Curriculum Units by Fellows of the National Initiative
2016 Volume VI: Making Sense of Evolution

Transitional Forms: The Evidence for Evolution by Natural Selection

Curriculum Unit 16.06.05, published September 2016
by Thomas Teague

Introduction

Having been born in 1991, *Jurassic Park* captured my imagination not only as a film, but also as a complex novel by Michael Crichton that touched on evolution, genetics, and chaos theory. While I can't say that my 8th graders are poring over the novel, the legacy of *Jurassic Park* lives on, inspiring an interest in paleontology and fossils to this day with incarnations like the recent summer blockbuster *Jurassic World.* Dinosaurs easily fascinate middle school students, but the mechanics of evolution is another story. Evolution mainly involves the deceptively simple concept proffered by Charles Darwin: evolution by the process of natural selection. This process explains how organisms gradually change over time to become better adapted to their environments by passing along beneficial traits to their progeny.

In the United States today we see an inherent contradiction between the role of the country as a leader in the global economy with regard to science and technology, contrasted against the acceptance and understanding of science in the popular consciousness. One key area of flagging public awareness in the United States is biological evolution. Evolution orders the natural world. In order to create a generation of informed citizens, educators must convey the importance of evolution.

Despite the evidence and universal acceptance of the theory of evolution by the scientific community, only 32% of the American public hold the opinion that human evolution is "due to natural processes such as natural selection."[1] There is a great need to correct the record and put students in a position to benefit from a firm grasp of evolutionary science.

Background and Rationale

Background

My 8th grade students are bright, inquisitive, and demanding, which creates a dynamic learning environment. Unfortunately, many students struggle with difficulties both in and out of the classroom. High poverty, high rates of student mobility, financial strains, struggles with basic transportation, and procuring school supplies all serve as the backdrop for many students just trying to make it day-to-day. Central High School, also the home of Central Junior High, was the very first high school in the city of Tulsa, Oklahoma. Originally located in downtown Tulsa, Central was pushed north and westward in the 1960s in order to comply with changing requirements about desegregation, and thus began serving a more racially diverse and socioeconomically challenged set of students. White flight out of the area complicated these plans for integration, leaving a diverse set of students that are socioeconomically challenged. As recently as 2011, discussions were floated to consolidate the building and move students elsewhere.

Tulsa Central Junior High School itself only exists as a result of Project School House, a program designed to save money by consolidating and shuttering numerous schools within the Tulsa District starting in 2011. Central High School was on the list of school sites to be shuttered, but continues to remain open with the addition of a junior high school that includes grades 7 and 8.

Budget cuts are again affecting Tulsa Public Schools, with teacher cuts, central office positions being whittled down, and numerous other cost saving measures being undertaken due to recent state revenue failures in Oklahoma. Low projected enrollment numbers for Central Junior High and High School have meant even more teaching positions and resources are being taken away from the students at my school site.

The student population of Central is impoverished, as 100% of Central Junior High students are eligible for a free/reduced lunch. Central is a racially diverse junior high, with African American students making up 54% of the population, followed by 28% white, 10% Hispanic, 6% Native American and 1% Asian. These challenges of are not unique to Tulsa, nor is the importance of critical thinking and learning around fundamental scientific concepts.

In years past, my students have described learning about evolutionary concepts as “scary” or in direct contradiction with personal belief systems. As a result, it is my intention to provide students with facts and evidence that will be accessible while helping them to gain critical understandings and frameworks for the natural world. As a result, this unit will be useful for any instructors teaching 8th grade and following the Next Generation Science Standards as well as for teachers local to Oklahoma, as these standards are largely similar.

Rationale

The teaching of evolutionary concepts to Junior High Students is paramount. Oklahoma is well known for taking a regressive stance on science in the educational realm. Yearly, the state legislature considers legislation that would undermine the teaching of fact based science in favor of “teaching the controversy” and mandating that students be taught intelligent design concepts or other versions of creationism in science courses. Such proposals have elicited strong reprimands from the National Association of Biology Teachers and the American Institute of Biological Sciences. These reprimands have not stopped the state legislature from taking up similar measures as recently as 2016.

Such ideological fights over science fall short of actual discussion of what is best for students. Oklahoma has a major gap of college-educated citizens, which in turn is creating a “brain drain” and a damper on the state economy. As the economy continues to favor skilled, technically adept, critical thinking workers, I fear that we will see our young people continue to fall behind.

