MEETS BIOLOGY ENGINEERING

AT THE UNIVERSITY OF CINCINNATI

Sound Localization Lesson Overview

Title	Sound Localization
Grade Level Target / Range	10 - 12
Subject Area(s)	biology, anatomy, engineering, computer science
Time Required	6+ hours
Group Size	Groups of 3 recommended
Materials Needed	Section 1 Sound Localization Slides Section 2 Sound Localization - Robot Activity (student guide) Sound Sensor or Sound Sensor with Potentiometer Sound Source (mp3 file) Robot Assembling Instructions Localization Directionality Program Protractor Meter or yard stick Large chart paper or non-permanent surface (on floor) Sound Localization Approach Program
Assessments	Sound Localization Student Questions
Expendable Cost Per Group	*Prices are Estimates as of April, 2022* Makeblock mBot Robot - $80 Sound Sensor - $7 4 AAA batteries - $2
Key Words	sensory biology, engineering, sound localization, phono taxis, robotics, block programming
National Educational Standards	Next Generation Science Standards (NGSS) International Society for Technology in Education (ISTE)
State Specific Educational Standards	Indiana Science Standards Ohio Science Standards West Virginia Science Standards

Introduction

In this robotic activity, students will create a robot that performs phono-taxis. Phonotaxis is defined as the directional movement of an organism with respect to a sound source. The robot will compare the loudness of the sound between two sensors to determine whether it has to turn left or right to get closer to the sound source. Humans (and many other animals) use several cues to localize sound, including the difference in time of arrival between the ears. However, the robot's sensors do not allow for precise timing of the time of arrival of sound at the microphones. Therefore, only the loudness (or intensity) to approach a sound source can be used.

Sound localization has various applications. For example, in engineering localizing the source of noise in a machine can be used to enhance its design. Engineers typically use arrays of many microphones as this allows pinpointing sound with higher precision than when using two microphones or ears. Other applications of sound localization include localizing a speaker. For example, some conference cameras will focus on the person speaking. This does not only provide visual information about who is speaking but it also increases the quality of the recorded sound. Sound localization is also increasingly used in robots to be able to approach sound sources. Robots that interact with people are often able to localize sound, in particular, speech. As for the conference cameras, this ability allows the robot to fixate (and identify the speaker). It also points the microphones in the optimal direction to improve sound quality. The following reference provides an overview of applications of sound localization.

Liaquat, M.U.; Munawar, H.S.; Rahman, A.; Qadir, Z.; Kouzani, A.Z.; Mahmud, M.A.P. Localization of Sound Sources: A Systematic Review. *Energies* **2021**, *14*, 3910. https://doi.org/10.3390/en14133910

This unit was created collaboratively with faculty from the University of Cincinnati College of Arts and Sciences, College of Engineering, and School of Education. Combining biology with engineering activities provides students with a unique opportunity to understand the parallels between animal and robot behavior and sensory/sensor function and addresses broad Next Generation Science Standards (NGSS Lead States, 2013) and International Society for Technology in Education Standards (International Society for Technology in Education, 2022).

Investigating / Essential Questions

- How does a microphone differ from a human ear?
- How can we use information from living animals to improve human technology (biomimicry)?
- What is phono-taxis?

Learning Objectives

Students should be able to…

1. Identify three ways that a microphone is different from a human ear.
2. Measure and display the directivity of the microphones on a robot.
3. Design pinnae for a robot so that the microphones are no longer omnidirectional.

4. Explore the design and placement of the robot ‘ears’ to increase sensitivity to sound.

Prerequisite Student Knowledge

Students must be familiar with Microsoft Excel or Google Sheets and be able to enter data, create and read simple graphs. Students should understand how humans hear sound and have some understanding of algorithmic thinking and the design process.

Instructional Summary

This lesson is divided into two sections. In the first section, students will investigate the ways in which a microphone differs from a human ear. Then, in section two, students will use what they have learned to design and test pinnae (ears) for their robots so that the robot can move towards a sound.

