

Son of *ABE* (sort of...)

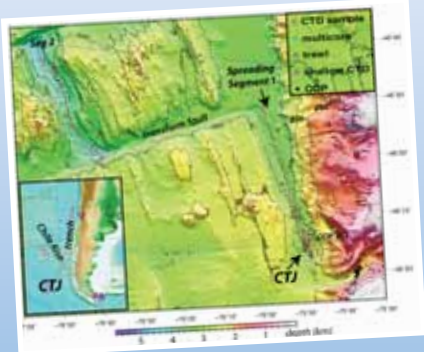


Image captions/credits on Page 2.

lesson plan

Focus

Autonomous Underwater Vehicles

Grade Level

7-8 (Physical Science/Technology)

Focus Question

How do ocean explorers use autonomous underwater vehicles to locate hydrothermal vents and cold seeps in the deep ocean?

Learning Objectives

- Students will discuss the advantages and disadvantages of using underwater robots in scientific explorations.
- Students will discuss ways in which the design of the AUV *Sentry* has improved on the design of the AUV *ABE*.
- Given a specific exploration task, students will identify key design requirements for a robotic vehicle that is capable of carrying out this task and describe practical approaches to meet identified design requirements.
- (Optional) Students will construct a robotic vehicle capable of carrying out an assigned task.

Materials

- Copies of *Autonomous Underwater Vehicles ABE and Sentry Student Guide*; one copy for each student group
- Computers with Internet access
- (Optional, if students will be required to construct a robotic vehicle) Materials to build a robotic vehicle, such as PVC pipe, batteries, propellers for model boats, floats, Lego® Robotics components, and other materials identified by student groups
- (Optional, if students will be required to construct a robotic vehicle) A place to test students' robots, such as a swimming pool or child's wading pool filled with clear, fresh water

Audio-Visual Materials

- (Optional) Interactive white board

Teaching Time

One 45-minute class period, plus time for student research

Seating Arrangement

Groups of 2-4 students

Maximum Number of Students

30

Key Words

Autonomous underwater vehicle
Hydrothermal vent
Autonomous Benthic Explorer (ABE)
Sentry

Background Information

NOTE: Explanations and procedures in this lesson are written at a level appropriate to professional educators. In presenting and discussing this material with students, educators may need to adapt the language and instructional approach to styles that are best suited to specific student groups.

Along the western coast of Chile, three of Earth's tectonic plates intersect in a way that does not occur anywhere else on the planet (see Figure 1). Chile, and the other countries of South America, lies on top of the South American tectonic plate. To the west of Chile, the Nazca Plate extends beneath the Pacific Ocean and meets the Pacific Plate along a divergent plate boundary called the East Pacific Rise. The southern edge of the Nazca plate adjoins the Antarctic Plate along another divergent plate boundary called the Chile Rise. The eastern edge of the Chile Rise is being subducted beneath the South American Plate at the Chile Triple Junction (CTJ), which is unique because it consists of a mid-oceanic ridge being subducted under a continental tectonic plate. The eastern portion of the Nazca Plate is also being subducted along the Peru-Chile Trench, and the Andes Mountains are one consequence of this process. Not surprisingly, complex movements of three tectonic plates at the CTJ result in numerous earthquakes. In fact, the largest earthquake ever recorded occurred along the Peru-Chile Trench in 1960. While earthquakes and volcanoes are often associated with massive destruction and loss of human life, the same processes that cause these events are also responsible for producing unique habitats for very different life forms.

The INSPIRE: Chile Margin 2010 Expedition was directed toward three key questions about the CTJ:

- Does intense seismic activity just north of the CTJ cause increased flow of hydrothermal or cold seep fluids?
- Does the complex and unique interaction between ridge and trench tectonic processes at the CTJ produce different types of hydrothermal vent systems than have been found in other areas?
- Are similar organisms found in various chemosynthetic ecosystems near the CTJ, or do these ecosystems have species that are endemic to a particular type of habitat?

