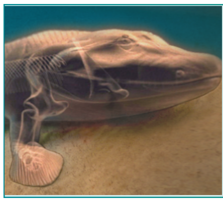


IN-DEPTH FILM GUIDE

DESCRIPTION

In the HHMI film *Great Transitions: The Origin of Tetrapods*, we join University of Chicago evolutionary biologist Neil Shubin as he relives the exciting discovery of *Tiktaalik roseae*, a species that lived around 375 million years ago (mya) and had characteristics of both fish and four-legged animals (or tetrapods). The film takes us on a compelling journey through the process of science—including the asking of important questions, synthesizing known facts in novel ways, generating and testing hypotheses, and persevering despite repeated failures.

KEY CONCEPTS

A. Species descend from other species. Even distantly related species, like humans and sponges, can trace their shared ancestry back to a common ancestor.
B. The fossil record provides a history of life on Earth. It includes fossils with features that are intermediate, or transitional, between those of major groups of animals.
C. When a series of transitional fossils are viewed together, they reveal the gradual sequence of change connecting one major group to another.
D. Evidence that land vertebrates descended from fish includes transitional fossils, anatomical similarities among embryos and adult animals, and genetic evidence of common ancestry.
E. The limbs of mammals, amphibians, reptiles, and birds look different, but they are all built on a shared basic arrangement of "one bone, two bones, many bones, and digits."
F. To find fossils, scientists develop hypotheses about the types of habitats in which earlier animals lived and when they lived there. They then predict which types and ages of rocks would house fossils of those animals.

CURRICULUM AND TEXTBOOK CONNECTIONS

Curriculum	Standards
NGSS (April 2013)	MS-LS4-1, MS-LS4-2 HS-LS4-1, LS4.A, LS4.B, LS4.C, LS4-2, LS4-4, LS4-5, HS-ESS1-5, HS-ESS2.B
AP Biology (2012–13)	1.A.1, 1.A.2, 1.A.4, 1.B.1, 1.C.1, 1.C.3, 1.D.2, 4.B.3, 4.B.4
IB Biology (2016)	5.1

Textbook	Chapter Sections
Miller and Levine, *Biology* (2010 ed.)	16.2, 16.3, 16.4, 17.3, 19.1, 19.2
Reece et al., *Campbell Biology* (9th ed.)	22.1, 22.2, 22.3, 25.2, 25.5, 25.6

PRIOR KNOWLEDGE

It would be helpful for students to be familiar with the concepts of natural selection and adaptation, and to have learned about tectonic plate movements.

Published November 2014
Revised March 2017

PAUSE POINTS

The film may be viewed in its entirety or paused at specific points to review content with students. The table below lists suggested pause points, indicating the beginning and end times in minutes in the film.

	Begin	End	Content Description	Review Questions	Standards
1	0:00	5:00	• Darwin predicted that transitional organisms' fossils could be intermediate forms between different groups. Many fossils of transitional organisms have been found and have enabled scientists to reconstruct the origins of many groups. • Although they don't always look or function similarly, the limbs of mammals, amphibians, reptiles, and birds have a common architecture, suggesting a connection between very different groups of animals. • The history of vertebrates is captured in rock that can be dated; birds are youngest, then mammals, reptiles, and amphibians. At 370 million years ago, there are no fossils of tetrapods. • Fish and tetrapods are both vertebrates, and in early development they look very similar. DNA evidence indicates that fish are tetrapods' closest relatives.	• What are transitional fossils? Why are they important? • What evidence suggests that four-legged animals evolved from fish?	NGSS (April 2013) MS-LS4.A, MS-LS4.C, MS-ESS1.C, HS-LS4.C, HS-LS4.D AP Biology (2012–13) 1.A.1, 1.A.4, 1.B.1, 1.C.1, 1.C.3, 4.B.4 IB Biology (2016) 5.1
2	5:01	13:10	• Finding fossils can be challenging. To find fossils, scientists develop hypotheses about the types of habitats in which earlier animals lived and when they lived there. They then predict which types and ages of rocks would house fossils of those animals. • Fossilization happens only under certain conditions. • After years of searching, a team of paleontologists discovered *Tiktaalik* at a remote field site in Alaska with Devonian age rocks.	• Why did the paleontologists decide to hunt for the transitional fossil in Alaska?	NGSS (April 2013) MS-ESS1.C AP Biology (2012–13) 1.A.4, 1.B.1 IB Biology (2016) 5.1
3	13:11	17:11	• *Tiktaalik* has a mix of fishlike and tetrapod-like features. It has scales and fins with fin rays, like a fish. Like a tetrapod, it has a flat head with eyes on	• Why is *Tiktaalik* considered a transitional fossil?	NGSS (April 2013) MS-LS4.A, MS-LS4.C, MS-ESS1.C, HS-LS4.C, HS-