Instructional Plan

1.1 Introduction and Motivation

Let's compare the microphone to our ears.

Ask: How can cues be artificially enhanced to increase sound localization?

Answer: Using physical pinnae to increase directionality. The placement of the ‘ears’ at certain angles can increase the ability to determine the interaural level difference, therefore, determining sound direction.

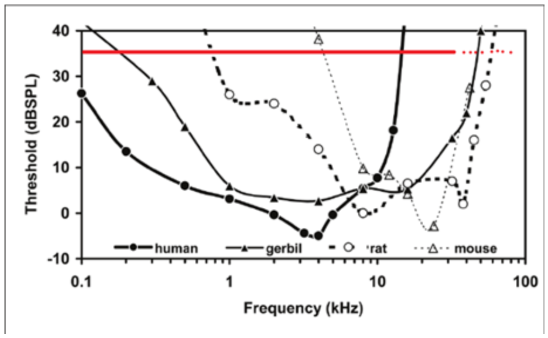
Use the slides on Sound Localization to help guide a discussion with students to help them understand the difference between human ears and a microphone. By the end of the discussion, students should be able to list at least three aspects describing how a microphone differs from the human ear:

- First, it is much less sensitive than our ears.
- Second, it is equally sensitive to a broad range of frequencies.
- Third, it is equally sensitive to most directions.

The following information provides background for the images on the slides.

A microphone is less sensitive than our ears (Slide 3)

Show students the graph on slide 3 (below). Explain that the red line represents the approximate hearing threshold for the microphone that the robot will use. Have students participate in a notice and wonder to start.



Our ears are most sensitive to frequencies around 3000 Hz (3 kHz). The graph above shows the hearing threshold for different animals as a function of frequency. The curve indicates the faintest sound an animal can detect at that frequency. These are average curves. The hearing threshold for individual people (and animals) can differ quite a bit. From this graph, it can be seen that humans tend to be most sensitive (lowest point on the curve) around 3000 Hz. A small animal, like a mouse typically has a higher best frequency. If you want to find similar curves for other animals, google 'audiogram x,' with x the animal in which you are interested. Researchers have measured the audiograms of many different species.

The hearing threshold for the microphone is estimated based on some numbers provided by the manufacturer of the microphone. Two conclusions can be drawn from this about the differences between our ears and the microphone. First, the "hearing threshold" of the microphone is much higher than the threshold of our ears. This is not surprising. Animal ears are unbelievably sensitive. This implies that many sounds we can detect, the microphone can not. The hearing threshold of the microphone is about 36 DB_{spl}. Students can use the table below (slide 4) to find out which sound intensities correspond with this intensity. It is estimated that the microphone is not able to detect any sounds with a decibel value below 36.

Sound source	dB SPL
Colt 45 pistol - 8 meters	140
Threshold of pain	130
Rock Concert	120
Night club music	110
Chainsaw / Jet ski	100
Lawnmower	90
Cabin of jet aircraft cruising	80
Car - 10 meters	70
Average conversation - 1 meter	60
Average suburban home (night)	50
Quiet auditorium	40
Quiet whisper - 1.5 meters	30
Extremely quiet recording studio	20
Anechoic Chamber	10
Threshold of hearing	0

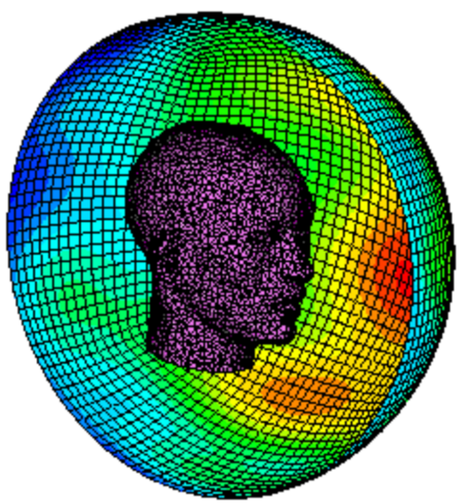
A microphone is equally sensitive to a broad range of frequencies (slide 5)

