

## How Eyes Evolved – Analyzing the Evidence

Human eyes are complex structures with multiple parts that work together so we can see the world around us. Octopus eyes are similar to human eyes. Both types of eyes have:

- a similar overall shape and structure
- a lens which focuses light to form an image on the retina
- a retina with many photoreceptor cells that contain light-sensitive molecules.

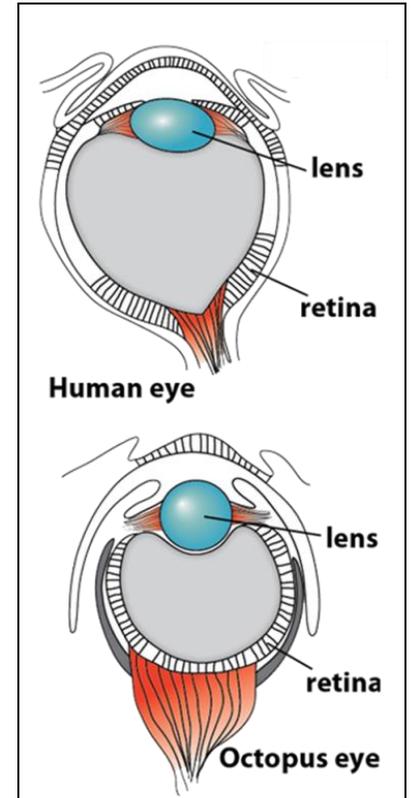
The photoreceptor cells respond to light and send signals to nerve cells. The nerve cells carry visual information from the eye to the brain.

1. In these drawings of the human eye and the octopus eye:

- Use an arrow to show the path of light into the eye through to the retina.
- Label the photoreceptor cells.
- For the human eye, label the nerve that carries visual information from the eye to the brain.
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The main questions we will investigate in this activity are:

- How could something as complex as the human eye or the octopus eye have evolved by natural selection?
- How can scientists learn about the evolution of eyes, given that there is very little fossil evidence?



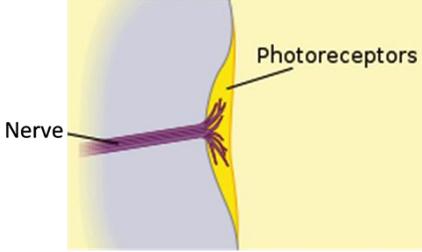
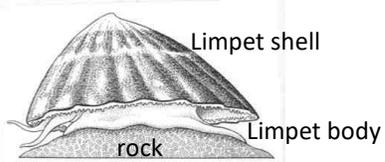
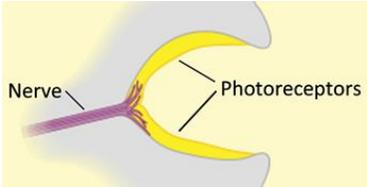
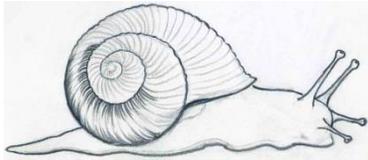
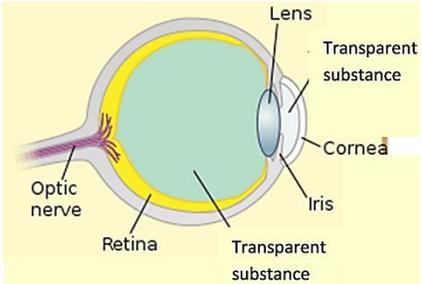
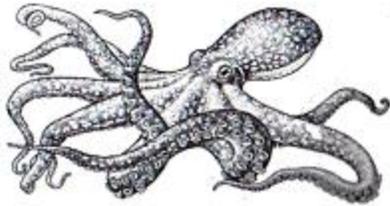
### Evidence from Comparative Anatomy

Scientists believe that, in the very early evolution of animals, the precursor of modern eyes had a single photoreceptor cell. How could a single photoreceptor cell have evolved into a complex eye like the eye in a human or octopus?

