Can you Engineer an Insect Exoskeleton?

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Grade level targeted: 4th Grade, but can be easily adapted for later grades

Big ideas: Insect exoskeleton, engineering, and biomimicry
Main objective: Students will be able to design a functional model of an insect exoskeleton which meets specific physical requirements based on exoskeleton biomechanics

Lesson Summary

We humans have skin and bones to protect us and to help us stand upright. Insects don't have bones or skin but they are protected from germs, physical harm, and can hold their body up on their six legs. This is all because of their hard outer shell, also known as their exoskeleton. This hard layer does more than just protect insects from being squished, and students will get to explore some of the many ways the exoskeleton protects insects by building one themselves! For this fourth grade lesson, students will work together in teams to use what they learn about exoskeleton biomechanics to design and build a protective casing. To complete the engineering design cycle, students can use what they learn from testing their case to redesign and re-build their prototype.

Prerequisites

No prior knowledge is required for this lesson. Students should be introduced to the general form of an insect to facilitate identification of the exoskeleton. Live insects would work best for this, but pictures and diagrams will work as well.

Instruction Time

45 – 60 minutes

Next Generation Science Standards (NGSS) Framework Alignment

Disciplinary Core Ideas

LS1.A: Structure and Function

- Plants and animals have both internal and external structures that serve various functions in growth, survival, behavior, and reproduction. (4-LS1-a),(4-LS1-b)
- 4-LS1-a. Use simple models to describe that plants and animals have major internal and external structures, including organs, that support survival, growth, behavior, and reproduction.
- 4-LS1-b. Design, test, and compare solutions that replace or enhance the function of an external animal structure necessary for survival.*

ETS1.A: Defining Engineering Problems

- Possible solutions to a problem are limited by available materials and resources (constraints). The success of a designed solution is determined by considering the desired features of a solution (criteria). Different proposals for solutions can be compared on the basis of how well each one meets the specified criteria for success or how well each takes the constraints into account. (4-PS3-e)

ETS1.B: Designing Solutions to Engineering Problems

- Research on a problem should be carried out—for example, through Internet searches, market research, or field observations—before beginning to design a solution. An often productive way to generate ideas is for people to work together to brainstorm, test, and refine possible solutions. (4-ESS3-b)
- Testing a solution involves investigating how well it performs under a range of likely conditions. (4-ESS2-b),(4-ESS3-b)
- Tests are often designed to identify failure points or difficulties, which suggest the elements of the design that need to be improved. At whatever stage, communicating with peers about proposed solutions is an important part of the design process

ETS1.C: Optimizing the Design Solution

- Different solutions need to be tested in order to determine which of them best solves the problem given the criteria and the constraints. (4-LS1-b)

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a Practice, Disciplinary Core Idea, or Crosscutting Concept.

Science and Engineering practices

Developing and Using Models

- Develop a model using an analogy, example, or abstract representation to describe a scientific principle or design solution. (4-LS1-c)
  Identify limitations of models. (4-LS1-c)

Constructing Explanations and Designing Solutions

- Use evidence (eg. measurements, observations, patterns) to construct a scientific explanation or design a solution to a problem (4-LS1-b)
  apply scientific knowledge to solve design problems (4-LS1-b)

LS4.C Adaptation

- Particular organisms can only survive in particular environments; Changes in an organism's environment are sometimes beneficial and sometimes harmful.

Crosscutting Concepts

Structure and Function

- Substructures have shapes and parts that serve functions. (4-LS1-a),(4-LS1-b),(4-LS1-c)

Interdependence of Science, Engineering, and Technology

- Knowledge of relevant scientific concepts and research findings is important in engineering. (4-PS4-d)

Entomology Literacy Elements

Element 2: Develop ability to use insects in inquiries and provide examples of insects' investigative value

- Insects are valuable research organisms
- Insects are useful for demonstrating/learning the scientific method via inquiry based activities

National Science Standards

- ✓ Characteristics of organisms
- ✓ Structure and function in living systems (5-8th grade Science Standard, allows for adaptation for use in higher grade levels)
- ✓ Abilities necessary to do scientific inquiry
- ✓ Understandings about scientific inquiry

Materials Needed

Paper Resources
- Printed exoskeleton chart - Images from: Boevé, J. L., Ducarme, V., Mertens, T., Bouillard, P., & Angeli, S. (2004). Surface structure, model and mechanism of an insect integument adapted to be damaged easily. Journal of nanobiotechnology, 2(1), 10.