A second difference between our ears and the microphone is that the microphone is almost equally sensitive to frequencies from 20 Hz to 20,000 Hz (and probably even somewhat higher frequencies, hence the trailing dots at the right side of the red line). To humans, sounds with the same physical amplitude at 2000 Hz and 10,000 Hz have a very different loudness. The 2000 Hz tone will sound louder than the 10,000 Hz tone. Introduce this idea to students using the online tone generator (link on slide 5).

Play a sound of 2000 Hz. Next, stop the sound and move the slider to 10,000 Hz before playing the new tone. Students will notice the difference in frequency, of course. However, they should also note that the 10,000 Hz tone sounds less loud.

A Microphone is Equally Sensitive to Most Directions (slide 6)

The microphone is almost omnidirectional. This means that it is nearly equally sensitive to sounds coming from different directions. Our ears are not equally sensitive to all directions. Our heads and our external ears block sound from specific directions and (somewhat) increase (amplify) sounds from other directions. Seeing this is a bit tricky, as this effect depends on the frequency of the sound. Use the figure below (on slide 6) to convey this idea.



This figure shows the sensitivity of the left ear (for a given frequency) as a function of direction. The sphere is cut in half so that you can see inside. Red colors mean the ear is more sensitive to those directions. From this image, students can see that the ear is less sensitive to sound coming from behind. It is also less sensitive to sounds coming from straight ahead. The left ear is most sensitive to sound coming from the left. This is why humans turn one ear towards a sound source if they are trying to hear very faint sounds. Human ears are less sensitive to sounds coming from straight ahead. Luckily, that is where our eyes are focusing.

At this point, ask students to list the three main differences that microphones and human ears exhibit. These three differences affect the way we use the microphones to steer the robot to sound. After formatively assessing that students have a good understanding of the differences, it is time to consider how these aspects would affect the robotic sound localization.

Ask: How do the differences you learned between the human ear and a microphone inform you about robot sound localization?

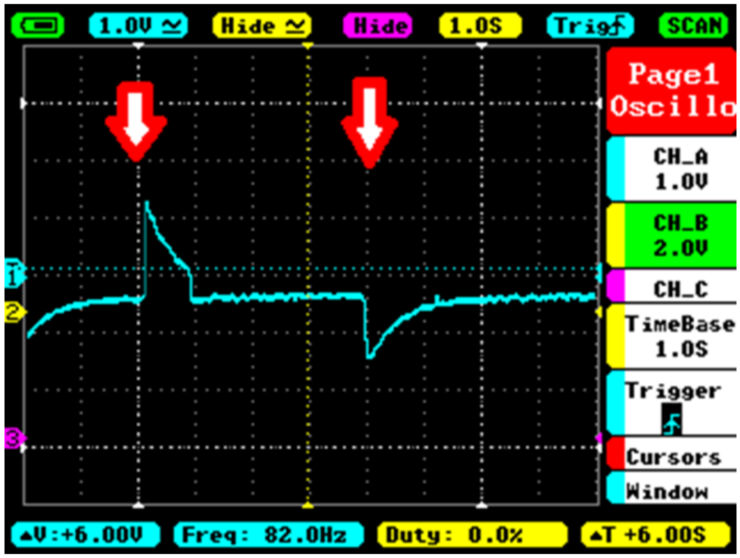
Answer:

1. Because the microphones are not as sensitive as our ears, we will have to use quite loud sounds and place the sound source close to the robots to ensure it detects the sound.
2. Because the microphone is not particular about the frequency, we can use 'broadband' sounds. Broadband sounds are sounds that contain a wide range of frequencies.
3. Because the microphones are about equally sensitive to all directions, we will need to increase their directionality (a technical term meaning 'the degree to which the microphone is selective for sounds coming from a given direction').