To begin to answer this question, scientists have studied the anatomy and function of different types of eyes in a variety of contemporary animals. None of these contemporary animals was an evolutionary ancestor of humans or octopuses. However, the different types of simpler eyes in some contemporary animals can suggest a possible sequence of intermediate steps that may have occurred during the evolution of the human eye or octopus eye.

This evidence also indicates how each intermediate step in the evolution of a complex eye could have been useful and contributed to increased fitness (the ability to survive and reproduce).

Each type of light-sensitive organ can be useful for the animals that have it. For example, eye spots which detect light vs. dark are useful for limpets that are active at night and not active during the day. When the limpet's eye spots detect light, the limpet clamps its conical shell down on the rock to avoid predation and drying out during the day.

| Light-Sensitive Sensory Organs in Several Types of Contemporary Animals   |  |  |
|---|--|--|
| <p><u>Eye spot</u><br/>(e.g. in a limpet that scrapes algae off of rocks and glides or creeps along, similar to a snail)</p>                                    |  <p>Photoreceptors<br/>Nerve</p>   |  <p>Limpet shell<br/>Limpet body<br/>rock</p> |
| <p><u>Eye cup</u><br/>(e.g. in a snail that feeds on sponges and moves by gliding or creeping along)</p>  |  <p>Nerve<br/>Photoreceptors</p>  |   |
| <p><u>Complex eye</u><br/>(e.g. in an octopus, an active predator that relies on vision to hunt prey; it moves by swimming or using its arms for crawling.)</p> |  <p>Lens<br/>Transparent substance<br/>Cornea<br/>Iris<br/>Retina<br/>Optic nerve<br/>Transparent substance</p> |   |

**2a.** One advantage of an eye cup is that the shape of the eye cup allows an animal to detect which direction light is coming from, since the photoreceptor cells on each side of the eye cup are only stimulated by light coming from the opposite side. In contrast, all of the photoreceptor cells in an eye spot are stimulated by light coming from any direction, so an animal with an eye spot cannot detect which direction light is coming from.

To demonstrate this difference between an eye spot and an eye cup, use arrows to show which photoreceptor cells are stimulated by light coming from the left and light coming from the right in the figures below. (Remember that light travels in a straight line).



Eye Spot

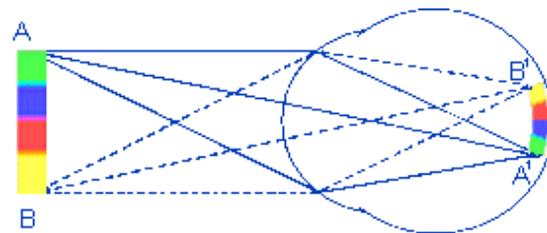


Eye Cup

**2b.** Suggest one way that a snail with eye cups could benefit from being able to detect which direction light is coming from.

This figure shows how a lens that bends light can focus the light from each point in the environment on a specific part of the retina. Thus, the lens in a human eye or octopus eye produces a clear, sharp image on the retina.

Thus, in a complex eye, each photoreceptor cell in the retina receives light input from a different point in the environment. The resulting pattern of activity in the photoreceptor cells provides detailed visual information to the brain.



Incoming light rays from each point on the object are bent by the cornea and lens so that (in normal vision) they come together at a single point on the retina. Note, however, the image is inverted. The brain ultimately interprets the image as rightside-up.

**3.** Explain why eyes with a lens and the ability to form images would be more useful for an octopus than for a limpet. (Hint: See the information about feeding habits on the top of page 2.)

**4.** Summarize your understanding of different types of eyes by matching each item in the top list with the best matches from the bottom list. Write your answers on the lines provided.