Technology & Multimedia Resources
This lesson does not require any technology, but there are some supplemental pictures and videos to assist with lesson design.

Physical Resources
Note: most of these resources were found at the I.D.E.A. store in Urbana, Illinois. For items like toilet paper rolls and Styrofoam it is recommended to solicit recycling centers, big chain stores (e.g. for cardboard and packing materials), or parents. Overall cost will depend on access to resources, but many of our items were purchased for little to no real cost.

One more recommendation is a recycling challenge – have the students bring in a week's worth of *clean* recycling as additional building materials to supplement what you can find.

Examples of inexpensive building materials:

- Cardboard
- Saran wrap
- Paper clips
- Yarn
- Glue
- Plastic "packing" foam
- Aluminum foil
- Plastic bags
- Rubber bands
- Duct tape
- Scissors
- Wax paper
- Toilet paper tubes
- Binder clips
- Clear tape
- Styrofoam

** (assorted packing material in general is recommended for many of the challenges)

Supplies should be divided into challenge-specific bags before the lesson. There are three total challenges, so the class should be divided so that all challenges are covered by at least one group. One bag should be made for each group, plus extra supplies as needed.

Example building materials by challenge:

- Group Challenge 1 – Hardness – Will it get squished under a big heavy book?
  - Egg carton, hard foam, strawberry containers, twist ties/pipe cleaners, rubber bands, tape, bubble wrap
- Group Challenge 2 - Lightweight and strong – Can it fall without breaking?
  - Bubble wrap, foam, tissue paper, tape, rubber bands, non-slip material (pre-cut)
- Group Challenge 3 - Waterproof - Don't let the filter paper get wet!
  - Pre-cut wax paper, saran wrap, tape, rubber bands, aluminum foil

Required supplies for testing designs and estimated costs (Overall - $20):

- Spray bottle, 1 ($3)
- Dixie cup, 1/group
- Home-made clay or play dough, 1 quarter-size ball
- Filter paper, 3-4 ($7/pack)
- Styrofoam ball, 1 for each Challenge 2 and Challenge 3 group ($5/pack)
- Plastic pearl beads or other small beads, enough to cover the Styrofoam balls for Challenge 2 ($3/pack)
- Glue (to adhere beads to the Styrofoam ball, Elmer's glue is sufficient) ($2/bottle)
- Textbooks, 2 for each Challenge 1 group

Optional supplies:

- Plywood to illustrate the laminar (layered) nature of parts of the insect cuticle

Teacher preparation for the lesson:

Make testing supplies

- Challenge 1
  - Either make your own clay out of flour, water, and salt or use pre-made clay.
    - 2 1/2 cups flour + 1 cup flour + 1 cup water (add slowly until is desired consistency)
    - Other clay recipes can be found online
    - For example, see: http://chemistry.about.com/od/chemistryactivities/a/modeling_clay_recipes.htm
  - Make one ball per Challenge 1 group, about the size of a small lime. Keep clay soft by keeping it in a ziplock bag while not in use.
- Challenge 2
  - Use a Styrofoam ball found at any arts and crafts store and glue beads over the surface. Beads do not have to coat the entire ball, but there must be enough that when dropped from 3 feet without protection more than 1-2 beads fall off.
  - Using Elmer's school glue worked well for us.
- Challenge 3
  - Using tape to secure wrap a Styrofoam ball with filter paper, or any other paper that will change colors when it comes into contact with water.

Make supply bags

- Supplies should be divided into challenge-specific bags before the lesson. There are three total challenges, so the class should be divided so that all challenges are covered by at least one group. One bag should be made for each group, plus extra supplies as needed. Example supplies are given below under each challenge description.

