"Shell Shocked" – Instructor's Guide

Overview: In this hands-on investigation of seashell morphology, students study the elaborately whorled, sculpted, and ornamented seashells of gastropods not as objects of beauty, but as artifacts reflecting an evolutionary tradeoff: shells are costly to build and carry around, yet essential for survival. First, students evaluate real seashells for their ability to deter predators. They then watch *Shape of Life* footage highlighting the research of the famous paleontologist Geerat Vermeij, who has been blind from an early age and studies fossilized shells with his hands. Finally, students examine examples of Vermeij's graphs showing 500 million years of seashell evolution. They use their new insights about shell design to interpret fossil trends as a case of **coevolution**: an "arms race" between shelled molluscs and shell-breaking predators.

Grades: 7-12. The high school version employs evolutionary concepts, while the middle school version uses the language of animal adaptations but not evolution. Also adaptable for upper elementary.

Subjects: Earth science, biology, paleontology, evolutionary science, predator-prey ecology

Key Concepts / Unifying Theme: Macroevolution, coevolution, predator/prey "arms races"

Essential Skills / Scientific Process: Interpreting biological adaptations as instances of "form follows function." Analysis of graphs and time series.

NGSS/CCSS Connections: (See below.)

Approach: The lesson plies an "explore-before-explain" pedagogy, with a dose of inquiry and data analysis. It opens with a short, simple laboratory in which students evaluate seashells for their ability to deter predators. Next, they watch select segments from "The Survival Game" episode of *The Shape of Life* video series (free online), which develop a more formal understanding of predator-prey "arms races" (a case of coevolution) and highlight the research of the famous paleontologist Geerat Vermeij. Finally, students examine a selection of Vermeij's graphs showing 500 million years of actual seashell fossil data. They use their new insights about shell design to interpret fossil trends as evidence of a relentless coevolutionary arms race between shelled molluscs and shell-breaking predators.

Logistics: 45-60 minutes. 2-4 students per team. This lesson can be done as a stand-alone lesson or on the heels of the preceding lesson on gastropods. In the latter case there will be some overlap here; modify as needed. There are both high school and middle school versions of the lab activity.

Materials: An assortment of 8 to 12 gastropod seashells. Try to get a variety of forms that exhibit the different shell design strategies. Please try to borrow or collect your own shells rather than purchase them from vendors. Good specimens include whelks, conchs, cowries, olives, augurs, murexes, turbans, etc. On a tight budget, you can carry out this lab with just ONE of each species, by keeping all the shells at a central station and allowing each team to take only one at a time for analysis, before exchanging it for a new one. Alternatively, you can provide each team with its own set of 6 or more shells.

Suggested instructional sequence:

1. Distribute the handout "Shell Shocked." Have students read the front page and then carry out the lab activity on the second page. Logistically, you can approach this in one of two ways, depending on the availability of shells:

a) Place your entire collection at a central station with species labels. In that case, each team is to take only one shell at a time, analyze it and record ratings in the data table, and then exchange it for a new shell.

b) Provide each team with its own set of 6 or more shells. The advantage to this approach is that students can make direct comparisons between species and assign relative ratings.

2. Continue until all teams have evaluated all or most of the species. (Note: Students should wait until after viewing the relevant *Shape of Life* segments – see below – before beginning the data analysis exercise on pages 3-4.)
3. After the lab activity, spend a few minutes reviewing results through whole class discussion. Then tell your class that the study of anti-predator seashell designs has been the lifelong obsession of renowned paleontologist Geerat Vermeij of the University of California at Davis. Then show select video segments from the Shape of Life website (http://www.shapeoflife.org/):
    - Essential viewing: "Geerat Vermeij, Evolutionary Biologist: Reading A Shell's Story" (7.5 min; in the Scientists hub). This segment nicely develops the theme of predator-prey co-adaptations and "arms races," and sets up the student data analysis exercise to follow.
    - Recommended: "Mollusc Animation: Shell Repair" (1.5 min; in the Animation hub). A quick piece on how molluscs manufacture and repair their shells.
4. Now have students carry out the data analysis exercise on pages 3-4 of "Shell Shocked," which asks students to interpret 4 graphs drawn from Vermeij's own research. Afterwards go over their answers via whole class discussion. See below for an interpretation of Vermeij's data.
5. Closure: Show *The Shape of Life* segment "Molluscs: The Survival Game" (15 min; in the Phyla hub) – an excellent overview of the biology, behavior, and body forms of the main molluscan taxa (gastropods, bivalves, and cephalopods) which reinforces the theme of predator-prey co-adaptations and "arms races."