Eye spots \_\_\_\_\_ Eye cups \_\_\_\_\_ Complex eyes \_\_\_\_\_

- All the photoreceptor cells receive light input from all directions.
- Each photoreceptor cell receives light input from a different point in the environment.
- Photoreceptor cells on each side only receive light input from the opposite side.
- can detect which direction light is coming from
- can form images
- can only detect light versus dark

**5a.** An eye cup provides more detailed visual information than an eye spot. What is the additional visual information provided by an eye cup and not an eye spot?

\_\_\_\_\_ images      \_\_\_\_\_ light vs. dark      \_\_\_\_\_ which direction light is coming from

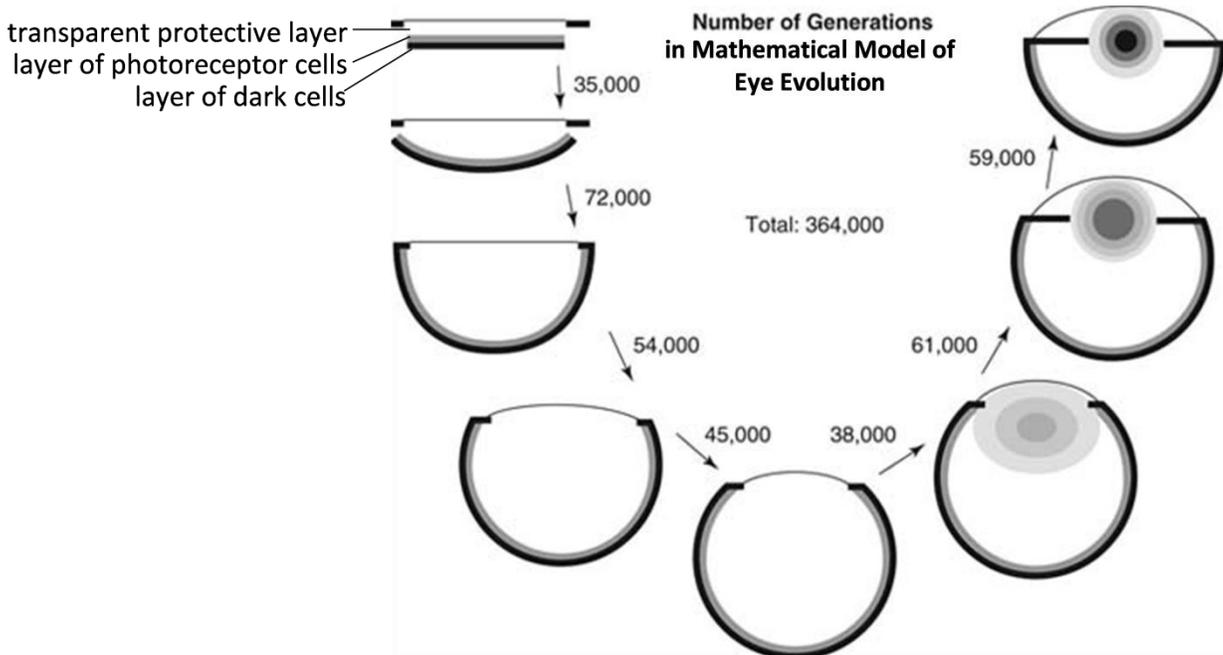
**5b.** Which type of eye sends the most detailed visual information to the brain?

\_\_\_\_\_ complex eye      \_\_\_\_\_ eye cup      \_\_\_\_\_ eye spot

### A Mathematical Model

Our next question is whether natural selection could have resulted in gradual evolution from simple eye spots to eye cups to complex eyes with a lens. To answer this question, scientists developed a mathematical model to mimic natural selection. At each step in this mathematical model, selection favored any small change in the model eye that resulted in an improved ability to provide more detailed visual information.

This mathematical model began with a flat three-layer structure (shown in the upper left of this figure).



In the early generations in this mathematical model, selection for improved ability to provide more detailed visual information resulted in increasing curvature of the layer of photoreceptor cells (shown on the left side of the figure).

