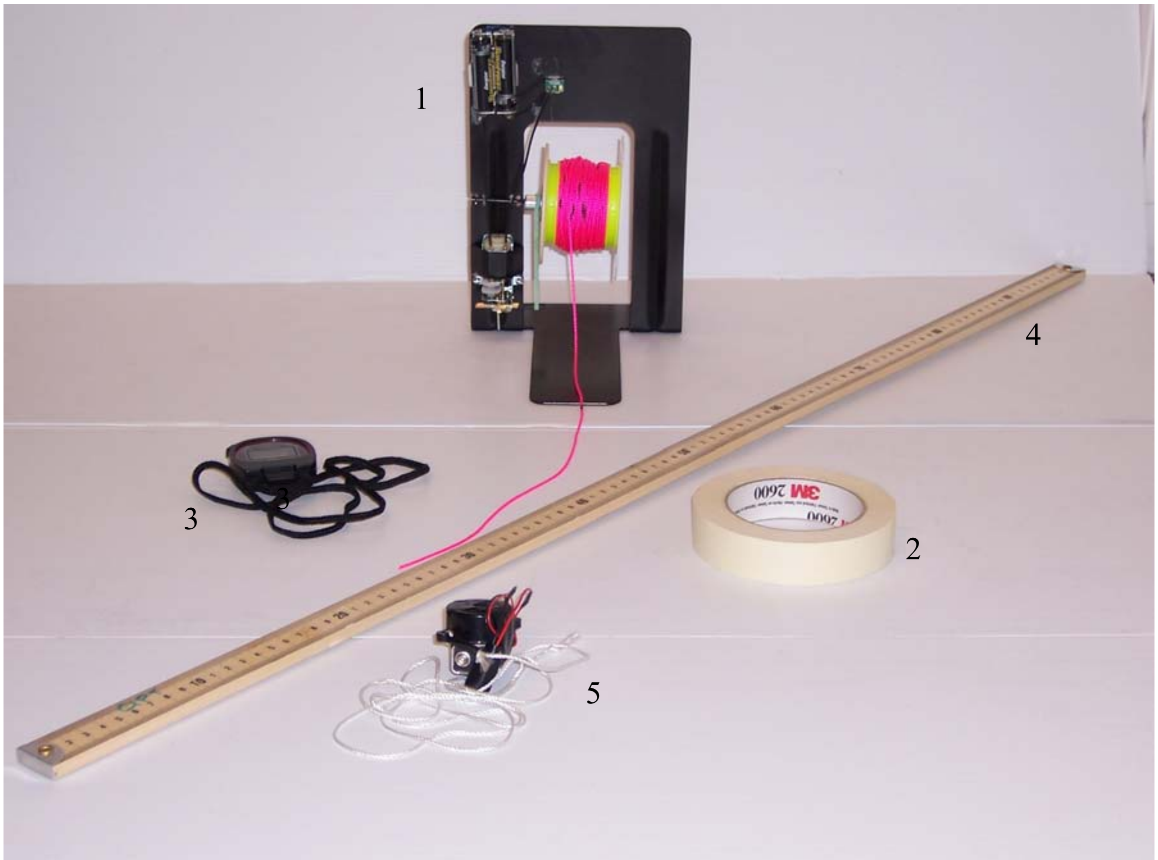
Dr. Kris H. Green of St. John Fisher College suggested a mechanical analog for Doppler Effect in The Science Teachers Bulletin, Volume 70, Number 2, Spring 2007, STANYS.

Wikipedia has a **very** thorough university level examination of Doppler Effect.

Assumed Prior Knowledge of Students:

The students have a basic understanding of waves. They should also be comfortable working with the wave formula ($v = f\lambda$) and with simple motion concepts and equations, particularly ($d = vt$).

The Doppler Effect



Item Number	Quantity	Item
1	1	Motorized wave analog
2	1	Masking tape
3	2	Stop watches
4	1	Meter stick supplied by teacher (or trundle wheel or metric tape measure)
5	1	Piezo buzzer Doppler Effect demonstration setup

The Doppler Effect (or Doppler Shift)

<u>Introduction</u>:

Your favorite TV show is interrupted … News Flash! Announcer voice comes on: "Our Triple Doppler Radar is showing a band of unusually heavy lake effect snow. All area schools are closed!"

What is this Doppler thing?

You might have heard the word Doppler mentioned in relation to a Doppler ultrasound exam for a heart problem or an image of a developing baby in-utero (also called a sonogram). You might know someone who got a speeding ticket after being 'clocked' with a Doppler radar gun. The speed of pitched baseballs is routinely clocked with a similar device for broadcasts of baseball games and to help pitchers develop better technique. You might have even heard of the light spectrum from a distant star being 'Red Shifted' by the Doppler Effect.