Answer key / Notes for post-lab discussion:
The first graph shows that predators with an ability to break shells first appeared about 450 ma. Since then their numbers have risen, right up to the modern day. Among predators, then, natural selection is clearly favoring traits that enable shell-breaking, and thus those traits are increasing in frequency. Meanwhile, as the other three graphs show, soft-bodied molluscs are evolving ever better defenses against the shell-breakers. Many gastropods foil the new predators by developing high spires or narrow apertures with thickened margins. Bivalves and others escape by heading down into the sediments or boring into rocks. And cephalopods reinforced their shells by coiling them or "sculpturing" them with ribs, bumps, knobs, and spines. At the same time, snails with a "weak shell design" steadily diminished in number. Among prey, then, natural selection is clearly increasing the frequency of traits that protect against shell-breaking predators, while weeding out traits that do not.

- A side question to explore with students: Why aren't "weak designs" completely weeded out? Probably because there is a cost to making bigger, heavier, more spiny shells. They take lots of calories and chemicals to build. Those are resources that could instead be invested in the production of offspring. Also, such shells probably slow an animal down, forcing it to burn more calories during foraging and diminishing the amount of calories collected for survival and reproduction. It's an evolutionary tradeoff: There are both benefits and drawbacks to the trait.

Coevolution occurs when two different groups of organisms mutually influence each other's traits. They perpetually adapt to one another. In terms of natural selection, each acts as a "selective pressure" upon the other. It is easy to see here that molluscs have been evolving in response to the ever increasing threat of shell-breakers, but coevolution implies that the predators are evolving in response to the prey, too. Do we have evidence of this? Perhaps. Since shell-breakers are increasing in abundance and diversity (number of different taxa), it is clear that shell-breaking continues to be a successful way to make a living. So presumably, even as the prey are developing better and better defenses, the predators are successfully evolving new and different ways around those defenses. It's an arms race that continues today!

However, Vermeij himself has argued that this coevolution is asymmetrical: Prey are pressured to evolve specialized adaptations to predators more strongly than predators are pressured to specialize to their prey. Thus, the fossil record here does not exhibit the sort of tight, reciprocal, species-specific adaptation that shapes a hummingbird bill to fit its favorite flower – and vice versa. Rather, predator-prey "arms races" are often more of a "diffuse" coevolution in which whole suites of prey adapt in general ways to whole suites of predators, and vice versa. Vermeij dubs this "escalation": Prey evolve ever more sophisticated defenses, yet there is no "progress" in it, for predators tend to keep pace.

Next Generation Science Standards supported in this module:

MS-LS2-2 Construct an explanation that predicts patterns of interactions among organisms across multiple ecosystems *[this includes predator-prey relations; c.f., DCI LS2.A]*

MS-LS2-4 Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations *[c.f., DCI LS2.C]*

MS-LS4-1 Analyze and interpret data for patterns in the fossil record that document the existence, diversity, extinction, and change of life forms throughout the history of life on Earth under the assumption that natural laws operate today as in the past. *[c.f., DCI LS4.A]*

MS-LS4-6 Use mathematical representations to support explanations of how natural selection may lead to increases and decreases of specific traits in populations over time. *[c.f., DCI LS4.C]*

MS-ESS1-4 Construct a scientific explanation based on evidence from rock strata for how the geologic time scale is used to organize Earth's 4.6-billion-year-old history. *[this includes "the evolution or extinction of particular living organisms"; c.f., DCI ESS1.C and the clarification statement accompanying MS-ESS1-4]*