Teaching the facts of evolution as well as the critical thinking to understand it are pivotal to individual students. I believe this to be critical from a social justice standpoint. All students deserve to have a quality education that can yield for them tangible benefits, whether those benefits come in the form of a greater understanding of the natural world, the building of fundamental critical thinking skills, or a newfound love of science that could propel an entire career in a Science Technology Engineering and Math (STEM) field.

Historical Innovations in Science

One of the hardest things to grasp about science is that it is constantly changing. Conceptions of the way the world works are not necessarily permanently fixed in science, and can be amended through the discovery of additional evidence, experimentation, and reexamination of findings. Before Darwin could make the breakthroughs that redefined modern biology and our understanding of the natural world, discoveries in other fields had to occur. This background knowledge will be useful in framing relevant issues that made Darwin's understandings possible. As far as my students are concerned, many of these findings will already have been discussed or implemented in units prior to this one, but a review may give additional insight or frame the issues for readers of this curriculum unit.

Geology

While it is my intention to have introduced the concepts of geologic time, index fossils, the law of superposition, and even continental drift to my students before engaging in this unit, it might be worthwhile to review the state of geology leading up to Darwin's breakthrough and the eventual widespread acceptance of evolution. Before the 19th century scientists were not interested in overturning traditional religiously based views of the natural world. By the 19th century, these traditional views were impeding the progress of naturalists more interested in fact than upholding a misguided and limiting world view.

In the early part of the 19th century, scientific consensus surrounding geology began to shift, and Darwin's contemporaries began to move away from a literal interpretation of the Bible that pegged the age of the Earth to only thousands of years. Scientists, including James Hutton, began to look for natural explanations for geological formations, which included consideration for geologic forces coming from within the Earth due to a molten core, and the pushing-up of granite from below the Earth's surface.[2] Hutton's theory essentially framed a fundamental law of geology about how gradual forces have been changing the surface of the Earth throughout history. This stood in opposition to the traditional notion of special creation, namely that the Earth was created by God and was immutable.

Evidence for these gradual geologic changes are actually easier to find in fossils than just in rock or other geological formations. The discovery of fossilized elephants in North America, Europe, and Siberia by paleontologist Georges Cuvier demonstrated that environments must have changed over time, supporting different living things at different times.[3] Cuvier also discovered that fossils allowed geologists to peg the relative age of layers of rock from one location to another even in areas where those fossils might not have been found but were still clearly part of the same strata.[4] In fact, most layers of rock strata were discovered and labeled before Darwin's breakthrough in evolution and were labeled based on the fossil discoveries contained within them – with drastic changes in the fossil record demarcated by mass extinctions as well as the appearance of new species in the fossil record.[5] The geological events and periods of Earth's history are organized into the geological time scale, and include eras, periods, and epochs.

With the discovery of fossils and a resulting understanding of basic geological principles, scientists were able to organize the fossil record. Branches of life, speciation, and evolution can be seen through the fossil record. The fossil record does a good job of showing that more complex organisms arose from earlier ones. However, the fossil record is far from complete. Some organisms do not fossilize well because they decayed too rapidly for fossilization to occur, or were too soft to make an imprint in rock strata that formed later as sediment accumulated in the area.[6] Another issue is that only a small fraction of life forms ever become fossils due to localized conditions, but also because fossils have to survive within rocks that are undisturbed for millions of years of geologic changes.[7] With all of this in mind, Darwin was armed with the fundamental knowledge that vast amounts of time had passed during which the Earth underwent a myriad of geologic changes as well as drastic changes in the animal life that had populated the planet.

Biology

In not too dissimilar fashion from the breakthroughs in geology, the19th century saw changes in how key topics in biology were perceived well before Darwin published his groundbreaking findings in *The Origin of Species by Means of Natural Selection* in 1859. Just as theological ideas about the age of the Earth had clashed with and perhaps even limited breakthroughs in geology, the same was true for the biological sciences leading up to the 19th century. Despite fear of reprisal, some scientists and naturalists did consider that life could change through time to become better adapted to survive.[8] Darwin's own grandfather, Erasmus, was one such free thinker. Erasmus Darwin died six years before the birth of his grandson. His thinking did left an impression in the scientific community. Likewise, John Baptiste Lamarck was another early proponent of evolution; though he was incorrect about the mechanisms for evolution. Lamarck incorrectly believed that organisms could adapt during their lifetime and then pass along any adaptations directly to their offspring; Darwin would later demonstrate that adaptive variants in a population are 'born lucky' and this allows them to leave more offspring because they happen to better match the environmental challenges. Thus, adaptations take place in populations across many generations and natural selection is the guiding force behind incremental changes over time. Despite Lamarck's confusion regarding the specific mechanism for evolution, he was spot on when he found that: "the fixity of species was an illusion."[9]