			top, interlocking ribs suggesting it had lungs, a neck, a hip bone, and a forelimb with the beginning of a bone pattern like that of tetrapods. • The great transition from fish to tetrapod happened gradually over many millions of years. • Other fossils have provided evidence of other transitions.	• Did the transition from fish to tetrapod happen quickly or slowly?	LS4.D AP Biology (2012–13) 1.A.1, 1.A.2, 1.A.4, 1.B.1, 1.C.1, 1.C.3 IB Biology (2016) 5.1

BACKGROUND

Tiktaalik (pronounced tic-TAH-lick) means "shallow water fish" in the language of the Nunavut people who live in the Canadian Arctic, where *Tiktaalik* was found in 2004. The team that made the discovery included Neil Shubin; his former graduate student, Ted Daeschler, who is now at The Academy of Natural Sciences of Drexel University; and Shubin's former graduate advisor, Harvard University evolutionary biologist Farish Jenkins. The discovery of *Tiktaalik* is described in detail in the accompanying article "It's a Fishapod!" by Sean B. Carroll http://www.hhmi.org/biointeractive/article-fishapod. *Tiktaalik* is a tetrapod—a group that includes four-legged animals like dogs and horses, as well as whales and snakes, which evolved from four-legged ancestors but no longer have four legs.

How Are Fossils Found?

One of the major themes of the film is how fossils are found. The first step in locating fossils of the right age and type is to make predictions about where and when the organism would have lived. Before about 385 million years ago (mya), no tetrapods are known from the fossil record. The first fossils of tetrapods, *Acanthostega* and *Ichthyostega,* were dated to 365 mya. So, Shubin and his colleagues hypothesized that the fish in the process of becoming more tetrapod-like lived between 385 and 365 mya. This 20-million-year-span is within a geological epoch called the Upper Devonian.

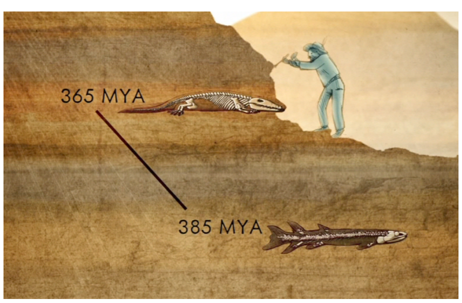


Figure 1. Rocks aged between 385 and 365 mya were predicted to contain fossils with transitional features between those of fish and tetrapods.

In the film, we see a map of Devonian rocks. The map comes from a textbook entitled *Evolution of the Earth* by Dott and Batten, which contains many geological maps. Like all maps, geological maps are designed to show where certain things are located. Whereas the maps we know best show the distribution of roads, rivers, or county boundaries, a geological map shows the distribution of geological features, including different kinds of rocks (e.g., sedimentary, igneous, and metamorphic) and the different ages of rocks. These maps are typically generated to guide oil and mineral expeditions.

The map in the film shows three Devonian deposits in North America. Two of those deposits had already been searched for fossils. The third Devonian deposit had been explored by Canadian geological surveyors and a few oil company geologists but no fossil hunters. This third formation contained sedimentary rock layers—the type of rocks where fossils are most commonly found. After some additional research, Shubin and Daeschler discovered that the rocks had formed in what were shallow, meandering streams in Devonian times.