HS-LS2-2 Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. *[this includes effects of predation and food availability, as well as skill in "determining trends, and using graphical comparisons of multiple sets of data": c.f., LS2.A and the clarification statement accompanying HS-LS2-2]*

HS-LS4-2 Construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment. *[this includes "using evidence to explain the influence each of the four factors has on …morphology …and subsequent survival of individuals and adaptation of species"; c.f., DCI LS4.B, LS4.C, and the clarification statement accompanying HS-LS4-2]*

HS-LS4-4 Construct an explanation based on evidence for how natural selection leads to adaptation of populations. *[c.f., DCI LS4.B and LS4.C]*

HS-LS4-5 Evaluate the evidence supporting claims that changes in environmental conditions may result in: (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. *[c.f., DCI LS4.C]*

Cross-Cutting Concept #1: Patterns

Cross-Cutting Concept #6: Structure and Function

Scientific and Engineering Practice #4: Analyzing and Interpreting Data

Scientific and Engineering Practice #7: Engaging in Argument from Evidence

Common Core State Standards for Literacy in Science and Technical Subjects supported in this module:

Writing Standard 1.b, Grades 6-8	Write arguments focused on discipline-specific content: Support claim(s) with logical reasoning and relevant, accurate data and evidence that demonstrate an understanding of the topic or text, using credible sources.
Writing Standard 1.b, Grades 9-10	Write arguments focused on discipline-specific content: Develop claim(s) and counterclaims fairly, supplying data and evidence for each while pointing out the strengths and limitations of both claim(s) and counterclaims in a discipline-appropriate form and in a manner that anticipates the audience's knowledge level and concerns.
Writing Standard 1.b, Grades 11-12	Develop claim(s) and counterclaims fairly and thoroughly, supplying the most relevant data and evidence for each while pointing out the strengths and limitations of both claim(s) and counterclaims in a discipline-appropriate form that anticipates the audience's knowledge level, concerns, values, and possible biases.
Writing Standard 2, Grades 9-12	Write informative/explanatory texts, including the narration of historical events, scientific procedures/experiments, or technical processes.
Writing Standard 4, Grades 9-12	Produce clear and coherent writing in which the development, organization, and style are appropriate to task, purpose, and audience.

Common Core State Standards for Mathematics supported in this module:

Grade 8 (8.SP.A.1)	Statistics & Probability – Investigate patterns of association in bivariate data: Construct and interpret scatter plots for bivariate measurement data to investigate patterns of association between two quantities.
High School (HSS.ID.B.6)	Statistics & Probability – Interpreting Categorical and Quantitative Data: Summarize, represent, and interpret data on two categorical and quantitative variables.
High School (HSS.IC.B)	Statistics & Probability – Making Inferences & Justifying Conclusions: Make inferences and justify conclusions from sample surveys, experiments,a nd observational studies.

References:

Vermeij, G. J. (1978). *Biogeography and Adaptation, Patterns of Marine Life.* Cambridge, MA: Harvard University Press

Vermeij, G. J. (1987). *Evolution and escalation: An ecological history of life.* Princeton, NJ: Princeton University Press.

Endler, J. A. (1991). Interactions between predators and prey. In J.R. Krebs & N. B. Davies (Eds.), *Behavioral Ecology: An Evolutionary Approach* (3rd ed.). Oxford, UK: Blackwell Scientific.

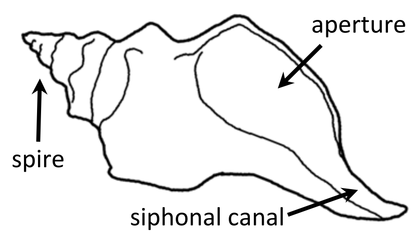
Shell Shocked

Lab Activity: Snails vs. Shell-breaking Predators

Few things in nature are as beautiful and fascinating as seashells, with their graceful spirals, marvelous shapes, and dazzling colors. However, these handsome snail homes (actually their external skeletons) are built at great cost. Producing and maintaining a shell requires a huge investment of energy and building materials, so there must be a big payoff for the snail. That payoff, of course, is protection. Snails build their expensive shells not for beauty, but for a darker function: to defend their soft bodies against the sharp claws of hungry crustaceans and the strong jaws of predatory fish.

