EXTREME ARTHROPODS: EXPLORING EVOLUTIONARY ADAPTATIONS TO POLAR AND TEMPERATE DESERTS

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Abstract: Arthropods in the Namib Desert face some similar stresses to those in Antarctica. Here, students investigate arthropods from both places, creating "toolboxes" necessary for survival in extreme environments.

In this inquiry, Namib and Antarctic arthropods are used to illustrate several important biological principles. Among these are the key ideas that "form follows function" and that the environment drives evolution. In addition, learners will discover that the climate of the Namib Desert and the Antarctic Peninsula are similar in several ways, and that these arthropods have evolved some analogous adaptations. This investigation is a good introduction to the phylum Arthropoda, the most successful group of animals on earth, and spotlights the group's ability to occupy some of the most challenging niches on the planet (National Science Content Standard C; NRC 1996).

On the first day of this lesson, small groups of students design imaginary arthropods able to survive in either Antarctica or Namibia. On the second day, student groups use evolutionary "toolboxes" to pick out appropriate adaptations for actual Namib and Antarctic arthropods, using a menu of authentic names, adaptations and photos. This inquiry involves the students in evolutionary thought and allows them to collaborate on assembling adaptations, using aspects of technological design to overcome specific environmental problems (Content Standards A and E; NRC 1996).

The Central Namib Desert

The Namib Desert, on the west coast of South Africa (roughly 25ºS, 15ºE), receives about 23 mm of rainfall per year (Hachfeld and Jurgens 2000) and contains sand dunes of every known type, including some of the world's largest dunes. Almost all of the moisture available to the organisms that live here is in the form of fog, which comes about 60 nights each year. Wind is also a major part of the dune environment; in addition to moving the fog, wind shapes the dunes and causes plant and animal detritus to collect on the dune slip-faces. Though relatively sparse, this nonliving organic matter is an important part of the dune food web (Cloudsley-Thompson 1990). Finally, temperatures in the Namib can be extremely high, reaching 45°C at the sand's surface.

Tenebrionid Beetles of the Central Namib

Numerous species of beetles in the family Tenebrionidae – a group that includes mealworms— exhibit remarkable adaptations to the conditions of the Central Namib. Namib tenebrionids have the highest body temperatures measured in any ectothermic animal, and come nearer their upper lethal temperature limit than most other ectotherms. To avoid the sand's extremely high temperatures they bury themselves under its surface, emerging periodically each day (Seely et al. 1988). To conserve water, their Malpighian tubules (insect kidneys) produce nearly dry waste in adults, and larvae can actually absorb moisture from the air. Many tenebrionids also secrete a layer of wax that coats the exoskeleton, reflecting some of the sun's radiation and protecting beetles from water loss, abrasion and microorganisms (Chown and Nicolson 2004). Most of these species have extended lifespans of up to six years spent mostly as adults, allowing them time to gather the energy they need to reproduce (M. Seely pers. comm.). These beetles are flightless, having evolved fused wing covers; this may or may not function as an adaptation for water conservation (Duncan 2003), but makes sense for an insect that frequently buries itself in a windswept environment.

A few adaptations of individual tenebrionid species are particularly striking. *Onymacris unguicularis*, the fog basking beetle, stands on its head, collecting droplets of fog on its body that run down grooves into its mouth (Hamilton and Seely 1976). *Onymacris bicolor* has a partially white exoskeleton, reducing the amount of heat it absorbs from visible light. Both these beetles have evolved especially long legs; when they are overheated, they can temporarily elevate their bodies above the dune surface ("stilting"). In specific wind conditions, a few millimeters of elevation can significantly reduce their body temperature (Chown and Nicolson 2004). The flying saucer trench beetle, *Lepidochora discoidalis*, exploits the fog by digging long trenches in the sand perpendicular to advancing fog, from which it drinks condensed water droplets (Seely and Hamilton 1976). It is also able to "listen" to the wind while it is buried beneath the surface, only emerging when it senses that wind speed is high enough to blow the detritus on which it feeds free of the sand (Hanrahan and Kirchner 1997).

The Antarctic Peninsula

The Antarctic Peninsula extends north from continental Antarctica toward the southern tip of South America. The islands associated with the Peninsula have three environmental characteristics in common with the Central Namib Desert: extreme wind, extreme temperature, and extreme aridity. Of course, in contrast to the Namib, the Antarctic Peninsula is cold, not hot: winter temperatures are well below freezing (-20° C and lower) for several months of the year. In many places, however, the Peninsula is very much a desert. Most of the precipitation is either locked up in ice or rapidly drains away because there is no soil to hold it in place. Summer thaws frequently make fresh meltwater available on the Peninsula. In addition, salty ocean water is splashed on organisms near island edges, so organisms living on these islands experience considerable fluctuation in the availability of fresh water (Block 1997; Convey 1997).