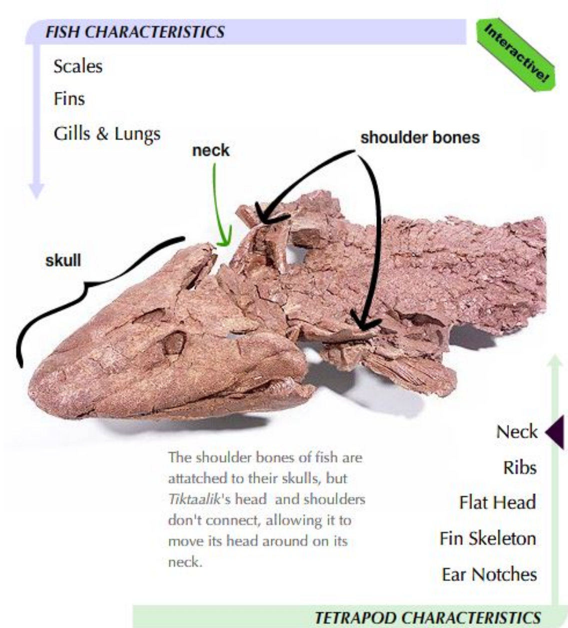
Even after identifying rocks of the right age and type, scientists cannot be sure that they will find fossils in those rocks. Almost all organisms that have lived on Earth left no trace of their existence. Most are eaten or decay before they are fossilized, and soft tissues do not fossilize well. And even if an organism is buried in sediments and becomes fossilized, the rock layer with that fossil has to become exposed on Earth's surface for someone to find it.

So how can paleontologists expect to find fossils at all, let alone fossils of species that existed at a particular point in time? One critical fact makes this possible. A single species can exist for millions of years and consist of hundreds of millions or even billions of individuals. The probability of finding the fossil remains of any one individual is tiny, but not impossible.

Finding *Tiktaalik*

In 2004, Shubin and colleagues found the fossil of a new species that shed light on a key transition in the evolution of tetrapods: the fin-to-limb transition. The crew was excavating one day in an area with lots of Devonian fish fossils (a "whole aquarium," as Shubin said in the film). Sticking out of a rocky edge in the quarry was the tip of the snout of a flat-headed fish. Why was the flat head such an important clue?

Many fish have flat heads. But what is significant in this case is that the earliest tetrapods that had been discovered (i.e., *Acanthostega* and *Ichthyostega*) had flat heads. So finding a flat-headed fish was a good indicator that this fossil was part of the gradual evolutionary sequence from fish to tetrapods.



Once the fossil was cleaned, it showed that it had two nostrils and two eyes mounted on top of its flat head. Most fish have nostrils, but tetrapod-like fish like *Tiktaalik* have a specialized kind of nostril that connects to the inside of the mouth. Fish that are not closely related to tetrapods have nostrils that only connect with the exterior.

Another important feature of this fossil is that *Tiktaalik*'s head was not connected directly to its shoulders like the head of a fish would have been (Figure 2). Instead, its head sat in front of the shoulders, at the end of a flexible neck—meaning the head was free to move up and down and sideways.

Figure 2. *Tiktaalik* has a mix of fish and tetrapod features. One of the important tetrapod characteristics is the presence of a neck, which allows *Tiktaalik* to more freely move its head. (Figure taken from the interactive "Meet *Tiktaalik roseae*" available on the University of Chicago website at http://tiktaalik.uchicago.edu/meetTik2.html).

Like a fish, the fossil of *Tiktaalik* shows evidence of scales, gills, and fins. But inside the fins, *Tiktaalik* contains limb bones that are characteristic of an early tetrapod. One bone (the humerus) extends from the shoulder and connects to two additional bones (the radius and ulna), which are shared by all lobe-finned fish (i.e., coelacanths, lungfish, tetrapods, and all their extinct relatives). What is special about the fin of *Tiktaalik* is that those three bones then connect to many small bones that form what Dr. Shubin describes as "a version of a wrist."