Let's start with sound waves …

<u>Part One</u>: What is 'Doppler Effect'?

1. The teacher will turn on a rather loud buzzer. Describe the pitch (frequency) of the buzzer.

2. The teacher will now spin the buzzer in a circle with a string. Describe the frequency you hear coming from the buzzer now. How is it different from before?

3. Pay careful attention as the teacher repeats the spinning of the buzzer. What do you notice when the buzzer is in the part of the circle where it is moving <u>towards</u> you?

4. What do you notice when the buzzer is in the part of the circle where it is moving <u>away</u> from you?

5. (If possible, your teacher will play a short video clip) When you watch a NASCAR race on TV … what do you notice about the sound of the engines when the cars are heading basically towards the camera, pass the camera, and then are heading basically away?

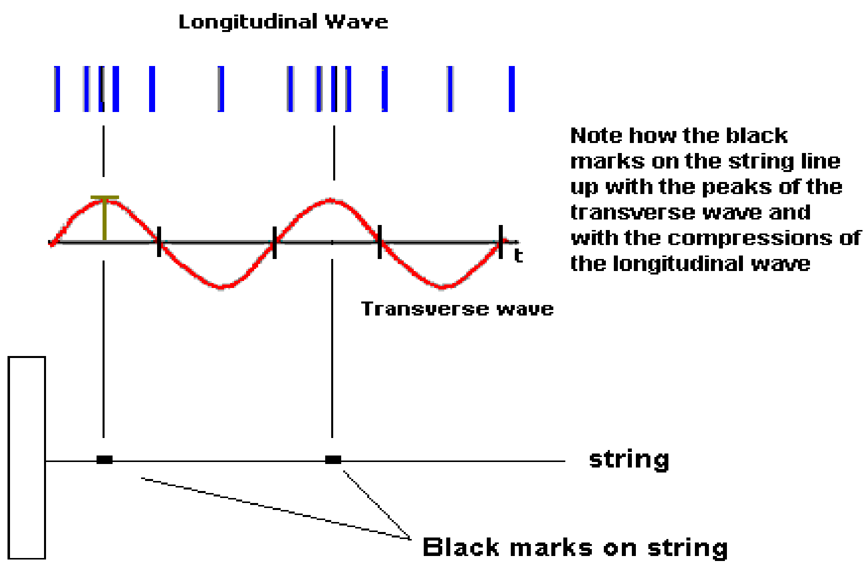
Summarize your observations in the following table:

Source of Wave	No relative motion between source of sound and observer	Source of sound and observer getting closer together	Source of sound and observer getting further apart
Piezoelectric buzzer			
NASCAR race			

6. Doppler Effect is the name used to describe what you have been observing. Based on what you have heard so far, write a first draft definition of Doppler Effect.

Part Two: What is the wave in this model like, and how much Doppler Effect is there?

The demonstrations so far deal with sound waves, but this effect is not limited to sound. In this part of the experiment, you will use a model, also called a mechanical analog, to analyze the way a wave system behaves. In this model, a colored string represents the wave, and the black marks on it represent the peaks of the wave. The figure shows how the mechanical model relates to a transverse or longitudinal wave.



7. Each black mark represents a peak. Carefully examine the string. Measure and record your best judgment of the wavelength of the wave represented by the string.

   Wavelength = λ = ______________ cm

8. Why was it inappropriate to measure just *one* wavelength on the string?

9. Compare a real wave (for example: sound, light, or water) with this wave analog?
   (How are their characteristics and their measured properties the same and how are they different?)

In fact, the measurement of wavelength on the string is quite a good analog to the wavelength of a real wave, even though the string is not a very good model of a wave in other respects. As you should already know, a wave involves the transfer of energy without any associated transfer of material.

Your teacher will demonstrate how to use the motorized wave analog. It is quite simple:

- to reel out the cord, slip the rubber band off the drive shaft of the motor.
- to run a trial
  - replace the rubber band
  - flip the switch to turn the motor on.
- The student who runs the motor drive must gently keep the string centered on the spool.

Keep in mind that the source of the wave is located at the far end of the hall, and the wave is emanating (being emitted) from that source, NOT from the motorized unit. (In so far as the wave is concerned, pretend the motor unit isn't there!)

Experiment 1: Determine the wave speed and frequency

Now the fun begins! You get to 'do it your way'!