Lesson

Students will work in groups for the activity and discussions. Sort into at least 3 groups (or a number divisible by 3) before you begin the lesson

Observations

1) **Introduction**

- Tell the students that animals protect themselves in many different ways, such as running away from danger, growling (bearing their teeth), or even fighting if they have to. Animals also have structures on their bodies that help protect them every day. For example, trees have hard bark to protect them from rain, hail, snow, and clumsy animals that might run into them.
- Ask the students to talk to their group about what parts of the human body help to protect us against the weather, germs, and even falling down.
  - Answers should include skin, bones, eyelids, and human-made items such as helmets, clothes, shoes, etc.

- Insects have structures that help protect them as well. Ask the students if anyone knows what one of these structures is (answer: **exoskeleton**) and how it might help the insect (many answers: hard, light, protects from drying out, etc. See rest of lesson for all possible answers.)
- Exoskeleton means that insects have their skeleton on the outside. So unlike us, insects don't have a backbone. Instead, they have a hard covering, kind of like a hard shell, called an exoskeleton. The exoskeleton helps insects in many different ways which we'll talk about today. We will also design and build a protective case that is inspired by the exoskeleton!

2) **What superpowers would you gain by having your skeleton on the outside?**

- Ask the students to put their thumb up if they think insects have organs like a heart, lungs, and a stomach and their thumbs down if they think insects don't have any organs on the inside of their body.
- Insects do have important organs like a heart and lungs that are soft and squishy and need to be protected.
- What protects these organs? The exoskeleton!
- What do we humans use to protect our organs? Answer: a rib cage (bones), muscles, and skin.
- The exoskeleton means that insects can fall from a greater distance and they can run into each other without getting hurt. Engineers can use this as an inspiration to design a protective shell for humans or animals so we can protect ourselves as well as insects can.
- Have the students come up with 3 examples of protective hard coverings that engineers have designed to protect our bodies.
    - Answers can include armor, shoes, helmets, knee or elbow pads, etc.

3) **Properties of insect exoskeleton.**

- The exoskeleton isn't just a hard layer, though – so besides protection **what does the exoskeleton do for the insect?**
    - **Needs to be hard.** One of the first things that comes to my mind is that the exoskeleton is hard so that insects don't get squished. (You can also mention here or later that it needs to be hard so that muscles can attach to it. There are some pretty strong insects out there!)
    - **Waterproofing.** Another thing that you might not think about, is that water is really important for insects. This exoskeleton also needs to make sure it holds the water in so that the insect doesn't dry out. What happens to a piece of bread if you leave it outside of the bag overnight?
    - **Lightweight.** If you imagine a knight with his hard, heavy armor, it's really difficult to move around. What would happen if this knight fell down? It would be pretty difficult to get back up, right? Insects don't want this exoskeleton to be too heavy or they wouldn't be able to move around quickly. They also need to be light enough to fly.
    - **Thinner and more elastic at joints.** Like our skin, the insect exoskeleton completely covers the insect. In order to move around, and fly!, there needs to be

areas of the exoskeleton that are thinner so that it can bend at those joints, much like joints in a knight's armor.

- **Avoiding fatigue.** Paper clips and plastic bread bag clip/tag are a good way to illustrate **material fatigue**, but should be handled by the teacher only to avoid injuries. With each bend, small cracks are formed in the material and eventually the whole item will bend. All materials have different fatigue measures, and insect exoskeleton needs to be able to be bent a large number of times and not break.
  - Demonstrate the fatigue of a paperclip and a bread tag

There are many other important things that the exoskeleton can do, especially in specialized insects, but for now we're going to focus on the five above.

Extension: Show videos of insects in nature and how their exoskeleton protects them

- *Resources*
  - *Stag beetles fighting: http://www.youtube.com/watch?v=r34FSI2HKPY*

Question: Using the materials you are given can you design a model of the insect exoskeleton that stands up to your group challenge?

4) **Experiment overview**:

- Students will design their own protective casing using what they know about the insect exoskeleton - can students rise to the challenge? If possible students should sketch their design and have it checked by the instructor.
- Students will build their design using materials provided. Each group should get a bag of supplies and access to some extra materials if needed (up to the discretion of the teacher).
- Test designs as a class. It is important for students to see all aspects of the exoskeleton tested since they will not be doing each challenge themselves.