6. This mathematical model began with a model eye that resembles an \_\_\_\_\_.  
(eye cup/eye spot)

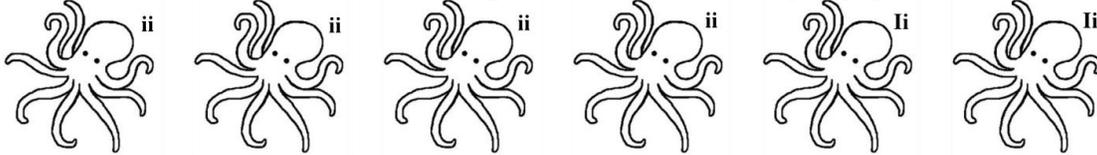
The first 107,000 generations of selection produced a model eye that resembles an \_\_\_\_\_.  
(eye cup/eye spot)

Continued selection for improved ability to provide more detailed visual information resulted in increasing concentrations of transparent proteins in the opening where light enters the eye (shown on the right side of the figure). These proteins bend light as it enters the eye to produce a more focused image on the layer of photoreceptor cells.

7. This mathematical model of the evolution of an eye began with a model eye that resembled an eye spot. 364,000 generations of selection for improved ability to provide more detailed visual information produced a model eye that resembled a complex eye. In the final model eye (shown in the upper right in the figure), label the structures that correspond to the retina and the lens of a complex eye.

8. Researchers believe that natural selection has produced results similar to the results of this mathematical model. Explain what natural selection is. Include in your explanation the words adaptive trait, fitness, heritable, and population.

9. To demonstrate one step in natural selection for a better lens, imagine an ancient population of octopuses where most of the octopuses had the genotype (**ii**) which resulted in a lens that produced fuzzy images, but a few of the octopuses had a new allele (**I**) that resulted in a better lens that produced sharper, clearer images (assume that the **I** allele is dominant relative to the **i** allele). Explain how, as a result of natural selection, this new allele would become more common in future generations of this octopus population.



Natural selection for small improvements that increase fitness can take a long time to produce an organ as complex as the octopus eye or human eye. This table shows the estimated amount of time needed for natural selection to produce a complex eye and the amount of evolutionary time available.

|   |                       |
|---|-----------------------|
| Estimates from model of how long it would take for natural selection to produce the basic shape and lens of an octopus eye or human eye | ~400,000 generations* |
| Scientists' estimates of how long it took for the eye of humans and other vertebrates to evolve   | ~100,000,000 years    |
| Scientists' estimate of how long animals have been evolving   | >500,000,000 years    |

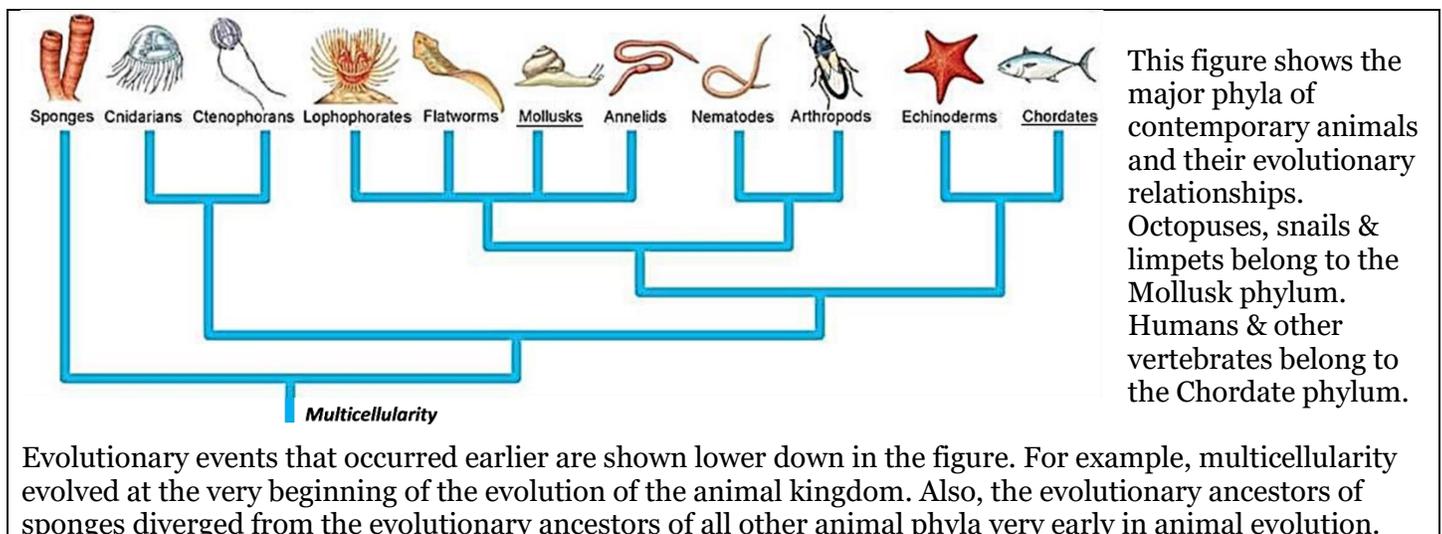
\*Scientists estimate a generation time of roughly one year per generation for the ancient animals in which eyes evolved.