Antarctic Arthropods

In this lesson, we focus on two arthropods found on islands surrounding the US research base Palmer Station (64°46'S 64°03'W): the wingless fly *Belgica antarctica,* and a springtail called *Cryptopygus antarcticus*. For the most part, these arthropods are considered to be "pre-adapted" to the conditions in Antarctica—that is, the adaptations they possess were not evolved specifically in response to the Antarctic environment, but rather are commonly found in many closely related species on other continents (Block 1997, Convey 1997).

Like Namib tenebrionids, neither of these Antarctic arthropods have wings. Antarctica is the windiest continent on earth, and the islands around Palmer Station are similarly gusty—an arthropod with wings would be easily blown off these islands into the ocean. In fact, there are no flying arthropods native to Antarctica. Also similar to Namib tenebrionids are the prolonged development times of Antarctic arthropods. Both Antarctic species live for two or more years, giving them time to gather enough energy during the short Antarctic growing seasons (Convey 1997). However, unlike *Onymacris bicolor's* white, sun-reflecting coloration, these Antarctic arthropods are both darkly pigmented, enabling some absorption of heat from sunlight.

Belgica antarctica is the world's southernmost holometabolous (undergoing complete metamorphosis) insect, and is considered Antarctica's largest terrestrial animal (penguins and seals do not remain on land year-round). This wingless midge (Order: Diptera, Family: Chironomidae) is the only Antarctic arthropod known to be freeze-tolerant—able to survive the freezing of its body water. It lives for two years, all but two weeks of which are spent in a series of four worm-like larval stages. In its second summer, it pupates and emerges as an adult, which lives for about 10 days, during which time it mates and lays eggs (Sugg et al. 1983). *Belgica* synthesizes a variety of cryoprotectants ("antifreezes"), including glycerol, fructose, glucose, trehalose and sorbitol, which help it to survive internal freezing (Baust and Lee 1980). During the long winters, *Belgica* larvae are frequently encased in ice, and freezing causes extensive cellular dehydration as ice forms extracellularly (Baust and Lee 1987). They can also lose water quickly to the air, and survive the loss up to 70% of their body water—it is, in fact, likely that *Belgica* dehydrates protectively, using lack of water to survive low temperatures (M. Elnitsky *et al*., unpublished data). The larvae can also survive immersion in meltwater and penguin guano, and tolerate wide swings in salinity, pH, and oxygen availability (Baust and Lee 1987).

Cryptopygus antarcticus is a springtail (Order: Collembola), a "proto-insect" that does not undergo metamorphosis. In other words, it grows in size but does not significantly change its body form throughout its life, which lasts 3-7 years. Unlike the midge, *Cryptopygus* is not able to survive freezing, and is thus considered freeze-susceptible. Rather, like other Antarctic arthropods, it can cool to -20 to -30°C without freezing! These springtails avoid freezing in part because they are very small: if you wanted to make a tiny droplet of pure water into an ice cube, you would have to wait until the water reached -15° C or below. *Cryptopygus* also can lower its freezing point by synthesizing cryoprotectants and clearing its gut of food particles that could act as nuclei for ice crystal formation. Finally, this species has a waxy, hydrophobic cuticle which enables it to float on water and avoid being encased in ice, and promotes the formation of large "rafts" of individuals on the surface of meltwater pools (Cannon and Block 1988).

Extreme Arthropod Lessons

In popular auto racing video games, one can choose special tires, shocks, and engine modifications to suit a particular racing environment. The activities presented here get at the idea that any organism is such an accumulation of modifications, though evolved over thousands or millions of years in response to the environment. While engaging students with the idea of designing the perfectly adapted arthropod, the lesson allows them to discover the extraordinary designs of real arthropods, which survive in varied and extreme conditions. The lessons presented here guide students to think of arthropods as having a "toolbox" of evolutionary adaptations.

First, students are asked to create an arthropod "from scratch," inventing adaptations that will help it survive either Antarctica or the Namib Desert. Second, students are given a real arthropod to construct, which they do by choosing from a menu of adaptations to enable that arthropod to survive.

