Voyager and Ozobot: A Quantitative Experiment on the Doppler Effect
By Richard Born
Associate Professor Emeritus
Northern Illinois University

Christian Doppler, during the first half of the 19th century, pointed out that just as the pitch of sound changes when there is relative motion between the sound source and an observer, there must also be a change in the color of a luminous object under similar conditions. This so-called *Doppler Effect* applies to all wave forms. Physics students observe this effect in sound waves emanating from a tuning fork when it swings around their instructor's head in a classroom demonstration. Students of astronomy discuss this as a Red-Shift when explaining the concept of an expanding universe. Police often use Doppler radar to determine the speed of a vehicle on the highway. Most everyone has noticed how the siren of an emergency vehicle has a high pitch when approaching and a lower pitch when receding.

What we are interested in accomplishing is the **development of a laboratory experiment** in which students **quantitatively** verify a major theoretical equation that is often derived in general physics textbooks. When the wave *source is at rest* with respect to the medium and the *observer is moving* through the medium with a velocity v_0, then:

$$f' = f\left(\frac{v \mp v_0}{v}\right), \qquad \text{(Equation 1)}$$

where v is the speed of the wave in the medium and f is the frequency of the wave when the observer is at rest. f' is the frequency perceived by the observer when moving through the medium perpendicular to the wave fronts. The plus sign holds when the observer is moving toward the wave source, and the minus sign holds when the observer is moving away from the wave source.

The Medium, Wave Source, and Observer

The medium for our waves can be an iPad, Chromebook™, or Android device with a flat screen that can access the Internet and rest on a horizontal surface. The author used an Asus Chromebook™, as shown in Figure 1. The wave source is a JavaScript program written by the author and can be loaded through this URL: rborn.org/doppler/WaveSimulation.html. The observer is the Voyager/Ozobot team coupled by a small piece of modeling clay. To keep this team on the "straight-and-narrow", a pair of balsa sticks has been taped to the surface of the device. The distance between the sticks is just a little larger than the width of Voyager. Ozobot pushes Voyager. In Figure 1 Voyager is, therefore, moving away from the wave source. Voyager's orange side is down so that the *waves can be sensed by Voyager's light intensity sensor*.

Figure 1

The OzoBlockly Program Running on Ozobot

Figure 2 shows the OzoBlockly program that has been loaded into Ozobot. The program begins by setting the color of Ozobot's top light to red. The program then pauses for 10 seconds, giving the user time to start data collection on Voyager. The top light then turns green and Ozobot moves a distance of 120 mm at a speed of 15 mm/s before stopping and turning off. Note that the speed of 15 mm/s applies when Ozobot does not have a load to push. The user will need to determine the actual speed of the Voyager/Ozobot team using a stopwatch to time the team as it moves between two marks of known distance. The timing should be done with the team resting on the surface of the device—not a piece of paper—as the traction of the wheels might be slightly different on the paper.
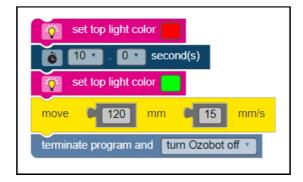

Figure 2

Data Collection

Figure 3 shows two snapshots. In both snapshots Voyager is initially at rest for several seconds. In the upper snapshot, Voyager then starts moving toward the wave source (to the left). In the lower snapshot, Voyager is then starts moving away from the wave source (to the right). It is clear that the frequency increases in the upper snapshot where Voyager is moving toward the source and decreases in the lower snapshot where Voyager is moving away from the source. Accompanying this lesson are links to two videos showing all of this action. The videos were taken with the PocketLab app.
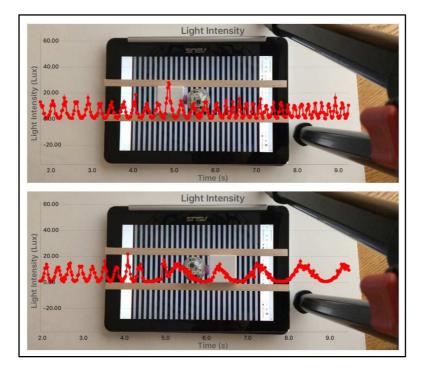