Hints to form a hypothesis:

- Before starting, how many layers will you need for your design?
- Why is it important to draw or plan things before building?
- In your design, why might it be important to consider the amount of supplies that you are using? (What is it that we as humans need to grow healthy nails and skin and be big and strong? Food, vitamins, etc… Building an exoskeleton can be costly.)

Experiment start:

- As a class, read through all challenges. Groups may be assigned a challenge by placing one labeled bag next to each group. As the challenges are read the teacher or a group member must write down the main points of each challenge on a whiteboard/piece of paper and leave it with the appropriate group(s) for reference

Group Challenge 1: Hardness

Example materials provided: Egg carton, hard foam, strawberry containers, twist ties/pipe cleaners, rubber bands, tape

- Insects have delicate organs, such as a brain and heart-like organs that need to be protected. The exoskeleton is made up of many layers of tough materials and this makes their shell incredibly hard. This is what prevents the insects from being easily squished. Like a knight's armor the protective layer can help defend insects in battle as well. Using their hard shell to shield their delicate organs in a fight can mean they end up with the best places to live and the best food!
- Use a piece of composite wood (plywood) to demonstrate that when layers are oriented in different directions it makes the material even stronger than the layers on their own, or even if they were oriented in the same direction.
- Students will use this information as inspiration for a design of their own. Tell the Challenge 1 group: "Your group will get a soft ball of clay - this is what you must protect. Your ball cannot be squished when two textbooks are stacked on top of it."
- **After testing their design:** A hard shell protects insects from being squished and also gives them something for their muscles to be attached to. The part of the exoskeleton where muscles are attached is thicker than other parts of the exoskeleton.

Group Challenge 2: Lightweight and strong

Example materials provided: bubble wrap, foam, tape, rubber bands, non-slip material (pre-cut), extra supplies can be included depending on availability of items

- Many insects fly, even if they aren't very good at it. They must be light enough to lift themselves off of the ground and they must have a strong enough exoskeleton so they won't get hurt if they fall to the ground. The exoskeleton covers the entire insect, even the legs, antennae, wings, and their eyes! It must be strong enough to keep their delicate legs and antenna from being damaged if they bump into something or fall to the ground. Knights also had to cover and protect every part of their body. Was it easy for them to walk around? Do you think they could jump up in the air or run very fast? No! This armor is bulky, heavy, and is hard to move around in. Just think, even though the exoskeleton protects the entire body of the insect it is still light enough for them to fly!
- Demonstrate how easily the beads can fall off of a Styrofoam ball when dropped from only chest high (approximately 3 feet). Insects have much bigger appendages (if this word is new, use legs, antennae, etc. instead) that must be protected!
- Tell the Challenge 2 group: "Your group will be given a ball with beads glued on the outside. Your challenge is to build a case that will cushion the ball as it is dropped from chest high, or about 3 feet. You have passed the challenge if only 1-2 beads fall off."
- Remind the group to be gentle while building and assembling their case. They need to be able to get it on and off without removing any beads or their test will not work.
- **After testing their design:** What is the least amount of items that we could use for this challenge? Insects need to frugal/thrifty in the amount of energy they use to make their exoskeleton. If we want to get muscular we need to eat lots of food, lots of proteins. If insects want to make more exoskeleton they need to eat a lot more, and there isn't always an easy meal to find!

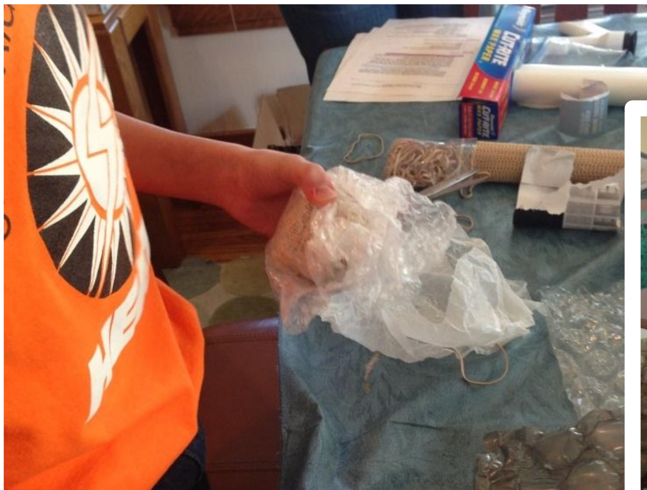
Group Challenge 3: Waterproof - Don't let the filter paper get wet!
Example materials provided: pre-cut wax paper, saran wrap, tape, rubber bands, extra supplies may be necessary