For the technically inclined, there is a fourth way in which our ears differ from the specific microphones used by the robot. The electronic components processing the input of the microphone make the robot sensitive to short bursts of sounds. In contrast, the robot cannot detect long sounds, no matter how loud they are.

When observing the Mblock sound sensor, it should be evident that the microphone is the round black disk on the sensor board. However, you will notice that the board contains many other (tiny) electronic components. These serve primarily to increase (amplify) the signal of the microphone before sending it to the robot. However, these electronic components do something else as well: they filter the signal from the microphone such that it is high for short, loud bursts of sound. For long bursts of sound, almost no signal is passed on to the robot.

The image below (also on slide 7) plots the signal that is sent to the robot for a period of about 10 seconds. At the position of the first red arrow, a sound started playing. Notice that, in response, the signal jumps up. This tells the robot the microphone is picking up sound. However, it can be seen that the signal decreases over time. After about a second, the signal is back to baseline, even though the sound is still playing. At the instance of the second arrow, the sound was switched off. The signal responds by becoming negative for a second or so.



The take-home message is the following: the robot does not detect sounds that are longer than about 1 second. The robot detects only the onset (and offset) of sound. This explains why, below, a pulsed sound is provided to use in the robotic activities. If you were to use a constant sound, the robot would be functionality insensitive to it.

1.2 Procedure

1.2.1 Instructional Notes

Warning: noise ahead

This robotic activity works best if the sound source the robot is supposed to approach is the only sound source around. This implies that it is difficult to do this activity with different groups in the same room.

Because the robot's sensors are not very sensitive, the volume of the speaker or phone should be turned up quite high. However, care should be taken not to turn the sound up so much that it is uncomfortable, or you need to raise your voice to be understood by someone 3 feet away. Too loud noise can damage hearing. If in doubt, students could wear hearing protection.

Sensors

Two Mblock sound sensors will be used for this activity. The newer versions of the sensor have a potentiometer that allows adjusting its sensitivity. For example, this sensor has a small, round dial next to the microphone. A screwdriver can be used to – very gently – rotate the dial to adjust the sensitivity of the sensor. If your sensor has such a dial, turn the dial on both sensors to the same halfway position.

2.2.2 Running the robot

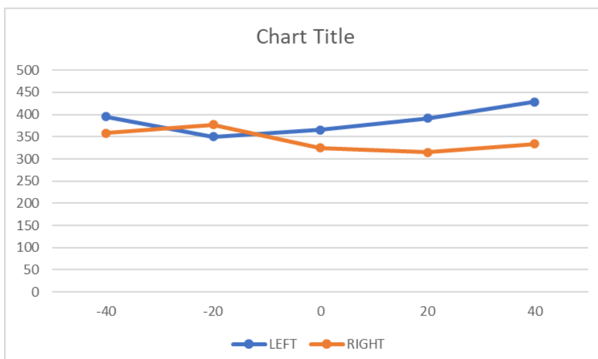
Students will follow directions on the student sheet, Sound Localization - Robot Activity. Guide them as they go, asking questions below.

Step 1: Measuring the directivity of the ears

Ask: Why is it important to measure the directivity of the ears on the robot?

Answer: If we wish to find the sound by comparing the intensity of the sound at both receivers, the left microphone must be more sensitive than the right one for sound coming from the left. However, this is not necessarily so. Remember, we discussed the properties of the microphones and compared them with our ears? We said that the microphones are almost (but not entirely) omnidirectional. Therefore, they pick up sound almost equally well from all directions. In fact, they might be so omnidirectional that a sound at the left of the robot stimulates the left and the right microphone equally. In this case, the robot could not tell whether to turn left or right.

Once students have plotted data from each microphone, pause for a class discussion. Use the sample data below (also on slide 8) to discuss similarities and differences.



Ask: What conclusions can you draw from these graphs?