10. Could natural selection have operated quickly enough to produce the complex eyes of octopuses and humans in the evolutionary time available? What evidence supports your answer?

### Molecular Evidence

#### Light-sensitive molecules in photoreceptor cells

- All types of animals except sponges have photoreceptor cells with a fundamentally similar type of light-sensitive molecule that combines an opsin protein with a molecule like retinal (a form of vitamin A).
- All types of animals except sponges have one or more genes for an opsin protein.
- The similar nucleotide sequence of these opsin genes and additional molecular evidence indicates that all the contemporary opsin protein genes are descended from an opsin protein gene that evolved very early in the evolutionary ancestors of all animals except sponges.



Evolutionary events that occurred earlier are shown lower down in the figure. For example, multicellularity evolved at the very beginning of the evolution of the animal kingdom. Also, the evolutionary ancestors of sponges diverged from the evolutionary ancestors of all other animal phyla very early in animal evolution.

**11.** Write opsin in the figure to show when in animal evolution light-sensitive molecules with opsin proteins first appeared. What molecular evidence supports your answer?

Lens proteins

- Although octopus eyes have a lens with lens proteins, many other Mollusks have eye spots or eye cups with no lens or lens proteins.
- Different types of animals have different types of lens proteins. For example, the type of protein in the lens of an octopus eye is different from the type of protein in the lens of a human eye.

**12.** Based on this evidence, do you think that lens proteins evolved \_\_\_\_\_ in the shared evolutionary ancestors of Mollusks and Chordates?  
\_\_\_\_\_ more recently during the evolution of octopuses and humans?  
Explain your reasoning.

**13.** Summarize two different types of evidence that support the conclusion that photoreceptor cells evolved before lenses evolved.

Evolution results in two different kinds of similarity:

- **Homology** refers to similar characteristics which are the result of common descent from a **shared ancestor**.
- **Analogy** refers to similar characteristics which are the result of **convergent evolution**, i.e. similar characteristics which evolved independently as a result of natural selection for a similar function.

**14a.** Octopus and human eyes both have similar light-sensitive molecules that contain opsin proteins. Is this similarity due to \_\_\_\_\_ homology or \_\_\_\_\_ analogy? What evidence supports your answer?

**14b.** Octopus and human eyes both have transparent proteins in their lens. Is this similarity due to \_\_\_\_\_ homology or \_\_\_\_\_ analogy? What evidence supports your answer?

**Challenge Question:** Think about the findings from comparative anatomy, the mathematical model, and the molecular evidence. Write a brief paragraph, draw a flowchart, or make a table to summarize a likely sequence of three major steps in the evolution of octopus and human eyes. Include brief explanations of how each of these evolutionary steps could have contributed to increased fitness.