Here are some good shell designs and traits for thwarting predators:

- **Thick walls**: Heavy armor is the most basic defense, but costly to build.
- **Spikes, spines, and other protrusions**: These are a less expensive way to keep the claws and jaws of predators at a safe distance from the snail's soft body. And they make for an uncomfortable mouthful.
- **High spires:** Most snails create a twisted shell. Sometimes this is a "flat" coil shaped like a roll of Scotch tape or a fire hose rolled onto a spool. But others spiral out to a tall, sharp point resembling an ice cream cone. High spires are harder to swallow and also add distance between attackers and the wide part of the shell where some of the snail's most vital organs are located.



- **Narrow aperture:** The shell's opening – or **aperture** – is the place most vulnerable to attacks. A slender, slit-like opening is tougher for predators to infiltrate than a wide, oval one.
- **Long siphonal canal:** Some snails do have a wide, oval aperture instead of a narrow one. Such snails usually also have a hard **operculum**, an oval "door" that seals across the opening whenever the animal retreats inside. However, this door also prevents the snail from breathing. Consequently, these snails have a **siphon**, a slender snorkel that pokes out and draws in water and oxygen. The snail extends its siphon through a tight **siphonal canal** in the shell. A long canal is less vulnerable to entry by predators than a short one. It also lets the snail burrow to safety without suffocating: Most of the animal remains safely buried, with only the siphon and siphonal canal raised into the water for breathing.
- **Thickened margins:** The outer rim or "lip" of the aperture is especially vulnerable to the shell-breaking grip of attackers. The thicker the better.

Study the armor from different species of gastropods. Grade each one (A, B, C, D, F) on each of the six defensive traits and fill out the report card.

Seashell Report Card

Species	Thick Shell	Protrusions	High Spire	Narrow Aperture	Long Siphonal Canal	Thickened Margins	GPA

Who's the valedictorian (top of the class)?

The salutatorian (2nd highest)?

Sweat hogs (bottom of the class)?

Class clown (weirdest)?

Homecoming queen (purtiest)?

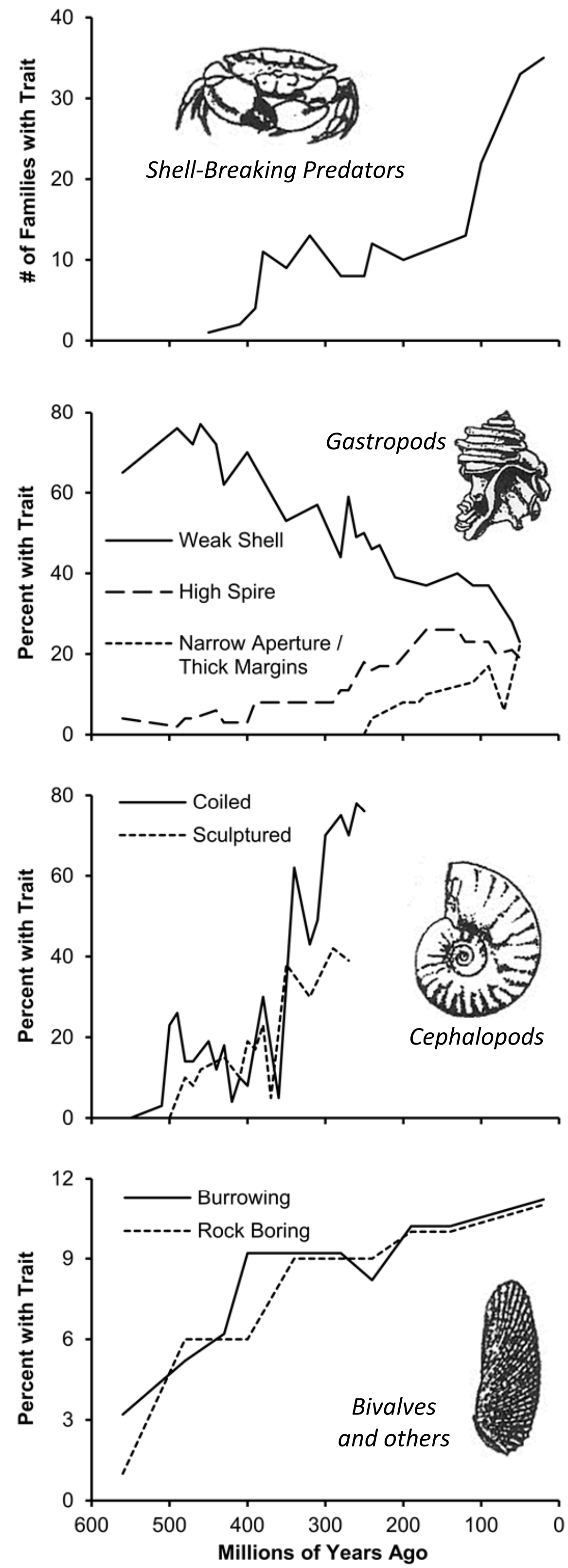
One nice thing about seashells is that they preserve well as fossils. So do the hard claws, jaws, and teeth of shell-breaking predators. Geerat Vermeij (say "ver-MAY") is probably the paleontologist who has done the most careful surveys of fossilized seashells. His renowned studies are especially remarkable because he's been blind since birth. He collected all his data (tons of it) by studying the fossils with his hands!