Materials

Day 1:

1. Art supplies
2. One per student: Student Page 1 (students should also keep this sheet for day 2).

Day 2:

1. Glue, scissors
2. Two per group: Student Page 2, 3.
3. One per group: Student Page 4, 5.

Procedures

Day 1: EXTREME ARTHROPOD FROM SCRATCH

1. Engage students with a video game analogy, if possible; any video game where one chooses modifications to suit one's environment will do. Auto racing games are especially relevant.
2. Explain to students that the Antarctic Peninsula and the Namib Desert present unique challenges to all life forms. Students will focus on the terrestrial arthropods that inhabit these environments.
3. Visually present class with a list of the extreme conditions from Student Page 1. Discuss ways organisms might survive these conditions.
4. Organize students into small groups. Explain that they will design an arthropod that can survive in one of these two environments, and that it must possess at least one adaptation for each of the environment's extreme conditions. Distribute Student Page 1.
5. Groups should creatively **draw and present their arthropod to the class**, explaining how each adaptation addresses each extreme.

Day 2: BUILDING A REAL EXTREME ARTHROPOD

1. Break students into small groups. Distribute two copies per group of Student Pages 2 and 3. Tell students that with millions of years of evolution by natural selection, populations of arthropods in extreme environments have developed a variety of ways to deal with conditions that would kill other organisms—and that this "toolbox" will be available to them

as they design another extreme arthropod, this time trying to come as close to a real-life organism as possible.

2. Distribute one copy per group of Student Page 4. Assign each group one arthropod from the Namib and one from the Antarctic Peninsula—explain that in their groups, they will each be asked to build these two arthropods, using their toolboxes.
3. Instruct students to complete the questions on Student Page 4, and then cut and paste the arthropod description and toolbox adaptations appropriate to each arthropod directly onto Student Page 2.
4. If you like, have them draw on the back what they think their arthropod looks like, then pass out Student Page 5 and ask them to paste their correct photo onto Student Page 2—alternatively, cover the photo captions and ask them to choose the correct photo based on the adaptations they've decided their organism has.
5. Key— arthropod genus matched to adaptation card number.

Arthropod Genus	**Adaptation card #**
Onymacris:	1, 2 or 3, 4, 6, 7, 9, 12, 13, 14
Lepidochora:	3, 5, 6, 7, 9, 12, 13, 14, 15
Belgica:	3, 6, 8, 11, 12, 17
Cryptopygus:	3, 6, 8, 10, 12, 16, 17

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Part I. EXTREME ARTHROPOD FROM SCRATCH

Your job in this activity is to PICK ONE EXTREME ENVIRONMENT, and then BUILD YOUR OWN EXTREME ARTHROPOD. It must:

1. **Be an arthropod, with a hard exoskeleton and jointed legs** **5 pts**
2. **Have at least ONE ADAPTATION to help it survive EACH of your environmental conditions.** **10 pts**
3. **Show effort, creativity and understanding of the environment** **10 pts**

EXTREME ARTHROPOD ENVIRONMENTS
1. THE ANTARCTIC PENINSULA • Extreme cold in the winter, -20°C (-4°F) and below • Extreme temperature variability—summer temperatures up to 7°C (45 °F), with rock and moss surface temperatures of up to 21°C (70 °F) • Very short period each year in which small arthropods are able to gather food, due to low temperatures and frozen conditions • High winds on small islands—it's easy to be blown into the ocean • Extreme dryness—Antarctica's freshwater is almost all frozen! Ice also tends to "steal moisture" from small arthropods • Exposure to acidity and lack of oxygen, due to immersion in penguin guano (waste) during summer breeding season • Possible immersion in both salt and freshwater due to snowmelt and waves/tides in the summer **2. THE DUNES OF THE NAMIB DESERT, AFRICA** • Extreme heat on sand surface during the daytime • Very little food, mostly detritus (dead plants and animals) blown into piles on the dunes by the wind • High winds that blow small animals off dunes and cause water loss from animals • Extreme dryness—the Namib is the driest temperate desert. FOG that occurs an average of 60 days each year is its only reliable water supply • Sand—the sand of the dunes is easily heated by the sun and blown by the wind, but also provides shelter for animals that can get below its surface

Part II. BUILD A REAL EXTREME ARTHROPOD

<table>
<tr><td colspan="3">Paste Extreme Arthropod description here.</td></tr>
<tr><td>Paste adaptations in these squares (up to 9 for each arthropod)—use “Extreme Arthropod Environment” sheet and the description you pasted above as clues.</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td>Paste extreme arthropod PHOTO here, when your instructor gives it to you.</td><td></td></tr>
</table>