Answers:

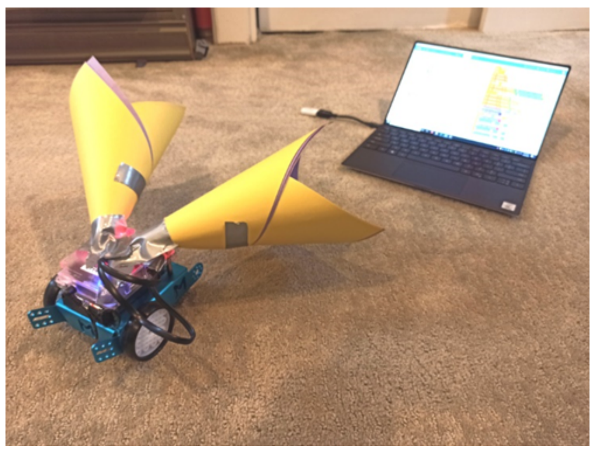
- First, the intensity of the picked-up sound does not vary a lot with the angle. This means that the microphones register about the same sound intensity irrespective of the angle towards the sound source. This is due to the microphones' omnidirectionally. Stated differently, from the sound intensity, picked up at the left and right microphone, you can not tell whether the sound is coming from the left or the right. That is not a good basis for sound localization.
- Secondly, across (most) directions, the left microphone (in the provided example) registered larger values than the right one. This seems to indicate that the microphones are not equally sensitive. The two microphones on the robot feature the same electronic components. Therefore, one would expect them to be similarly sensitive to sound. However, for various reasons, it often happens that one is more sensitive than the other. This makes localizing sound by comparing the intensity at both microphones harder.

In summary, from the measurements, we conclude that the microphones would not be suited for sound localization due to their omnidirectional character. However, this will be fixed in the next step.

Step 2: Making the Ears Directional

Students can make the ears (microphones) directional by constructing artificial pinnae around the microphones. Students can use paper, modeling clay, or other materials. In the example below, we made external ears for the robot using sheets of paper rolled up into a cone. Notice that the ears are quite large with respect to the robot. Larger ears typically result in higher directionality.

Once students have created ‘ears’ for their robots and collected data, monitor their graphs and corrections for the sensitivity of the microphones. Their final graphs should look similar to the example provided on their worksheet. The graphs of sample data on a robot with ‘ears’ are also on slides 9 and 10.



Step 3: Phono Taxis

Students’ robots should approach the sound source. If the robot fails to follow or approach a sound source, it might be necessary to repeat step 2 above. In sample trials, it was noticed that, after a while, the ears on the robot would sag. That changed their acoustic (sound) properties. However, once the ears were fixed back into their original position and step 2 was repeated, the robot was once again able to approach the sound from about 1 meter away.

Extensions

Have students design and test different robot “ears” to increase the ability of the robot to locate sound.

Assessments

Sound Localization Student Questions

Question 1: How does creating 'ears' on the robot increase the robot's ability to respond to sound? Support your reasoning using data from the graph.
Answer: The variability of each ear has increased. For example, for the right ear, the measurements vary from about 400 to 150. That is a range of 250. In the previous graph, the range of data for the right ear was less than 50. This increased variability is good: it means that the output of the microphone varies more as a function of the angle to the sound source. This increased directionality should make sound localization easier (or more reliable).

Question 2: Does angle placement of the ears on the robot increase or decrease the ability to locate sound? Support your reasoning using data from the graph.
Answer: At angle zero, we would expect the left and right ear to return about the same value. However, this is not the case. The left ear returns a larger value than the right one. This is due to the difference in microphone sensitivity we observed earlier – a technical difference between the microphones when they were made. We will correct this difference.