The fossil of *Tiktaalik* also revealed interconnecting (or imbricate) ribs that surrounded the lungs. Lungfish have lungs, but they do not have imbricate ribs. The lungs of lungfish and tetrapods are homologous, which means they evolved from a common ancestor that had lungs. The imbricate ribs of *Tiktaalik* and later tetrapods would have provided extra body rigidity in conditions in which the surrounding water could not support the weight of the animal (i.e., in shallow water or subaerial conditions). One hypothesis is that the ribs provided an advantage in those environments by keeping the weight of the animal from putting pressure on the lungs and preventing them from filling with air.

So why is *Tiktaalik* referred to as a transitional creature? Its mix of characteristics of fish and of tetrapods suggest that it represents one of the moments in the transition between fish and tetrapods.

DISCUSSION POINTS

- Students may incorrectly assume that discovering fossils is mostly about luck. Ask your students if any of them have found fossils. Ask those students who found fossils if their fossil finds were lucky or a product of deliberate searching. Explain that paleontologists do not accidentally stumble upon the fossils they discover, but that paleontology is a process of hypothesis testing. Through careful planning, reading scientific articles, and studying geology and geological time, paleontologists form hypotheses about the time periods and habitats occupied by certain organisms. They then develop predictions about what kinds of rocks certain fossils of those organisms should be buried within and where rocks of those types and ages are found on Earth.
- Students may wonder why we do not find more fossils—fossils of every type of organism that ever lived. Ask students to consider a mouse that is running near the school at this very moment. Ask them to consider the probability that that single mouse will die today, become fossilized, and be rediscovered a million years from now. The probability is nearly zero. To become fossilized, the mouse must not be eaten right after it dies and not decompose within a few days. Instead, the mouse's body must be quickly and completely buried in either volcanic ash or some kind of sediment. It must remain buried until the sediment and the mouse remains turn into rock—a process that may take thousands or even millions of years. Enough time has passed in Earth's history for some individuals, from the hundreds of thousands within any one species, to have been in the right conditions to become fossilized.
- A classic question students may ask about evolution is, "If we evolved from fish, why are there still fish?" Explain to students that humans and modern-day fish share a common ancestor that no longer exists. The aquatic habitats in which fish thrive today have been around for over half a billion years, and fish are well adapted to live in those environments. When some fish populations evolved stronger, limblike structures in fins, they were able to exploit new types of habitats and reduce competition with other fish for resources. But fish continue to exist because there are still environments in which fish can thrive.
- Ask your students what advantage a neck might provide. The lack of bones connecting the head to the body provides flexibility to move the head without moving the rest of the body. A flexible neck could have been beneficial in many possible scenarios. However, this flexibility may have also come at a cost—for example, the loss of the protective gill cover. We don't know exactly how *Tiktaalik* used its neck.

- Students may ask for examples of other transitions from earlier to later forms. The evolution of whales from terrestrial mammals and birds from dinosaurs are both excellent examples with rich fossil evidence and many transitional forms. Whales evolved from terrestrial mammals that walked and ran on four legs. A fun fact that supports this ancestry is that a swimming whale flexes its backbone up and down like a running cheetah, not side to side like a swimming fish. As whale ancestors transitioned from a terrestrial to a marine life, many characteristics changed. For example, legs can be a liability in an aquatic environment rather than a benefit. As a result, whale ancestors show a progressive decrease in the size of their hind limbs. All that remains of these limbs in some of today's whale species is a pair of tiny bones that are buried inside the body wall and are not even attached to the pelvis.
- Discuss with students why the term "missing link" is inaccurate. The term has been popular in the media and has been used to incorrectly imply that an unbroken chain of organisms is required to demonstrate that all species are related. The terms "transitional form" and "transitional fossil" more accurately describe species that illustrate the sequence of changes that occurred during the evolution of a new group of organisms.
- Is *Tiktaalik* our ancestor? *Tiktaalik* is representative of an animal that was an ancestor to modern tetrapods, including humans. But we cannot say whether it was a direct ancestor. A common misconception is that all fossils, including transitional fossils like *Tiktaalik*, are direct ancestors of modern species. Explain that fossils, like *Tiktaalik,* may be direct ancestors, but they are much more likely representative of what the actual ancestors looked like and not the ancestors themselves. In fact, the descendants of *Tiktaalik* may have gone extinct long ago, but another species, related to *Tiktaalik*, and yet to be discovered, may be the common ancestor to all modern tetrapods. We may never know, but we can be certain that the ancestor looked a lot like *Tiktaalik*.
- Students may be confused about why fossil animals like *Tiktaalik* that lived in warm habitats end up in barren locations like the Canadian Arctic Islands. Remind students that Earth's biological and geological histories are connected. Earth's crust is dynamic. Plate tectonics move land masses, and fossils that were once at the equator can be moved to distant locations.