Images from Page 1 top to bottom:

INSPIRE 2012 is a continuation of a multi-disciplinary study begun two years ago. Image courtesy of Scripps Institution of Oceanography.

http://oceanexplorer.noaa.gov/explorations/12chile/background/hires/studyarea_hires.png

Recovering *Sentry* after a dive involves teamwork. Image courtesy of Chris German, INSPIRE: Chile Margin 2012 Expedition, NOAA-OER.

http://oceanexplorer.noaa.gov/explorations/12chile/logs/hires/sentry_line_hires.jpg

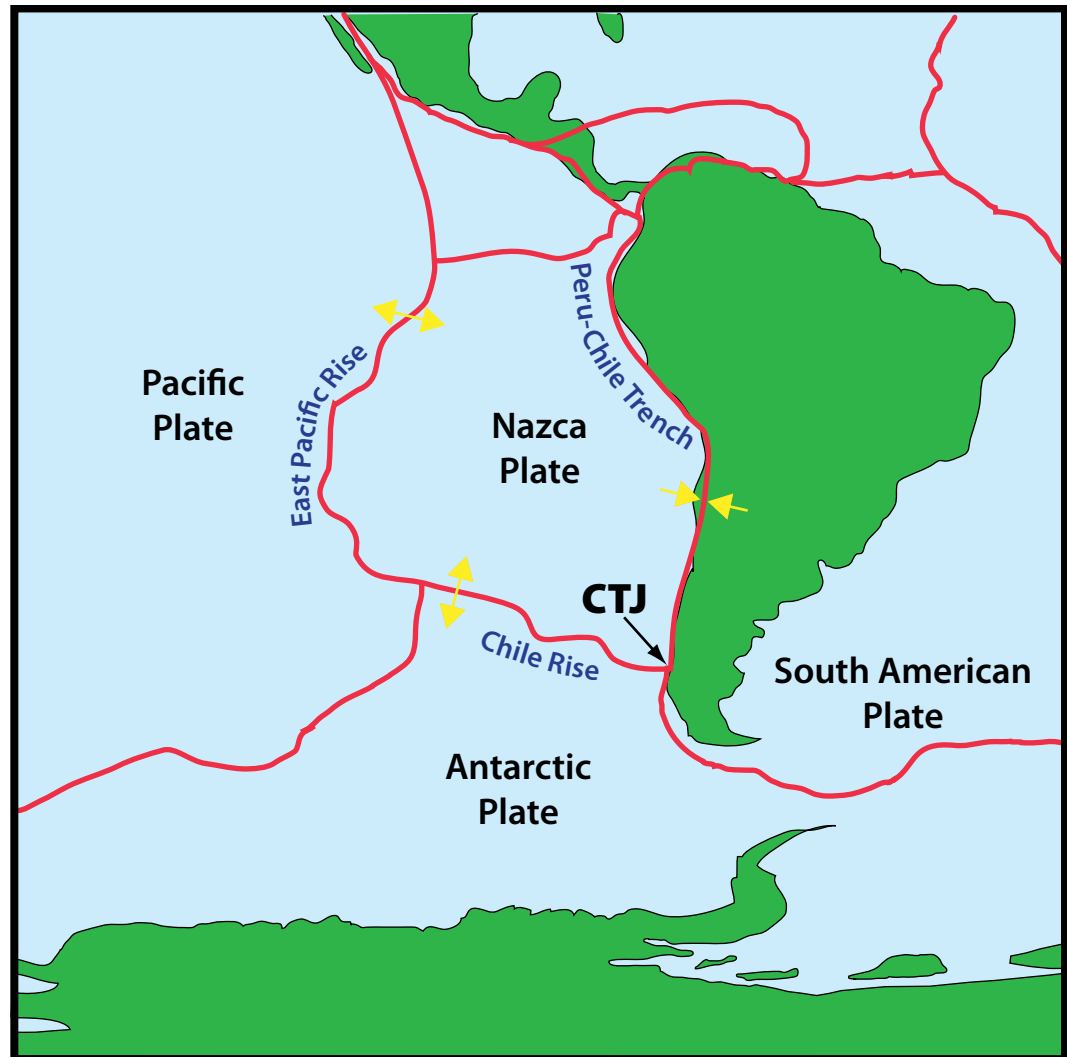
TowCam engineer John making similar final preparations for TowCam. As soon as *Sentry* is overboard tonight, TowCam will follow fast behind, surveying a different part of the seabed and sending images straight back to the operators aboard ship while *Sentry* stores its photos onboard its own computers to await return to the ocean surface on Friday. Image courtesy of Chris German, INSPIRE: Chile Margin 2012 Expedition, NOAA-OER.