Simultaneously, comparative anatomy was beginning to take shape during the 19th century. Comparative anatomy simply means taking structures found in different species and comparing them. Sometimes there are striking similarities. Homologous structures provide compelling evidence for evolution because the striking similarities between species demonstrates relatedness due to common ancestry. But the contemporaries of Darwin weren't just looking at homologous structures between adult specimens of various species, they were also looking at embryos that could be observed at various stages of development. Examples of homologous structures are rife in nature, and include the forelimbs of vertebrates ranging from the human arm, a bird's wing, seals, horses, and so on – in each you will find a humerus, radius, ulna, carpals, metacarpals and phalanges. This underlying similarity in anatomy is explained by common ancestry. With the study of development through embryos, scientists in Darwin's day suspected these similar structures arose due to similar developmental pathways.[10] Darwin was the first to proffer that these shared developmental pathways were caused by common ancestry, where vertebrates would have shared a common ancestor that passed down these traits, which became adapted over time for use by different but related species. This conceptual breakthrough was in direct contrast to the once dominant theory of special creation, which held that every organism was created separately, and logically should show no common ancestry.[11]

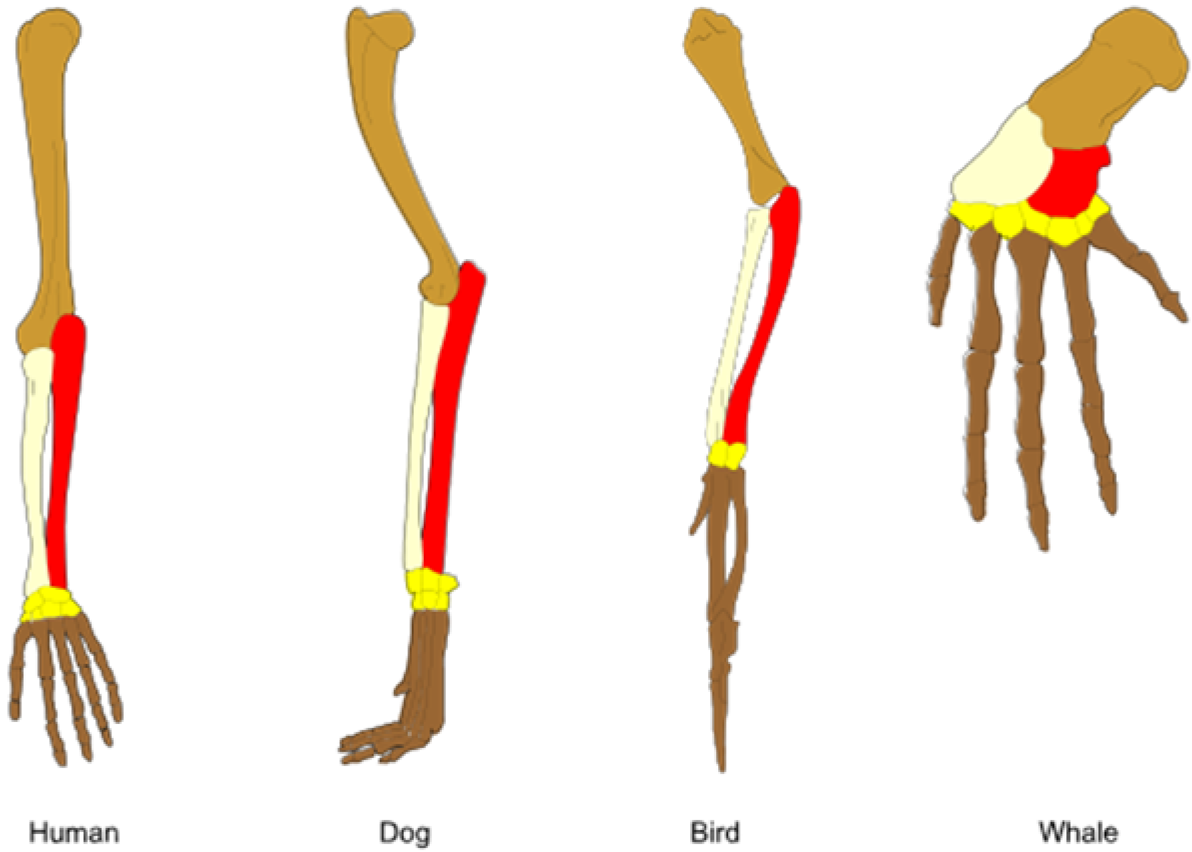

Fig. 1: Homologous Structures. Image Credit: Волков Владислав Петрович. CC 4.0

Darwin

Charles Darwin's fateful journey toward discovering the mechanism for evolution was undertaken in 1831 aboard the HMS Beagle and lasted for five years. His mission was simply to serve as the ship's naturalist, and he did not set out to restructure the science of biology by writing about natural selection. On this journey Darwin would spend time ashore, record his observations and collect samples.[12] It wouldn't be until his return to England that he would begin to put the evidence together for natural selection acting on living things and driving the process of evolution. Following his return, Darwin distributed various fossil samples and carcass specimens to well respected experts, but was surprised at their findings.[13] For example, James Gould informed Darwin that birds Darwin had classified, as entirely different species were in fact closely related species of finches, differing primarily in their beak structure. As the investigations continued, Darwin found that each island had specifically adapted but related species inhabiting them – leading to the conclusion that the animals had adapted to their environments over time, rather than having been specially created to inhabit their environments. Darwin realized that at some point a single species of finch could have flown there from the mainland. As finches arrived on different islands, they became specially adapted to the unique environment of each island thus maximizing their chances of survival.[14]