EXTREME ARTHROPOD TOOLBOX			
ADAPTATION 1 **Long legs**—"stilting" behavior which raises body safely above surfaces that are too hot **(CANNOT BE PAIRED WITH TRENCH-DIGGING)** **__Ant. __Nam. __Both**	**ADAPTATION 2** **White coloration** **(CANNOT BE PAIRED WITH DARK COLORATION)** **(CANNOT BE PAIRED WITH TRENCH-DIGGING)** **__Ant. __Nam. __Both**	**ADAPTATION 3** **Dark coloration** **(CANNOT BE PAIRED WITH WHITE COLORATION)** **__Ant. __Nam. __Both**	**ADAPTATION 4** **"Fog basking" —** "headstand" to condense fog droplets on their bodies, which run down grooves to their mouths **(CANNOT BE PAIRED WITH TRENCH-DIGGING)** **__Ant. __Nam. __Both**
ADAPTATION 5 **"Trench-digging"** behavior—able to dig long trenches in the sand which collect condensed fog—then drink water from trench **(CANNOT BE PAIRED WITH FOG-BASKING)** **__Ant. __Nam. __Both**	**ADAPTATION 6** **Wingless—**wings either absent or fused together **__Ant. __Nam. __Both**	**ADAPTATION 7** **Wax "blooms"** that cover exoskeleton, sealing it tightly, preventing water loss and **reflecting sunlight** to keep cool **__Ant. __Nam. __Both**	**ADAPTATION 8** **Cryoprotectants** like glycerol and sorbitol, which protect animals when temperatures become dangerously low **__Ant. __Nam. __Both**
ADAPTATION 9 **Abiltiy to survive high body temperatures** of up to 49°C (120°F) **(AN ARTHROPOD CAN HAVE ONLY ONE OF ADAPTATIONS 10-13)** **__Ant. __Nam. __Both**	**ADAPTATION 10** **Ability to supercool** to as much as -20°C (-4°F) without freezing **(AN ARTHROPOD CAN HAVE ONLY ONE OF ADAPTATIONS 10-13)** **__Ant. __Nam. __Both**	**ADAPTATION 11** **Freeze-tolerance:** ability to freeze without damage **(AN ARTHROPOD CAN HAVE ONLY ONE OF ADAPTATIONS 10-13)** **__Ant. __Nam. __Both**	**ADAPTATION 12** **Long lifespan** (2-5 years)—allows more time to gather scarce nutrients, storing enough energy to mature and reproduce **__Ant. __Nam. __Both**
ADAPTATION 13 **Ability to burrow into sand** **__Ant. __Nam. __Both**	**ADAPTATION 14** **Specialized kidney-like organs** which get rid of waste with almost no water loss, and can even reabsorb water from the air! **NAMIB DESERT ONLY**	**ADAPTATION 15** **Sensitivity to wind speed—**able to "hear" when wind is strong enough to blow food particles from under sand **(REQUIRES TRENCH-DIGGING ADAPTATION)** **__Ant. __Nam. __Both**	**ADAPTATION 16** **Hydrophobic exoskeleton—**float on water surface to avoid being encased in ice, also clump together in large "rafts" **(ONLY ONE ARTHROPOD HAS THIS)** **__Ant. __Nam. __Both**

EXTREME ARTHROPOD DESCRIPTIONS

Genus *Lepidochora*—Namib Desert flying-saucer **beetle**

These members of the family *Tenebrionidae* live on dunes in the Namib Desert.

Genus *Onymacris*—Namib Desert fog-basking **beetle**

These members of the family *Tenebrionidae* live on dunes in the Namib Desert.

Genus *Cryptopygus*—Antarctic Peninsula **springtail**

These insect-like hexapods must survive cold Antarctic winters. In summer, they are often found floating in clumps in pools of melted icewater.

Genus *Belgica*--Antarctic Peninsula **midge**

Belgica are **larvae** for most of their lives, gathering food and energy for the TEN DAYS they'll have as adults, when they need to mate. Larvae must survive Antarctic winters and are frequently encased in ice, and may freeze. During summer they live in mud, algae, and sometimes penguin guano—which can expose them to acidic and low-oxygen conditions.

EXTREME ARTHROPOD QUESTIONS

1. What conditions do the Antarctic Peninsula and Namib Desert share?

2. What adaptations do Antarctic and Namib arthropods have in common?

3. What are major differences in adaptations to the two environments?

4. What advantage would each of the following adaptations give an insect; White coloration? Dark coloration? Winglessness? Burrowing in sand?

EXTREME ARTHROPOD PHOTOS

Belgica antarctica larvae

Belgica antarctica adult

Cryptopygus antarcticus

(photo to be added later)

Onymacris bicolor

Onymacris unguicularis (Courtesy Gobabeb Training and Research Centre)

Lepidochora discoidalis (Courtesy Dr. Ek del Val de Gortari)