http://oceanexplorer.noaa.gov/explorations/12chile/logs/hires/towcam_prep_hires.jpg

Javier, Keith, Ben and Eulogio bring the precious sediment samples from the multi-corer safely on board as a stampede of sample-hungry biologists descend on the back deck to set to work in a flurry of activity. Image courtesy of Chris German, INSPIRE: Chile Margin 2012 Expedition, NOAA-OER.

http://oceanexplorer.noaa.gov/explorations/12chile/logs/hires/samplehungry_hires.jpg

Figure 1: Chile Triple Junction



To answer these questions, the 2010 expedition focused on:

- Locating hydrothermal vent and cold-seep ecosystems near the CTJ;
- Mapping and photographing two new hydrothermal vent sites and two new cold-seep sites near the CTJ;
- Seismic monitoring near the CTJ; and
- Chemical analyses of hydrothermal and cold-seep fluids.

To locate hydrothermal vent and cold-seep ecosystems, expedition scientists used data recorders that can detect chemical and physical water characteristics that signal the presence of hydrothermal vents and cold-seeps. Once plumes were located, scientists planned to use an autonomous underwater vehicle (AUV) to prepare high-resolution maps and collect overlapping photographs of vent and cold-seep sites.

AUVs operate without a pilot or cable to a ship or submersible. This independence allows AUVs to cover large areas of the ocean floor, as well as to monitor a specific underwater area over a long period of

time. Typical AUVs can follow the contours of underwater mountain ranges, fly around sheer pinnacles, dive into narrow trenches, take photographs, and collect data and samples. These capabilities make it possible to map and study benthic features in much greater detail than is possible with other survey methods. An additional benefit of AUVs is that they are much less expensive to operate than manned submersibles.

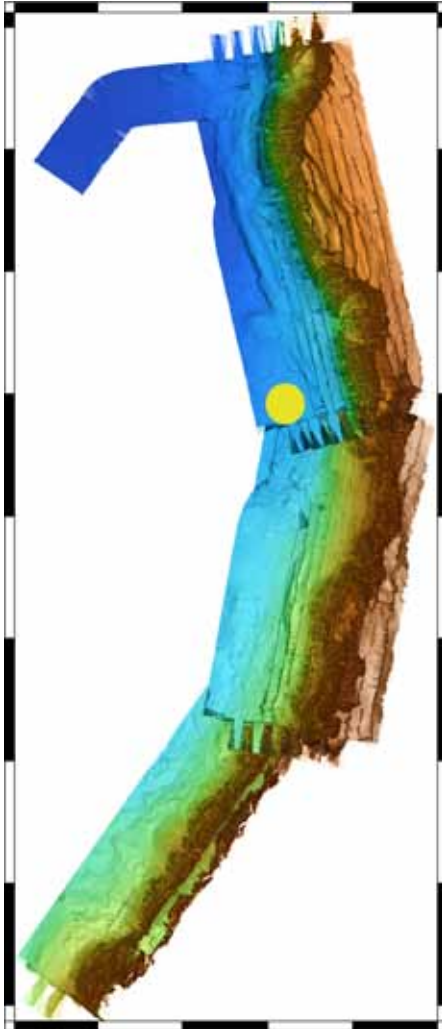
The INSPIRE: Chile Margin 2010 Expedition planned to use an AUV nicknamed *ABE* (an acronym for Autonomous Benthic Explorer) to make detailed maps and photographic images of vent and cold-seep sites. Unfortunately, less than halfway through the expedition, acoustic signals from *ABE* suddenly stopped and the vehicle was never heard from again (the daily log for March 6, 2010 at <http://oceanexplorer.noaa.gov/explorations/10chile/logs/mar7a/mar7a.html> provides additional information). This meant that several objectives of the 2010 expedition could not be fulfilled. The INSPIRE: Chile Margin 2012 Expedition is intended to complete this unfinished work.