Figure 3

Data Analysis

Figure 4 shows graphs constructed in Excel from the csv data files obtained from the two PocketLab runs of this experiment. From these graphs, we are able to determine the wave frequency f (3.51 Hz) when the Voyager is standing still, the experimental frequency (5.986 Hz) when Voyager is moving toward the source, and the experimental frequency (0.971 Hz) when Voyager is moving away from the source.

The wavelength of the waves can be measured directly when the wave pattern stops moving after about a minute has elapsed. For the author's setup, the wavelength λ = 0.75 cm. The speed of the waves is then calculated with the equation $v = f\lambda$ = (3.51 Hz) x (0.75 cm) = 2.63 cm/s.

The speed v_0 of Ozobot was found to be 1.90 cm/s by averaging 10 calculations of speed, timing Voyager/Ozobot for a known distance.

With f, v, and v_0 now known, we can calculate the theoretical frequency f' from Equation 1. The theoretical frequency when Voyager is moving toward the wave source as well as the theoretical frequency when moving away from the source agreed with the experimental frequencies to within 1%!
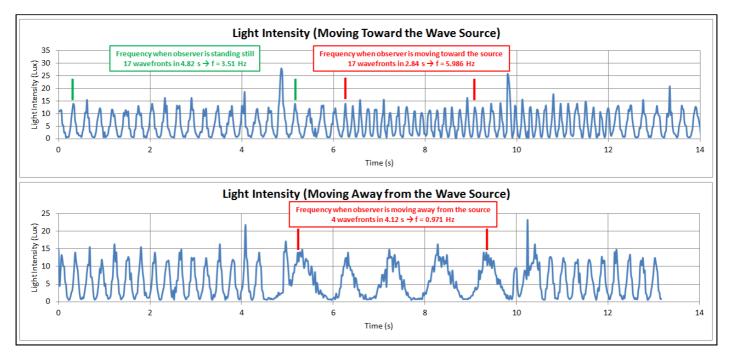

Light Intensity (Moving Toward the Wave Source)

Frequency when observer is standing still
17 wavefronts in 4.82 s → f = 3.51 Hz

Frequency when observer is moving toward the source
17 wavefronts in 2.84 s → f = 5.986 Hz

Light Intensity (Moving Away from the Wave Source)

Frequency when observer is moving away from the source
4 wavefronts in 4.12 s → f = 0.971 Hz

Figure 4

Note that Equation 1 applies only if the speed v_0 of Voyager (the observer) is less than or equal to the speed v of the wave source. If v_0 was greater than v, then f' would be negative. In order to avoid problems associated with this issue as much as possible, the OzoBlockly program sets the speed of Ozobot to the smallest allowable Ozobot speed. As long as the speed of the waves on your device's screen is reasonably greater than the speed of Ozobot, you should be okay.

Suggested Procedure

1. Set up the apparatus and start the JavaScript wave generation program through this URL: rborn.org/doppler/WaveSimulation.html.
2. Measure the wavelength λ of the generated waves when the wave pattern stops after about a minute.

3. Use the PocketLap app and the associated csv file of Light Intensity to measure the frequency f of the wave when PocketLab is at rest, the frequency f' when PocketLab is moving toward the source, and the frequency f' when PocketLab is moving away from the source.
4. Compute the velocity of the wave in the medium from the equation $v = f\lambda$.
5. Determine the speed v_0 of Voyager on the device screen by use of a stopwatch, measuring the time required for Voyager to travel a known distance. Average several readings to get the speed v_0.
6. Compare the experimental frequencies f' obtained in step 3 with the theoretical frequencies predicted by Equation 1.
7. Calculate the percent difference in the experimental and theoretical frequencies. What factors might account for this percent difference?