The massive weight of these findings were not lost on Darwin, who began to realize the vast implications of his evidence. If all living things evolved from a common ancestor, then the natural laws that applied to the animal kingdom also applied to human beings, and he realized that monkeys and apes were probably our closest evolutionary relatives.[15] These lines of thinking ultimately led Darwin to refine his thinking and publish

The Origin of Species by Means of Natural Selection in 1859.

Evolution: An Overview

In *The Origin of Species by Means of Natural Selection*, Darwin provides four postulates:

1. Individuals within species are variable
2. Some of these variations are passed on to offspring
3. In every generation, more offspring are produced than can survive
4. Survival and reproduction are not random: The individuals that survive and go on to reproduce, or who reproduce the most, are those with the most favorable variations. They are naturally selected.[16]

Variations within species are essential for natural selection to occur and drive evolution. While Darwin had no understanding of the underlying genetics to support his theory in the 19th century, modern genetics has allowed scientists to find these genetic variations and mutations. Even sexual reproduction itself is important for creating variations that can allow for changes in species, because genes from parents are combined to make unique combinations in the offspring. Obviously, these variations must be passed on to offspring in order for these variations to drive natural selection, and simply by necessity more offspring must be created than can survive. The most "fit" individuals of a species are the ones to survive and to pass on their useful variations and characteristics on to the next generation. This is as a result not a random process. Natural selection is a process with a definitive and logical steps that are driven by successful reproduction and passing on of traits by organisms that are better adapted to survive.

There are a few key ideas of Darwin's that should also be explained, as they continue to endure to this day. One of Darwin's enduring ideas is common ancestry*.* Common ancestry, as previously noted, explains that all species must have come from common ancestors. Obviously this helps to explain homologous structures in more closely related species, but it also explains why the vast majority of all living things use the same DNA code to store genetic information. As a result of this common ancestry, all of life can be displayed as branches on a common family tree. Another key concept handed to us by Darwin is gradualism*.* Gradualism states that changes in species and adaptations come slowly, in small steps.[17] Evidence for this can be found in many transitional forms, which are intermediate steps between two related species that have been preserved as fossils.