The AUV *Sentry* will replace *ABE* for the INSPIRE: Chile Margin 2012 Expedition. In this lesson, students will compare these two research tools, identify key design requirements for a robotic vehicle that is capable of carrying out an assigned task, and describe practical approaches to meet identified design requirements.

Sentry (on the right) has already been slid out of its van far enough to be ready for a crane-lift aboard ship. TowCam is about to be pulled out of the left-hand van as Tim (yellow hat) and Greg (blue) look on. Note the shoulder-high size of the wheel for the 70-ton crane visible to the left of, and behind, the TowCam container – that’s a serious-sized piece of equipment! Image courtesy of Ko-ichi Nakamura.

<http://oceanexplorer.noaa.gov/explorations/12chile/logs/hires/apr18-2-hires.jpg>





The first-cut version of the map made using the data acquired by Sentry overnight April 24, 2012. This is by no means the final version but it is good enough to plan follow-on surveys. The deep blues on the map reflect depths of 2900-3000 meters to the North and West while the brown colors to the South and East represent the top of the rise that marks the transition from the Ocean Crust of the SE Pacific to the continental margin of South America. The scientists believe the source of the methane anomalies lies somewhere on this map, perhaps associated with the steep scarp that marks the brown-blue transition that runs down the middle of the image. Image courtesy of Chris German, INSPIRE: Chile Margin 2012 Expedition, NOAA-OER.

http://oceanexplorer.noaa.gov/explorations/12chile/logs/pires/sentry_map_hires.jpg

Learning Procedure

1. To prepare for this lesson:
 - a. Review introductory essays for the INSPIRE: Chile Margin 2012 Expedition at <http://oceanexplorer.noaa.gov/explorations/12chile/welcome.html>.
 - b. Review:
 - The *Autonomous Underwater Vehicles ABE and Sentry Student Guide*;
 - Information about *ABE* and *Sentry* at <http://www.whoi.edu/oceanus/viewArticle.do?id=12335>, <http://www.whoi.edu/oceanus/viewArticle.do?id=55446>, <http://www.whoi.edu/main/sentry>, and <http://www.whoi.edu/main/ABE>; and
 - The Daily Log entry from the INSPIRE: Chile Margin 2010 Expedition about the loss of *ABE* (<http://oceanexplorer.noaa.gov/explorations/10chile/logs/mar7a/mar7a.html>).

You may also want to review the essays, "How We've Used ABE" and "Next Steps - Sentry" (<http://oceanexplorer.noaa.gov/explorations/12chile/background/abe/abe.html> and <http://oceanexplorer.noaa.gov/explorations/12chile/background/sentry/sentry.html>, respectively) for additional background about how AUVs are used for the INSPIRE: Chile Margin 2010 and 2012 Expeditions. These essays may be assigned as student reading, but will require supplemental explanation of technical terms such as Eh (an abbreviation for redox potential; see the Expedition Education Module (<http://oceanexplorer.noaa.gov/explorations/12chile/background/edu/edu.html>) for additional discussion).