- Design and perform an experiment to determine
  - the speed of the wave
  - the frequency of the wave.
- Do enough measurements and/or trials to have good confidence in your outcomes
- Clearly present your procedure, data and calculations below. Pictures or diagrams will help explain the procedure your team devised.

Summary:

Wavelength = λ = _________ cm

Wave Speed = V = _________ cm/s

Frequency of Wave Source = f_s = _________ Hz

Experiment 2: Determine the wave speed and frequency when moving *away from* the source

During the piezo buzzer demonstration you observed that the pitch (frequency) of the sound you heard earlier was (lower, higher, the same) when you and the sound source were getting closer together, and (lower, higher, the same) when you and the sound source were getting farther apart. How much higher or how much lower? It's time to find out!

Suppose the wave is moving down the hall from the source at whatever speed you just determined, and suppose you are walking down the hall in the same direction, but at roughly half that speed. Remember that the source of the wave is behind you, so you are moving away from the source (towards the hardware).

- Figure out a way to walk down the hall with a steady speed of roughly .50 $V_{wave.}$ You do not need exactly .50 V_{wave}, but you do need to know what your speed ($v_{observer}$) is with reasonable confidence, and repeatability.
- Describe your procedure below:

Now you need a way to determine the observed frequency of the wave from your moving frame of reference walking down the hall. Remember, you are getting farther from the source of the wave (walking towards the hardware), so the frequency you observe should be (more than, less than, the same as) the frequency you observe when you are standing still.

- Figure out a method to determine the observed frequency while you are walking at $v_o \approx .50 V_{wave}$, and record your procedure below. **This part is tricky, so be sure everyone in your lab team agrees your procedure is logical.**
- Collect your data
- Determine the 'observed frequency' of the wave while you are walking. Present your data and calculations clearly here and on the next page:

Summary:

Wavelength = λ = _________ cm

Wave Speed = V = _________ cm/s

Velocity of Wave Source = v_s = 0.0 cm/s
(The source of the waves is standing still at the end of the hall.)

Frequency of Wave Source = f_s = _________ Hz

Velocity of Observer = v_o = ______________ cm/s

Frequency Observed = f_o = ______________ Hz

10. Is the observed frequency lower than the source frequency, as your observations of the buzzer early in this lab predict it should be?

11. If it isn't, don't throw out your work! Scientists don't often get an experiment right the first time. Do you feel the issue is with the equipment, the procedure your group developed, the concept of how Doppler Effect works, or some other identifiable cause?

12. If something did go wrong, please write a short explanation, but be as specific as possible. If you feel it is something about the equipment, identify which part has the problem and whether that problem should cause the data to be too high or too low.

If you need to:

- Propose a new or modified procedure that might resolve the discrepancy.
- Run another trial and/or do what must be done to fix your procedure, data, and calculations here. This is how science really works! Record you new procedure and results below.

Experiment 3: Determine the wave speed and frequency when moving *towards* the source

13. Do you predict the observed frequency, f_o, will be greater than, less than, or equal to f_s this time?

14. Why might it be more difficult to get reproducible results from this experiment than from experiment 2?

Now, design and run an experiment where you are moving towards the source (away from the hardware) at $v_o \approx .50V_{wave}$, and measure the observed frequency.

- Write out your procedure, and then clearly present your data and calculations

Summary:

Wavelength = λ = _________ cm

Wave Speed = V = _________ cm/s

Velocity of Wave Source = v_s = 0.0 cm/s (The source of the waves is standing still at the end of the hall.)

Frequency of Wave Source = f_s = _________ Hz

Velocity of Observer = v_o = ______________ cm/s

Frequency Observed = f_o = ______________ Hz

15. Is the observed frequency higher than the source frequency, as your observations of the buzzer early in this lab predict it should be?

If it isn't, follow the same procedure detailed in experiment 2 for the case of unexplained outcomes. Describe your new procedure and report your new data below:

On the next page, you will find one form of the Doppler Effect equation. The symbols used are the same as those used in this lab. Pay particular attention to the way in which the plus and minus signs are determined and used.

Doppler Effect or Doppler Shift

The Doppler Effect is the change in the observed frequency of a wave caused by relative motion between the source of the wave and the observer.

$$\frac{f_o}{V - v_o} = \frac{f_s}{V - v_s}$$

f_o = frequency observed
v_o = speed of observer
f_s = frequency of the source of the wave
v_s = speed of the source of the wave
V = speed of the wave in the medium

Source   Observer
S ——————————→ O
Wave velocity = V
(The wave is moving to the right)

Clearly, the wave goes from the source to the observer in order to be observed! **This defines the 'standard' or 'reference' direction.**

- If the source or observer moves **in this 'standard' direction**, then its velocity is written as a **positive** value.
- If the source or observer moves **opposite to this 'standard' direction**, then its velocity is written as a **negative** value.