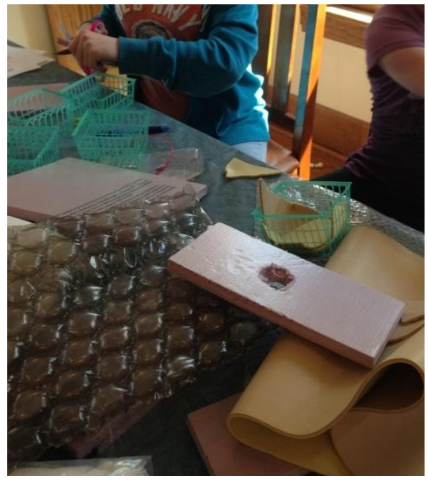
- Most insects live outside and are not well hidden from rain and water puddles. All insects must drink water to survive. How do they keep good water in and unwanted water out? Think about what happens when water is spilled on your clothes or onto the dirt. What happens? It goes right through! What happens to a puddle of water that is sitting out in the sun? It dries up/evaporates. Insects must find a way to keep unwanted water out and to keep the water they drink inside of their bodies. Tell the students to talk with their groups and list 3 materials that water cannot go through. These are materials that you could make into a drinking glass.
    - Example answers: Glass, plastic, wax paper, metal, styrofoam
    - If students cannot guess wax on their own, remind them about coffee cups and drinking cups. Pass around a Dixie cup and ask them what this is made of. It is made of paper, which will get soggy if it gets water on it, but it is coated with a layer of wax. This wax is what keeps the water in the glass.
- Insects also use a layer of wax to keep the water inside their bodies and from getting their exoskeleton wet.
- Tell the Challenge 3 group: "Your group will be given a piece of filter paper wrapped around a Styrofoam ball. The filter paper will turn a darker color when water hits it, so you will be able to see if a drop of water gets through. Your challenge will be to keep the filter dry when your design is sprayed with water for 30 seconds."
- Be sure to pat off the casing before removing the ball so no water gets on the paper after the testing is complete.
- **After testing their design:** What would happen if the insect or model was scratched and then we put it under water? In insects there is a layer called the cement layer that protects the wax layer from getting scratched!

Extension: Work together to combine all aspects of your models. What can't we do with our materials?

<u>Results</u>

In some cases, students will need to redesign their model if it fails to meet the challenge. Explain that this is a process that many scientists, including engineers, must go through. Pictures of the design process and items provided can be seen on the following page.





5) **<u>Discussion</u>**

After testing each of the challenges as a group, discuss the layers of the insect and how their models meet each of the properties of the exoskeleton. (10 min)

- Using the diagram of the exoskeleton (page 13) point out to students that the exoskeleton can protect the insect from falling down, being squished, and from drying out because it is so complex and has many different layers. Each layer has a different set of properties, some are really hard, some are thick, some are flexible, and some are waxy. Each of these layers functions in a different way for the insect, and not all insects - or places on the same insect - have the same number or types of layers.
    - You don't need to cover the specific names of each of the layers, focus mainly on their properties.
    - Assess understanding by asking the students:
        - If you wanted to make a container that was really hard, which layer of the exoskeleton could you use as inspiration for your design?
        - Which layer did you use to make your design waterproof?
        - Which layer did you use to make your design flexible and strong?

- Show the students pictures of real insect exoskeleton, taken by scientists. Point out the different layers in these pictures.
    - The paper below has SEM images (scanning electron microscopy) of the insect exoskeleton and cross sections as well. These cross sections are similar to slicing an orange, where you would see the top orange layer, a bigger white layer, and then the juicy inside of the orange.