- c. Decide on the desired level of complexity for this lesson. The simplest, quickest, and least expensive approach is to have students design, but not build, robotic vehicles that could be capable of performing prescribed tasks. If a more hands-on experience is desired, several underwater robot kits are available of varying cost and complexity (see Extensions, below). Another approach is to require the robotic vehicles to be capable of autonomous activity, so that students have to incorporate programmable robotics such as Lego® Mindstorms components (Note: Mention of commercial entities and trade names does not imply endorsement by NOAA). This approach might include having students construct intermediate subsystems capable of performing certain tasks as a proof-of-concept test for their designs. Such a subsystem, for example, might direct a robot to follow a pre-determined course, but change the course if an obstacle is encountered. A model system for a terrestrial robot to perform this task could be a proof-of-concept test for the program that provides appropriate controls for the robot's propulsion and sensor systems. The most involved (and also the most fun and rewarding)

approach is to require students to construct unique robots from their own designs. If you plan to have students construct their own robotic vehicles, you may want to review the books listed under "Resources." If you opt for one of the more complex approaches, at least a month should be available for students to complete their assignment; more time would be better.

- d. If students do not have access to the internet, make copies of relevant materials on underwater robotic vehicles from the Web site referenced above.

2. If students are not familiar with hydrothermal vents and cold seeps, briefly introduce these systems (see the Expedition Education Module (<http://oceanexplorer.noaa.gov/explorations/12chile/background/edu/edu.html>) for more information and resources).

Introduce the mission of the INSPIRE: Chile Margin 2012 Expedition, and discuss how expedition scientists prospect for undiscovered hydrothermal vents and cold seeps. You may want to briefly describe multibeam mapping and physical/chemical sensor arrays discussed in "The Oceanographic Yo-Yo" and "Mapping the Deep Ocean Floor" lessons included in the lesson plan collection for this expedition (<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/yoyo.pdf> and <http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/mapping.pdf>, respectively). Be sure students understand that the essence of the scientists' approach is to use different technologies to detect evidence of these features, beginning with sidescan sonar and towed sensors over large areas of the ocean floor. When chemical and/or physical clues are detected that signal the presence of vents or seeps, the search shifts to a strategy that uses underwater robots.

Have students read the Daily Log entry about the loss of *ABE*, then lead a brief discussion about this essay. This event highlights the fact that exploration is often a risky proposition, and underscores one of the major advantages of underwater robots: reducing threats to the lives of human explorers.

3. Tell students that their assignment is to learn some basic facts and acquire some ideas about AUVs by comparing major features of AUV *ABE* with the "next generation" AUV *Sentry*. Provide each student group with a copy of the *Autonomous Underwater Vehicles ABE and Sentry Student Guide*. When groups have answered the questions, lead a discussion of students' responses, which should include:

- Data table:

	ABE	Sentry
Maximum Depth	4,500 m	4,500 m
Number of Thrusters	5	4
Length	3 m	2.9 m
Weight in Air	550 kg	1,250 kg
Maximum Speed	0.6 m/sec	1.2 m/sec
Maximum Operating Time	14 - 20 hr	≤ 24 hr
Maximum Operating Range	20 - 40 km	50 - 100 km

- *ABE* reaches its working depth by sinking through the water attached to a heavy diving weight. To return to the surface, the vehicle drops another weight (the “ascent weight”) and floats up.
 - *Sentry* uses its pivoting thrusters to move up and down as well as forward and backward. It has a more hydrodynamic shape than *ABE*, so it is capable of greater ascent and descent speeds.
 - *ABE* resembles the *Starship Enterprise* because the three-hulled design puts most of the flotation near the top of the vehicle and heavy instruments and other gear near the bottom. This separation of buoyancy and mass makes *ABE* resistant to pitching and rolling, and also provides a safe location for the vertical thrusters between the three pods.
 - *Sentry’s* shape is the result of a design that provides a more hydrodynamic shape, which allows greater ascent and descent speeds. Mounting the thrusters on pivoting wings allows the same thrusters to be used for up-down as well as forward-reverse movement.
 - Compared to *ABE*, *Sentry* has improved speed, range, maneuverability, faster ascents and descents, improved navigation, and acoustic communications.
 - Advantages of underwater robots for ocean exploration compared to human-occupied submersibles include reduced risk to human life, much lower operating costs, and longer operating times (especially for AUVs). The major drawback is that the human presence is lost, which can make visual surveys and evaluations more difficult.
4. Tell students that their assignment is to design an underwater robotic vehicle that they could construct and that would be capable of moving in a horizontal direction at a fixed depth. You may also want to include a requirement that the robot must collect some type of information about the surrounding environment such as