Sample Problem:

On a particular day, the air temperature is such that the speed of sound is 340 m/s. The source of a 100. Hz sound wave is moving east, towards an observer, at 40.0 m/s. The observer is moving west, towards the source, at 10.0 m/s. What is the frequency of the sound the observer hears?

v_s = + 40.0 m/s ——→   ←—— v_o = -10.0 m/s

S ——————————→ O
\+   -

Velocity of wave = V = 340. m/s East
This is the reference direction

The source arrow matches the reference arrow
Therefore v_s is positive (+40.0 m/s)

The observer arrow opposes the reference arrow
Therefore v_o is negative (-10.0 m/s)

$$\frac{f_o}{(340.\,m/s) - (-10.0\,m/s)} = \frac{100.\,Hz}{(340.\,m/s) - (+40.0\,m/s)}$$

$$\frac{f_o}{350.\,m/s} = \frac{100.\,Hz}{300\,m/s}$$

$$(300.\,m/s)\,f_o = 35000\,\tfrac{m \cdot Hz}{s}$$

f_o = 117 Hz.

Since the source of the wave and the observer are getting closer to each other, one expects a higher frequency to be observed. This is indeed the case in this sample problem, and demonstrates how one can use the increase or decrease in frequency predicted in the concept of Doppler Effect to quickly check that the signs used were probably correct and the numeric answer was probably set up correctly.

16. Use the Doppler Effect equation to calculate what the observed frequency "should" have been in experiments 2 and 3. Show your calculations.

<u>Experiment 2</u> <u>Experiment 3</u>

17. Calculate the percent difference between the measured f_o and the calculated f_o. Use the calculated f_o as the reference.

<u>Experiment 2</u> <u>Experiment 3</u>

Application:

Now that you have heard and seen the basics of how Doppler Effect works, try this:

If you look at an electrically excited glass tube full of hydrogen through a spectroscope, you will see its glowing light spread out into the hydrogen bright line spectrum, and you can read off the frequencies of the individual spectral lines.

If you look at a distant star through a high quality telescope equipped with a spectroscope, the hydrogen spectral lines appear a little lower in frequency than those seen coming from the glowing tube.

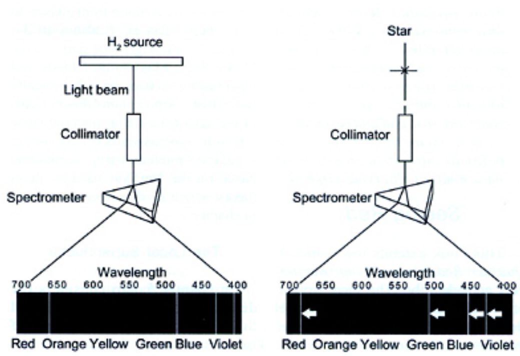


Fig. 1: Comparison of hydrogen and stellar hydrogen emission spectra

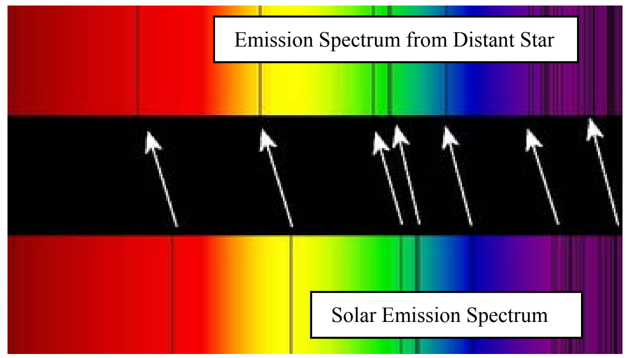


Fig 2: Comparison of solar and distant star emission spectra

18. What does this suggest about the motion of the distant star in Fig. 2?

19. This phenomenon is called "Red Shift"

Why RED shift?

Why red SHIFT?

Challenge: Try to explain the following using your knowledge of Doppler Effect and vectors:
During World Wars I & II, incoming artillery shells made a whistling sound. If the shell was traveling on a path directly towards someone in the field (whether the range was short, long, or right at the person), a steady Doppler shifted note was heard, and the person was justifiably scared. If the path of the shell was not directly in line with the person, a changing Doppler shifted note (pitch) was heard, and the person could feel a little more at ease for the moment. (Hint: the same phenomenon is observed at NASCAR races, when a car with a siren drives past you, and in many other cases.)