RELATED BIOINTERACTIVE RESOURCES

It's a Fishapod (http://www.hhmi.org/biointeractive/article-fishapod)

This article by Sean B. Carroll tells the story of the search for and discovery of *Tiktaalik*.

Great Transitions Interactive

(http://www.hhmi.org/biointeractive/great-transitions-interactive)

In this Click and Learn, students explore several transitional fossils in the transition from fish to tetrapods, including *Tiktaalik*.

Young Students Recognize a Transitional Tetrapod (http://www.hhmi.org/biointeractive/young-students-recognize-transitional-fossil)

This short video demonstrates the power of observation and the importance of fossil evidence. When Neil Shubin shows a *Tiktaalik* fossil to small children, they immediately notice the presence of both fish and tetrapod characteristics.

Explore Your Inner Animals

(http://www.hhmi.org/biointeractive/explore-your-inner-animals)

This interactive explores different anatomical features of the human body and what they reveal about the evolutionary history we share with other organisms, including earlier, long-extinct species.

USING THE QUIZ

The quiz is designed as a summative assessment that probes student understanding of the key concepts addressed in the film. However, some teachers use the quiz before and during the film to assess students' prior knowledge and to guide students as they watch the film. Teachers are encouraged to choose the use that best fits their learning objectives and their students' needs. Moreover, because the vocabulary and concepts are complex, teachers are encouraged to modify the quiz (e.g., only ask some of the questions, explain complicated vocabulary for ELL students) as needed. The last two questions are intended for students with prior knowledge about mutations, genes expression, and development.

QUIZ QUESTIONS AND ANSWERS

The student version of this quiz is available as a separate file. Key concepts covered by each question are noted here.

1. (Key Concept B) When Charles Darwin considered some of the unique structures found in modern animals, like the feathered wings of birds, he famously proposed that modern animals must have evolved from earlier forms that lacked those structures. He also predicted _______________. (Fill in the blank with one of the statements below.)

a. that it would be impossible to find fossil evidence for this idea because the fossil record is so incomplete.
b. that genetic evidence would show that all organisms share a common ancestor.
c. that fossils would be found with structures that are intermediate between early and modern forms.
d. that fossil evidence would instead show that all modern animals have always existed in their present form.

2. (Key Concepts B and C) Which of the following features describe *Tiktaalik*?

i. Neck
ii. Lungs
iii. Round head
iv. Fins

a. ii and iv only
b. i, ii, and iv
c. i, iii, and iv
d. i, ii, iii, and v

3. (Key Concept F). Examine the table below and select the row that best describes the setting, resources, and scientific processes used during the *Tiktaalik* expeditions.

	Location	Maps/Photos	Scientific Process
a.	**Canadian Arctic**	**Geological maps**	**Hypotheses testing**
b.	Iceland	Road maps	Predicting
c.	Alaska	Aerial photos	Questioning
d.	Arctic Circle	Animal track maps	Developing explanations

4. (Key Concept E) Which statement below is evidence that all tetrapods shared a single common ancestor?
a. All tetrapods live partly in water and partly on land.
b. All tetrapods are warm-blooded.
c. All tetrapod limbs consist of rearranged fish fin rays.
d. All tetrapod limbs have a common pattern of one bone, two bones, many bones, then digits.