temperature or visual images. If you want to require that the vehicles be capable of autonomous activity and/or actually constructed, add those instructions as well.

To help students get started, lead a brainstorming session of key components or systems that would have to be included in this kind of vehicle, such as:

- power system
- propulsion system
- communication system
- buoyancy control system
- information gathering system(s)

Discuss specific requirements for each of these systems. Emphasize that the intention of this assignment is for students to design an underwater robotic vehicle that they could construct (whether you actually require them to do so or not), so students' solutions to these requirements should be practical and involve materials to which they have access. Assign "milestone" dates by which certain tasks need to be completed. Have each group present a periodic progress report, identifying problems that have been encountered and proposed solutions. If you plan to have students construct their designs, provide information about available materials and other design constraints.

There are numerous reports and case studies on the Internet about underwater robotics projects, and students should be encouraged to locate these and learn from prior experience. Procedures for waterproofing motors and other components, programs for autonomous control of simple movements, and many other "lessons learned" are available. Tell students to be sure to document the sources for any "prior knowledge" that they use in designing their robots, and to keep a notebook in which they record the assigned requirements for their robot, their approaches to providing key systems, and (if their assignment includes constructing a robot) test procedures and results for each of these systems as well as for the assembled robotic vehicle.

On the date assigned for project completion, each group should present a report of their design solutions and demonstrate their assembled robotic vehicle (if this was part of their assignment).

The BRIDGE Connection

www.vims.edu/bridge/ – Click on "Ocean Science Topics" in the menu on the left side of the page, then "Human Activities," then "Technology" for links to resources about submersibles, ROVs, and other technologies used in underwater exploration.

The “Me” Connection

(from the “Ridge Exploring Robot” lesson) Many stories have been written about robots that have or acquire human characteristics (one of the most famous is “Data” from the television series *Star Trek: The Next Generation*). Have students write a brief essay describing how they think scientists felt about losing *ABE*, and how they would personally feel under similar circumstances.

Connections to Other Subjects

English/Language Arts, Mathematics, Earth Science

Assessment

Responses to *Student Guide* questions, design projects, and class discussions provide opportunities for assessment.

Extensions

1. Visit http://www.marinetech.org/rov_competition/rov_video_2007.php for a video from the the Marine Technology Society’s student ROV competition, and links to other sites about underwater robots.
2. For ideas about building your own underwater robots, see Bohm, 1997; Bohm and Jensen, 1998; and Moore, Bohm, and Jensen, 2010.
3. Some sources of underwater robot kits include:
 - Kelvin Educational (http://www.kelvin.com/Merchant2/merchant.mvc?Screen=CTGY&Category_Code=TRWASU);
 - ROV in a Bucket (http://monitor.noaa.gov/publications/education/rov_manual.pdf);
 - The SeaPerch Program (<http://www.seaperch.org/index>).

(Note: Mention of commercial entities and trade names does not imply endorsement by NOAA)

Other Relevant Lesson Plans from NOAA’s Ocean Exploration Program

Mapping the Deep Ocean Floor (Grades 7-8; PDF, 1.5 Mb)
<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/mapping.pdf>

Focus: Bathymetric Mapping (Physical Science)

Students will create a two-dimensional topographic map from bathymetric survey data, create a three-dimensional model of seafloor topography from a two-dimensional topographic map, and will be able to interpret two- and three-dimensional topographic data.