Natural selection is the central process driving evolution, as it provides the mechanism by which variations are passed across generations to better match organisms to their environments and to ultimately cause species to change over time. Natural Selection involves a process whereby variations in individuals determine their relative ability to survive and reproduce, and only the most successful variants pass along these traits to the next generation. If these variations provide a better match to the environment, the resulting traits are called adaptations*.* Adaptations may give the appearance that a species might have been specially designed to survive in a given environment, but in reality the natural selection process that occurred over sometimes millions of years is responsible for these adaptations.[18] The ability to fly was most certainly an adaptation for some ancestor of the ostrich. However, at some point the ostrich no longer needed to fly in order to be successful in survival and reproduction and the pressures of natural selection did not favor individuals with particularly good flying ability. As a result, the ostrich has since lost the ability to fly. The same is true for other flightless birds; though their wings may be adapted for new uses, they no longer serve the purpose for which they were originally selected.[19]

Vestiges & Atavisms

Because evolution occurs over great spans of time and traits are heritable, sometimes throwbacks appear either in the form of vestigial traits and atavisms. Vestigial traits are structures that an organism still exhibits but are now useless for their original purpose. As mentioned, an example of a vestigial structure is the wings on a flightless species of bird.[20] Similarly, true moles have lost the ability to see along with much of the structure of the eye. Similar pressures have occurred with certain species of burrowing snakes and many cave dwelling species that have lost the ability to see. Sight is not essential for cave dwelling species, and therefore natural selection did not favor individuals with the trait.[21]

One famous example of a vestigial organ in humans is the appendix. The length of the human appendix varies greatly, and in some people it is even absent; in animals with a plant based diet, the appendix is considerably larger and more developed, serving to house bacteria or for fermenting plant matter in order to digest it fully.[22] It no longer serves the same purpose in humans, and is therefore considered to be vestigial. However, the appendix may not be completely vestigial, as it could harbor helpful bacteria or serve other purposes. For another example, we also have the remnants of our ancestral tail, the coccyx, and when the genetics for that tail are expressed and a human baby is born with a tail, the trait goes from being a vestigial bone at the base of our spinal column to an expressed atavism, or throwback to the ancestral form.[23]

Whales, which will be a central focus of this unit due to the rich documentation of their ancestral transitional forms, harbor many examples of vestigial traits that illustrate their ancestry. Despite now being an entirely aquatic species, whales retain evidence of having ancestors that once lived on land. These vestiges include hind limbs and pelvic bones that are not even connected to the rest of the skeleton.[24]

Whales and the evidence from Transitional Forms

Sometimes it is far too easy for students to say that they grasp a concept simply because they are bored with it, or to simply not engage and grapple with a difficult topic. When the basics of evolutionary biology are taught in a vacuum, the connections to real world examples can be lost. For students who may want to dismiss the topic entirely because of social taboos, as well as for those struggling to make the connections, I want to provide solid evidence for their consideration. A key way to establish the fact of evolution is through the use of transitional forms. Transitional forms show intermediary steps between one species and another through geologic time, preserving the steps in the actual process of evolution through fossils. One example of a fairly complete record of transitional forms comes from cetaceans, specifically whales. What follows is a brief survey of transitional forms that have been discovered in the evolution of whales.

Indohyus

Indohyus was a four legged creature that probably spent most of its time on land. It has been described as looking somewhat like a deer and was probably the size of a housecat.[25] It is thought to be closely related to modern whales, and lived over fifty million years ago. The evidence for this comes from a few key characteristics found in fossils, namely that the bones of its legs were unusually thick, and that the bones of the middle ear in Indohyus suggest that they were well adapted for hearing underwater.[26] What drove this species and other ancestral species into the water and down the path of evolution to become the whale is unclear, but theories include richer food sources or avoidance of predators.[27] While Indohyus is a not a direct ancestor to modern whales, few would dispute that it hailed from a related lineage, being more of a cousin to lineages that eventually evolved into modern whales. Indohyus shows that the eventual evolution of modern whales required a drastic body plan change over millions of years. However, key trends such as eye position, nostrils, jaw structure, bone density and ability to hear underwater are trends that can be traced through transitional forms.