Supporting Activity Information / Background

More about the sensitivity of our ears
Let's express the sensitivity of our ears in some numbers. This will give us intuition about how sensitive we are to sound. The faintest sounds humans can detect (around 2 kHz) have an amplitude of about 20 micropascal. This means that the pressure of the air at the eardrum goes up and down by 20 micropascal around the average pressure. Therefore, the total pressure difference at this sound intensity is 40 micropascal (2 x 20). This change in air pressure pushes and pulls the eardrum back and forth. The movement of the eardrum will eventually be perceived as sound.

We can calculate how much force 20 micropascal change in air pressure exerts on the eardrum. Using an online converter, to avoid errors, we find that 40 micropascal is equal to 4.07×10^{-7} grams per square cm. The surface area of the eardrum is about 0.5 cm^2. Therefore, we have to divide this number by 2.

This result shows that our ears can detect (the equivalent of) of 0.0000002 grams put onto (and taken off) the eardrum at a rate of 1000 kHz. These are tiny forces, indeed! Imagine a kitchen scale that could detect something much smaller than a grain of salt!

A note on engineering: the bang-bang controller
The program we used for localizing the sound is called a bang-bang controller. This is a class of controllers that switches between two states, depending on the input. Some thermostats are

examples of bang-bang controllers. If it is too hot, they turn off the heating (or switch on the air conditioning). If it is too cold, they switch on the heating (or switch off the air conditioning). Our robot turns right if the sound is more intense at the right ear (and vice versa).

Another class of controllers are so-called proportional controllers. These adjust their behavior in proportion to the value of the input. For example, a proportional thermostat could turn up the heating in proportion to the current temperature. If it is much too cold, it would turn up the heating all the way. If it is barely too cold, it would turn the heating on, but only slightly. The program above could be adjusted to implement a proportional controller. You could adjust the turning rate of the robot, depending on the difference in intensity between the two ears. It would give you more control over the robot's behavior, but it also requires more tuning to get it to work.

National Educational Standards

<table>
<tr>
<td>NGSS</td>
<td>Performance Expectations:
HS-LS1-2. ~~Develop and~~ use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms.
HS-LS1-3. Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis. (Section 2 - note that it is the robot that is maintaining the homeostasis).
HS-PS4-2. Evaluate questions about the advantages of using digital transmission and storage of information.
HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

Disciplinary Core Ideas:
LS1.A: Structure and Function
Multicellular organisms have a hierarchical structural organization, in which any one system is made up of numerous parts and is itself a component of the next level.
Feedback mechanisms maintain a living system’s internal conditions within certain limits and mediate behaviors, allowing it to remain alive and functional even as external conditions change within some range. Feedback mechanisms can encourage (through positive feedback) or discourage (negative feedback) what is going on inside the living system. (Section 2)
PS4.A: Wave Properties
Information can be digitized (e.g., a picture stored as the</td>
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	values of an array of pixels); in this form, it can be stored reliably in computer memory and sent over long distances as a series of wave pulses. *PS4.C: Information Technologies and Instrumentation* ● Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them. **Crosscutting Concepts:** *Systems and System Models* ● Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales. *Stability and Change* ● Feedback (negative or positive) can stabilize or destabilize a system. ● Systems can be designed for greater or lesser stability. *Cause and Effect* ● Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects. ● Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system. ● Systems can be designed to cause a desired effect. **Science and Engineering Practices:** ● Asking Questions and Defining Problems ● Developing and Using Models ● Planning and Carrying out Investigations ● Analyzing and Interpreting Data ● Using Mathematics and Computational Thinking ● Constructing Explanations and Designing Solutions ● Engaging in Argument from Evidence ● Obtaining, Evaluating, and Communicating Information

ISTE Standards	1.1 Empowered Learner c. Students use technology to seek feedback that informs and improves their practice and to demonstrate their learning in a variety of ways. d. Students understand the fundamental concepts of technology operations, demonstrate the ability to choose, use and troubleshoot current technologies and are able to transfer their knowledge to explore emerging technologies. 1.4 Innovative Designer c. Students develop, test and refine prototypes as part of a cyclical design process. 1.5 Computational Thinker b. Students collect data or identify relevant data sets, use digital tools to analyze them, and represent data in various ways to facilitate problem-solving and decision-making. c. Students break problems into component parts, extract key information, and develop descriptive models to understand complex systems or facilitate problem-solving. d. Students understand how automation works and use algorithmic thinking to develop a sequence of steps to create and test automated solutions. 1.7 Global Collaborator c. Students contribute constructively to project teams, assuming various roles and responsibilities to work effectively toward a common goal.