The graphs to the right show data from Vermeij's research.* All four graphs share the same x-axis at the very bottom: He studied fossils spanning over 500 million years! Analyze the graphs carefully and answer these questions:

The top graph shows the number of fossilized predators that had claws or jaws powerful enough to break seashells. *How long ago did predators first develop shell-breaking traits? Since then, what has happened to the frequency of these traits in the fossil record?*

The next 3 graphs show 3 different groups of soft-bodied, shell-making animals (**molluscs**) common in the fossil record. **Gastropods** are snails that creep on the seafloor, like many we see today. **Cephalopods** are relatives of snails, but many fossil forms were actually swimmers: they could float above the seafloor and swim! **Bivalves** are also related to snails, but have two hinged shells that open and close like a box. Modern bivalves include clams and oysters.

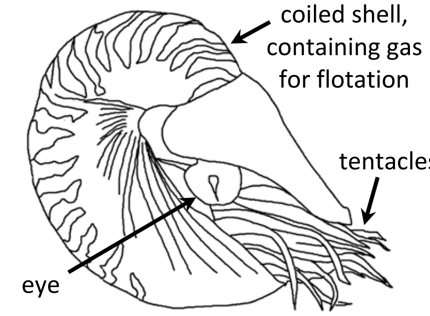
Over the past 500 million years, what gradually happened to the design of gastropod shells?



*Adapted from Vermeij, G. J. (1987). *Evolution and escalation: An ecological history of life.* As reproduced in Endler, J. A. (1991). Interactions between predators and prey. In J.R. Krebs & N. B. Davies (Eds.), *Behavioral Ecology: An Evolutionary Approach* (3rd ed.).

A coiled shell gives a soft animal a bigger space to retreat into. "Sculptured" shells have ribs and ridges that reinforce the shell, or bumps and spines that make it hard to swallow. For cephalopods, what pattern do we see in the fossil record?

(NOTE: On the graph it looks like cephalopods suddenly went extinct 250 million years ago. They didn't. Shelled forms went extinct, but other kinds without hard shells survived. These shell-less cephalopods can swim much faster, as we see in modern day cephalopods like squid. An exception is the chambered nautilus, which still has a coiled shell and sluggish lifestyle.)



Chambered nautilus, a modern cephalopod

Some modern bivalves – like clams – burrow into the seafloor. Others – like oysters – do not. Over the past 500 million years, what trend do we see in such behaviors?

What do you think prompted all these changes in the bodies and behaviors of gastropods, cephalopods, and bivalves over the past 500 million years? Back up your hypothesis with evidence from the 4 graphs.

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