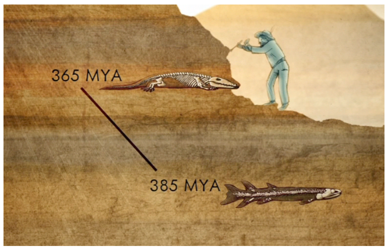
5. (Key Concept C) The transition from fish to tetrapods is best described as:
a. Like most of the great transitions in evolutionary history, it happened in very few big steps so that there are very few intermediate forms.
b. Like most of the great transitions in evolutionary history, it happened in many small steps leading to many intermediate forms.
c. Like no other transition in evolutionary history, it happened in many steps, so there are many intermediate forms.
d. Like most of the great transitions in evolutionary history, it happened in a single step with no intermediate forms.

6. (Key Concepts A and D) Which evidence supports the fact that tetrapods and fish are closely related?
i. The embryos of modern fish and tetrapod look similar.
ii. Both modern fish and tetrapods can swim.
iii. Both modern fish and tetrapods are vertebrates.
iv. The DNA of modern fish and tetrapods suggests that they have a common ancestor.
v. Modern fish have limb bones that support their bodies.
a. i, ii, and v only
b. i, iii, and iv only
c. iii and v only
d. i to v are all supporting evidence

7. (Key Concepts B) True or False. "Transitional organisms are not actual species." Justify your answer in one or two sentences.

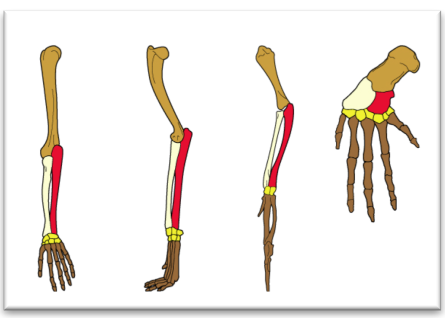
False. Transitional forms are species in their own right. They are called transitional forms because they possess traits, like fins, that are found in earlier fossil animals, but also possess traits, like limb bones, that are found in later fossil animals.

8. (Key Concepts F) Study the graphic below of rock layers with fossils in them. Explain how Neil Shubin and his team predicted that they would find a fossil animal like *Tiktaalik* in rocks around 375 million years old.



Students should explain that from the fossil record, Shubin and his team knew that *before* 385 mya the fossil record does not contain tetrapods. Around 365 mya the fossil record shows the first evidence of organisms with tetrapod limb characteristics, including digits. Shubin and his team hypothesized that the evolution of a functional tetrapod limb was a gradual process, and fossils showing intermediate steps in that process should be located in rocks of ages in between 385 million and 365 million years.

9. (Key Concept E) The diagrams below illustrate the bones in the forelimbs of four different organisms. Although these limbs all look different, they share some common patterns. These common patterns suggest that



a. These organisms are members of the same species.

b. The organisms existed at about the same point in time.

c. These organisms share a common ancestor.

d. These organisms have exactly the same genes.

10. (Key Concepts F) Explain why Neil Shubin and his colleagues had to travel to an area above the Arctic Circle to find the fossil of an animal that once lived in a warm swamplike habitat.

When *Tiktaalik* lived and became fossilized, the continent it was on was located closer to Earth's equator where warm, freshwater habitats were abundant. Over time, pieces of Earth's crust, and all the fossils in the rocks on top of the crust, moved to different locations due to continental drift. Students may also mention

that Shubin and colleagues knew that the Arctic contains rocks from the Devonian period that were explored at the surface.

11. (Key Concepts B and F) In the film, Neil Shubin is shown hiking up a rocky hillside while recalling for us one of the exciting moments during the hunt for a *Tiktaalik*-like fossil animal. Neil says, "Beneath our feet were fossil fish bones, fragments of fossil fish bones, many thousands of pieces. It wasn't just one fish; it was a whole aquarium, it was different species." What did this discovery mean for the fossil-hunting team?

The fossilized fish bones were evidence that the team had discovered a layer of rock that had formed in the kind of habitat where an animal like *Tiktaalik* could also have lived. The rock layer contained many fish species, so it might also contain an animal that existed during the transition from water to land.

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