Pakicetus

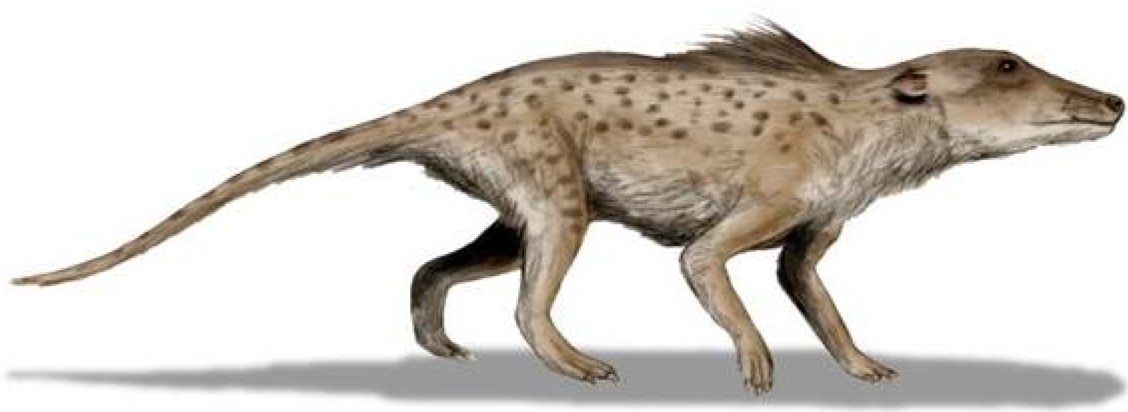

Fig. 2: Pakicetus Inachus. Image Credit: Nobu Tamura. CC 3.0

Pakicetus, which lived around 50 million years ago, is similar to Indohyus

in sharing adaptations that allow for better survival in aquatic environments, but Pakicetus remains a largely land based animal, and is considered the oldest ancestor of modern whales. Not yet recognizable as a whale, Pakicetus retains four legs and a tail, as long as sharp teeth. Like its cousin Indohyus, it has the heavier bones that allow for submersion into water as well as the ear structures that allow for underwater hearing.[28] Pakicetus was first discovered in Pakistan in 1983, and while clearly a land animal it has other distinctive features that link it to whales, including its elongated skull shape.[29]

Ambulocetus

Fig. 3: Ambulocetus natans. Image Credit: Nobu Tamura. CC 3.0

The next phase of evolution for whales comes in the form of Ambulocetus, which was discovered in Pakistan, and most likely lived in fresh water Ambulocetus reached lengths nearing four meters, and probably resembled a crocodile more than its land based predecessors. Ambulocetus featured eyes that faced sideways and were placed high on its head, a similar placement found in hippos, which are closely related to modern whales. This placement allowed the animal to see prey above the water even when it was submerged. The ear in Ambulocetus becomes more advanced, with a lower jaw featuring a fat-filled large cavity also found in modern whales that allowed for easier transmission of sound to the ear.[30]

This step in whale evolution also saw changes to the limbs of Ambulocetus, finding large feet on the hind limbs that could have allowed it to walk along the bottom of a body of water. It is uncertain if these limbs could have supported the full weight of the animal on land, but it certainly would have been clumsy.[31] Ambulocetus has limbs have been described as “paddle-like”.[32]

After Ambulocetus

Whale forms and related cetacean species that evolved after Ambulocetus saw continual development towards the form that we now see in modern whales. Nostrils gradually moved from the snout to further and further back until reaching the position of what we now call the blowhole located on top of the head.[33]

Whale and cetacean locomotion is unique from other species that live in the ocean. Having evolved from mammals, whales gradually show the full expression of their hind limbs and saw a drastic shrinking and disconnection of the pelvis from the rest of the skeleton. As a result, whales swim by undulating their whole bodies, with their horizontal tale propelling them forward. This is in contrast to how fish move, as they paddle their vertical fins back and forth to provide locomotion. While the development of fins exists both in fish and whale species, they are not homologous structures, as there are key differences between the vertical fin structure found in fish and the horizontal structures found in whale species. This is due to the evolutionary pressures on ancestral whale hindlimbs to move and undulate for locomotion, as opposed to the constant flapping of fins in many fish species.[34]