- Boevé, J. L., Ducarme, V., Mertens, T., Bouillard, P., & Angeli, S. (2004). Surface structure, model and mechanism of an insect integument adapted to be damaged easily. Journal of nanobiotechnology, 2(1), 10. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC524519/

- If possible, use live insects to demonstrate what the exoskeleton feels like and point out the different areas of the insect where it might be different (i.e. the wings). If students get to hold lubbers or other winged insects point out how the exoskeleton must be flexible enough to protect the insect *and* allow the wings to flap over and over while they are flying (it must be elastic and avoid fatigue).
- If time, point out that the exoskeleton also covers the compound eyes! It is clear and thin so they can see and it protects their eyes. A good demonstration of this is the old exoskeletons of cicadas. At the end of the summer their "skins" can be seen on trees, sides of houses, and many other vertical surfaces. Just gently pull them off and you can see their entire body was covered with exoskeleton, even the insides of their guts!

- Discuss **lamellar** design of insect exoskeleton
  - One way to show this is to bring in a small piece of plywood with its layers of wood where the grain of the wood goes in opposite directions so that it is super strong.
  - This is exactly what insects do to make their exoskeleton so strong! Each layer is facing a different direction and together these layers make a very strong exoskeleton. Insects are hard enough to not get squished and are still light enough to lift themselves off the ground and fly around by layering materials on top of each other in different orientations.

Extension: Talk about how the epidermis layer is made of living cells while the rest of the exoskeleton is not living. This is very similar to nails and hair which aren't living except at the base - this produces the thick strands of hair and strong nails that are not living but are still held to our bodies and serve important functions.

Estimated instruction time and cost: The lesson should take minimally between 45 – 60 minutes, but more time will be needed if students redesign their models. Most of the supplies can be obtained from household items and encouraging students to bring in recycling or packaging material. Instructors should expect to spend between $20-30 for items that cannot be found at home (see materials needed section).

Further Extension and Resources

1. Let kids hold and feel insects with different types of exoskeletons
   a. Examples:
      i. Thick cuticle and thin wax layer of the Madagascar Hissing Cockroach, who lives in the rainforest
      ii. Thin cuticle of the very hungry caterpillar, who must grow many times their original size before becoming a butterfly or moth
      iii. Thick wax layer of the desert-dwelling death feigning beetle
2. How do insects get larger when they have their skeleton on the outside?
   a. Answer: Through **molting** (shedding their exoskeleton).
   b. Resources
      i. Structure and function of the insect cuticle: http://www.youtube.com/watch?v=fZkNlvKdK3g
      ii. Molting http://www.youtube.com/watch?v=QfeEZl0VGs0
      iii. Insect Exoskeleton: structure and molting http://www.youtube.com/watch?v=6z_lJoYbdAc
3. Exoskeleton-inspired bioinspiration
   a. Resources
      i. Self-cleaning paint inspired by the lotus leaf surface, and collembolan cuticle :
         http://www.paintpro.net/Articles/PP705/PP705_ProductProfiles.cfm
         http://blogs.discovermagazine.com/notrocketscience/2011/10/02/incredible-skin-helps-springtails-to-keep-dry-underwater-and-always-stay-clean/
      ii. Dew-collection water bottle inspired by the Namib beetle cuticle: http://www.asknature.org/product/313a2fdcdc072fbfc7ae7e69962eab80
      iii. Iridescent color due to nanostructures on the wings of Morpho butterflies inspired the development of more advanced electronic display screens. http://ge.geglobalresearch.com/blog/nanostructures-of-morpho-butterfly-wing-scales-demonstrate-high-resolution-of-temperature-changes-at-high-speed/
      iv. The social interactions of honeybees and wasps inspired more optimal computer server communication http://en.wikipedia.org/wiki/Bees_algorithm

Acknowledgements

We would like to thank our Insect Physiology instructor Marianne Alleyne as the inspiration behind this lesson as the initial idea was largely influenced by an activity that we did in our graduate level course.