The Oceanographic Yo-Yo (grades 7-8; PDF, 1.2 Mb)
<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/yoyo.pdf>

Focus: Using ocean chemistry to locate hydrothermal vents

Students will explain the effects of hydrothermal vents on chemical and physical parameters of seawater, and how oceanographers can use these effects to locate hydrothermal vents.

The Ridge Exploring Robot (grades 9-12; PDF, 1.2 Mb)

<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/robot.pdf>

Focus: Autonomous Underwater Vehicles/Marine Navigation

Students will explain a three-phase strategy that uses an autonomous underwater vehicle (AUV) to locate, map, and photograph previously undiscovered hydrothermal vents, design a survey program to provide a photomosaic of a hypothetical hydrothermal vent field, and calculate the expected position of the AUV based on speed and direction of travel.

Other Resources

The Web links below are provided for informational purposes only.

Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

<http://oceanexplorer.noaa.gov/explorations/12chile/welcome.html> –
Web site for the INSPIRE: Chile Margin 2012 Expedition

Bohm, H. 1997. Build your own underwater robot and other wet projects. Westcoast Words. 148 pages.

Bohm, H. and V. Jensen. 1998. Build Your Own Programmable Lego Submersible: Project: Sea Angel AUV (Autonomous Underwater Vehicle). Westcoast Words. 39 pages.

German, C., D. Yoerger, M. Jakuba, T. Shank, C. Langmuir, K. Nakamura. 2008. Hydrothermal exploration with the *Autonomous Benthic Explorer*. *Deep-Sea Research I* 55:203-219

Moore, S., H. Bohm, and V. Jensen. 2010. Underwater Robotics Science, Design, and Fabrication. Marine Advanced Technology Education Center. Monterey, CA. 769 pp.

Yoerger, D., A. Bradley, M. Jakuba, M. Tivey, C. German, T. Shank, R. Embley. 2007. Mid-ocean ridge exploration with an autonomous underwater vehicle. *Oceanography* 20(4):52-61(available online at http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/20_4/20.4_yoerger_et_al.pdf)

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Correlations to Next Generation Science Standards

These correlations will be provided in an update to this lesson when the final version of the Next Generation Science Standards is released.

Correlations to Common Core State Standards for Mathematics

Grade 7-8 - Geometry

Solve real-life and mathematical problems involving angle measure, area, surface area, and volume.

Solve real-world and mathematical problems involving volume of cylinders, cones, and spheres.

Correlations to Common Core State Standards for English Language Arts

Grades 6-12 Reading: Informational Text

RI.9-10.4. Determine the meaning of words and phrases as they are used in a text, including figurative, connotative, and technical meanings.

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 2.

The ocean and life in the ocean shape the features of the Earth.

Fundamental Concept e. The ocean is three-dimensional, offering vast living space and diverse habitats from the surface through the water column to the seafloor. Most of the living space on Earth is in the ocean.

Essential Principle 5.

The ocean supports a great diversity of life and ecosystems.

Fundamental Concept e. Tectonic activity, sea level changes, and force of waves influence the physical structure and landforms of the coast.

Fundamental Concept f. Ocean habitats are defined by environmental factors. Due to interactions of abiotic factors such as salinity, temperature, oxygen, pH, light, nutrients, pressure, substrate and circulation, ocean life is not evenly distributed temporally or spatially, i.e., it is "patchy". Some regions of the ocean support more diverse and abundant life than anywhere on Earth, while much of the ocean is considered a desert.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 7.

The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they

will find great opportunities for inquiry and investigation.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.

Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

Send Us Your Feedback

We value your feedback on this lesson.