Dorudon & Rodhecetus

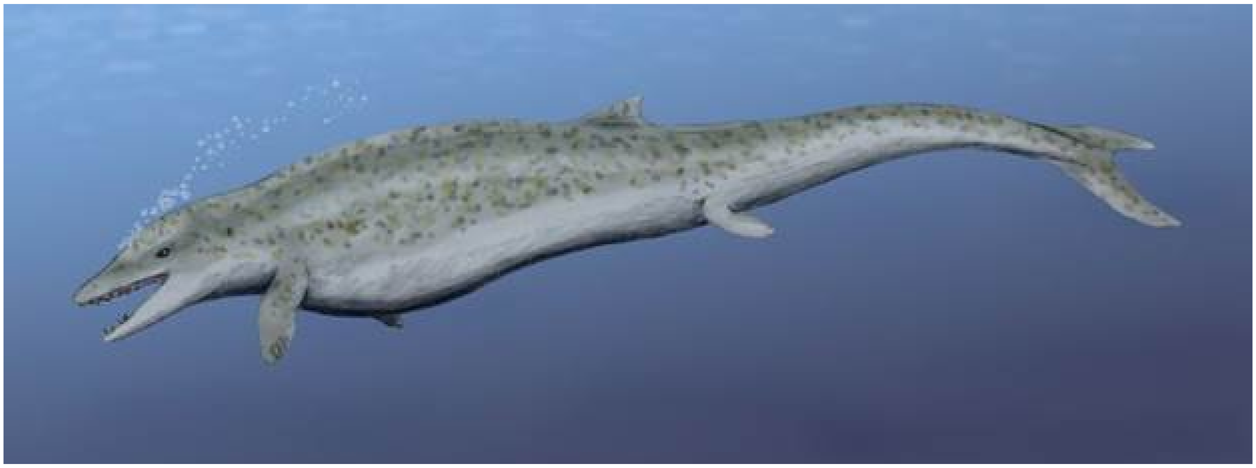

Fig. 4: Durudon atrox. Image Credit: Nobu Tamura. CC 3.0

Forty million years ago, whale ancestors Rodhecetus and Dorudon were fully aquatic marine mammals. Rodhecetus shows evidence of having been a good swimmer, but has extremely limited hind limbs and a small pelvis. Both show blowholes and have short necks. Dorudon, which measured around fifty feet long, had hind limbs that were only two feet long.[35]

Rodhecetus, also discovered in Pakistan, was around 2.5 meters in length. In addition to previously mentioned adaptations of its body plan to its aquatic environment, its ankle bones show a recurved ankle, streamlining the rear limbs toward the body, no doubt aiding in movement in the water.[36]

Dorudon in particular featured a completely detached pelvis, allowing the lower spine greater flexibility in powering movement. Forelimbs in Dorudon are flipper like. Dorudon continued the trend of having the ability to hear well underwater. This whale ancestor would look fairly similar to modern whales at this point in the evolutionary history.[37]

Conclusion & Implications

In evolutionary terms, the span of time that the whale's surface dwelling ancestors underwent massive changes to its body plan to become what we would recognize as a whale, which include elongation of the skull, movement of the eyes, nostrils, drastic changes to the extremities, changes in locomotion, and shrinkage and detachment of the pelvis - is quite short, taking only some ten million years.[38] Intermediate steps for these changes are rife in the fossil record, filling in gaps that scientists knew existed in whale evolution since Darwin's work on evolution. The last twenty years have yielded rich evidence, with transitional forms being found primarily in India and Pakistan. These fossilized remains show the gradual changes between related species, that modern cetacean's ancestors started out on land and were driven into fresh water and eventually the oceans, becoming better adapted and evolving the necessary body structures as they went.

It is often simple for opponents of evolution to point to a lack of evidence as their primary argument against Darwinian natural selection. However, given enough time, we have seen how the fossil record can be filled-in with new discoveries that show the transitional forms between related species. Of course, the process of fossilization that yields usefully preserved organisms is exceedingly rare, meaning the fossil record for many species will remain incomplete. These gaps are understandable considering the odds against fossilization occurring in the first place. The fact that we have such a complete record of transitional forms is a testament to the fact that evolution by natural selection is a fact of biology.

In terms of providing hard evidence for the process of evolution by natural selection, examples of cetacean evolution are prime sources of tangible evidence. In addition to marshalling evidence that shows gradual, documented, concrete evolution in whales, not only are these transitional forms documented in this unit and elsewhere, whales have a plethora of vestigial traits that are well documented and can be traced back to transitional forms. Examples of these vestigial traits include finger muscles present in the flippers of extinct whales, hind limbs that are still present but buried beneath tissue and disconnected from the skeleton, and the presence of the pelvic girdle.[39]

Classroom Activities and Strategies

Activities

Creating fossils: In order to capture the imagination of students and fully engage them in the topic, the creation of cast fossils will be a fun activity. There are multiple ways to create fossils in the classroom environment, including the use of plaster of Paris and dinosaur toys, leaves, or other found natural specimen to cast their fossils from. Students will be required to document the actual steps of fossil creation by the conclusion of this activity. This will help students to create fossils while instilling background knowledge about the fossilization process including permeneralization, how rare fossilization is, and what the products can look like based on local conditions. There are a number of activities and lesson plans available from the National Park Service which will be linked in Teacher Resources below.