State Specific Educational Standards

Ohio Science Standards	**AP.LO.3 Homeostasis (of the robot)** **AP.IC.2 Special Senses - Sense of Hearing and Balance** **Cognitive Demands for Science** ***Designing Technological/Engineering Solutions Using Science Concepts*** ● Requires students to solve science-based engineering or technological problems through application of scientific inquiry. Within given scientific constraints, propose or critique solutions, analyze and interpret technological and engineering problems, use science principles to anticipate effects of technological or engineering design, find solutions using science and engineering or technology, consider consequences and alternatives, and/or integrate and synthesize scientific information. ***Demonstrating Science Knowledge*** ● Requires student to use scientific practices and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather and organize data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments. ***Interpreting and Communicating Science Concepts*** ● Requires students to use subject-specific conceptual knowledge to interpret and explain events, phenomena, concepts and experiences using grade-appropriate scientific terminology, technological knowledge and mathematical knowledge. Communicate with clarity, focus and organization using rich, investigative scenarios, real-world data and valid scientific information. ***Recalling Accurate Science*** ● Requires students to provide accurate statements about scientifically valid facts, concepts and relationships. Recall only requires students to provide a rote response, declarative knowledge or perform routine mathematical tasks. This cognitive demand refers to students' knowledge of science fact, information, concepts, tools, procedures (being able to describe how) and basic principles.

Indiana Science Standards	**AP.1.3 Homeostasis (of the robot)** **AP.7.3 Special Senses** **Science and Engineering Process Standards (SEPS)** SEPS.1 Posing questions (for science) and defining problems (for engineering) SEPS.2 Developing and using models and tools SEPS.3 Constructing and performing investigations SEPS.4 Analyzing and interpreting data SEPS.5 Using mathematics and computational thinking SEPS.6 Constructing explanations (for science) and designing solutions (for engineering) SEPS.7 Engaging in argument from evidence SEPS.8 Obtaining, evaluating, and communicating information
West Virginia Science Standards	**S.HS.HAP.13** Apply the structure of the ear ~~and eye~~ to their function/dysfunction in relation to environmental perception. **S.HS.ETS.2** Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

References

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Authors (in alphabetical order)

Anna DeJarnette is an Associate Professor at the University of Cincinnati, School of Education, Cincinnati, OH 45221.

Anna E. Hutchinson is a postdoctoral fellow and program coordinator at the University of Cincinnati, Department of Biological Sciences, Cincinnati, OH, 45221.

John E. Layne is an Associate Professor at the University of Cincinnati, Department of Biological Sciences, Cincinnati, OH, 45221.

Erin Milligan is an Education Consultant at Hamilton County Educational Service Center, Instructional Services, Cincinnati, OH, 45231.

Stephanie M. Rollmann is a Professor at the University of Cincinnati, Department of Biological Sciences, Cincinnati, OH, 45221.

Dieter Vanderelst is an Assistant Professor at the University of Cincinnati, Departments of Biological Sciences, Electrical Engineering, Mechanical Engineering, and Psychology, Cincinnati, OH, 45221.

Contributor, Supporting Program, Acknowledgements, and Classroom Testing

We thank the teacher and student participants in the University of Cincinnati (UC) Biology meets Engineering summer program for their feedback. We thank Gloria Ononye and Valecia

Kelly for discussions of instructional frameworks. This material is based upon work supported by the National Science Foundation ITEST grant number 1759150 to SMR, JEL, AD, and DV.