Please contact Catherine Dana (cdana2@illinois.edu) or Christina Silliman (chansium@gmail.com) with any questions related to this lesson.

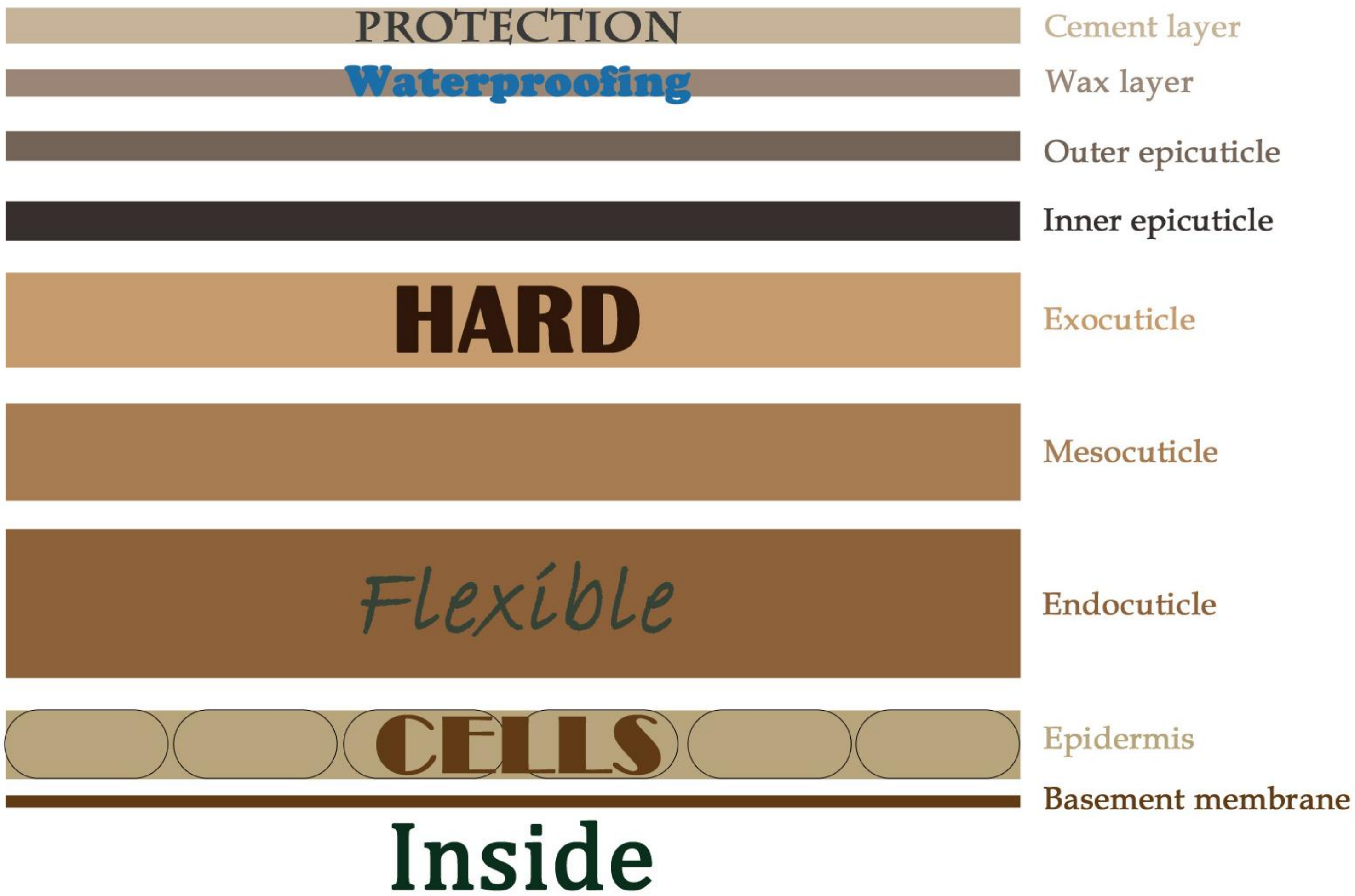


Diagram of the insect exoskeleton for use in lesson.