Please send your comments to:

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Autonomous Underwater Vehicles *ABE* and *Sentry* Student Guide

Autonomous Underwater Vehicles (AUVs) are underwater robots that operate without a pilot or cable to a ship or submersible. This independence allows AUVs to cover large areas of the ocean floor, as well as to monitor a specific underwater area over a long period of time. Typical AUVs can follow the contours of underwater mountain ranges, fly around sheer pinnacles, dive into narrow trenches, take photographs, and collect data and samples.

Until recently, once an AUV was launched it was completely isolated from its human operators until it returned from its mission. Because there was no effective means for communicating with a submerged AUV, everything depended upon instructions programmed into the AUV's onboard computer. Today, it is possible for AUV operators to send instructions and receive data with acoustic communication systems that use sound waves with frequencies ranging roughly between 50 hz and 50 khz. These systems allow greater interaction between AUVs and their operators, but basic functions are still controlled by the computer and software aboard the AUV.

Key systems found on most AUVs include: propulsion, usually propellers or thrusters (water jets); power source such as batteries or fuel cells; environmental sensors such as video and devices for measuring water chemistry; computers to control the robot's movement and data gathering functions; and a navigation system.

Navigation has been one of the biggest challenges for AUV engineers. Today, everyone from backpackers to ocean freighters use global positioning systems (GPS) to find their location on Earth's surface. But GPS signals do not penetrate into the ocean (for more about GPS, visit <http://oceanservice.noaa.gov/topics/navops/positioning/welcome.html>). One way to overcome this problem is to estimate an AUV's position from its compass course, speed through the water, and depth. This method of navigation is called "dead reckoning," and was used for centuries before GPS was available. Dead reckoning positions are only estimates, however, and are subject to a variety of errors that can become serious over long distances and extended time periods.

If an AUV is operating in a confined area, its position can be determined using acoustic transmitters that are set around the perimeter of the operating area. These transmitters may be moored to the seafloor, or installed in buoys. Some buoy systems also include GPS receivers, so the buoys' positions are constantly updated. Signals from at least three appropriately positioned transmitters can be used to accurately calculate the AUV's position. Although this approach can be very accurate, AUV operators must install the transmitters, and the AUV must remain within a rather small area.

A more sophisticated approach uses Inertial Navigation Systems (INS) that measure the AUV's acceleration in all directions. These systems provide highly accurate position estimates, but require periodic position data from another source for greatest accuracy. On surface vessels and aircraft equipped with INS, additional position data

are often obtained from GPS. On underwater vessels, the accuracy of INS position estimates is greatly improved by using a Doppler Velocity Logger (DVL) to measure velocity of the vessel's speed. On some AUVs, several of these systems are combined to improve the overall accuracy of onboard navigation. *ABE* uses acoustic transmitters as well as a DVL. For more information about INS and DVL systems, visit <http://www.oceanexplorer.noaa.gov/explorations/08aувfest>.

Use the following references to answer the questions below:

- "*ABE – The Autonomous Benthic Explorer*" (<http://www.whoi.edu/oceanus/viewArticle.do?id=12335>)
- "*Autonomous Underwater Vehicle ABE*" (<http://www.whoi.edu/main/ABE>)
- "*A New Deep-Sea Robot Called Sentry*" (<http://www.whoi.edu/oceanus/viewArticle.do?id=55446>)
- "*AUV Sentry*" (<http://www.whoi.edu/main/sentry>)

1. Complete the following table about *ABE* and *Sentry*:

	<i>ABE</i>	<i>Sentry</i>
Maximum Depth	_____	_____
Number of Thrusters	_____	_____
Length	_____	_____
Weight in Air	_____	_____
Maximum Speed	_____	_____
Maximum Operating Time	_____	_____
Maximum Operating Range	_____	_____

2. How do *ABE* and *Sentry* descend and ascend to and from the desired operating depth?
3. Why does *ABE* look like the *Starship Enterprise*?
4. Why does *Sentry* look like an iPod with fins?
5. What are some ways that *Sentry* has been improved compared to *ABE*?
6. What are some advantages and disadvantages of using underwater robots in scientific explorations?