Strategies

Guided Note Taking: Some content will require the use of guided notes and questions that will gauge understanding of the topic. Guided notes could be as simple as breaking down key ideas and supporting them with details and examples as directed by the teacher. Links to templates that are differentiated will be provided in the teacher resources section.

Venn Diagrams: Venn diagrams show the differences as well as the overlap between topics. Between each transitional form of ancestral whales, there are differences and overlapping areas of similarity. When students complete Venn diagrams they will see the transitional nature of evolution and the differences between each step. This is another way of anchoring students in evidence while allowing them to take notes.

Pair and Share: This is a well-known strategy, where students can think independently about a question before finding a partner and sharing their thoughts.

Think Time: It is often a challenge for educators to not answer their own questions. Students need to be given adequate time to think before answering, even if that means grappling with a topic that is difficult.

Research Project: There are a number of topics that students can engage on, research, and create a presentation to share. Research projects can be scaffolded based on student needs, but ultimately allow students to drive their own learning.

Seminar: Literacy skills around speaking and listening are critical for the students at my school. As such, the district has implemented professional development around creating and implementing seminars which allow students to drive discussions around topics. After students are familiar with the basic concepts about evolution by natural selection, have been exposed to the hard evidence and transitional forms apparent in the evolution of Whales, students should have the opportunity to discuss these findings and weight their implications.

Once students have received direct instruction and demonstrated some degree of mastery of the material I plan to implement a Socratic style seminar with students leading the discussion around key evolution topics. Rather than discuss a text which is common practice in English Language Arts, students will first explain key features found in the skeleton of the blue whale. Once key concepts are established by students in the discussion, I plan to introduce a diagram of the skeleton of a white shark which will allow for students to grapple with the differences and speculate as to the evolutionary causes for anatomical differences, despite similar environments. This seminar will essentially be a class discussion anchored in prior learning and visual literacy, along with practicing of speaking and listening skills. Additional resources for developing the seminar will be linked under teacher resources.

Additional Resources

Hands on activities and pre-created lessons from the U.S. National Park Service:

https://www.nps.gov/brca/learn/education/paleontology.htm

Seminar template from AVID:

http://pms.pasco.k12.fl.us/wp-content/uploads/pms/2014/08/Socratic-Seminar.pdf

Additional seminar resources from Paideia:

https://www.paideia.org/teachers/

http://www.debbiewaggoner.com/uploads/1/2/9/9/12998469/paideia_seminar_active_thinking_through_dialogue.pdf

Videos:

National Geographic on Whale Evolution: https://www.youtube.com/watch?v=-OCMx2VuP1U

NOVA, Great Transformations: https://www.youtube.com/watch?v=ujYNSDYIZKw

Computer animation: http://ocean.si.edu/ocean-videos/evolution-whales-animation

Appendix

Implementing District Standards

Tulsa Public Schools is moving away from the State of Oklahoma's Priority Academic State Standards (PASS) and is implementing Oklahoma's new Oklahoma Academic Standards (OAS). For science, this means that standards will be aligned with Next Generation Science Standards (NGSS) used throughout much of the nation. Two critical NGSS standards for this curriculum unit are included, along with Tulsa Public Schools additional clarification statements and additional framing.

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. Clarification Statement: Emphasis is on finding patterns of changes in the level of complexity of anatomical structures in organisms and the chronological order of fossil appearance in the rock layers.

MS-LS4-2

Apply scientific ideas to construct an explanation for the anatomical similarities and differences among modern organisms and between modern and fossil organisms to infer ancestral relationships. Clarification Statement: Emphasis is on explanations of the ancestral relationships among organisms in terms of similarity or differences of the gross appearance of anatomical structures

This unit aligns directly with MS-LS-1 and MS-LS-2 in that it provides direct evidence for the existence, diversity, extinction and change in life forms throughout Earth's history. Teachers may want to do additional work and framing around the fossil record to meet MS-LS-1 standards. Additionally, teachers and students can utilize this unit and the information contained within it to construct explanations for anatomical similarities and differences in organisms from the ancient fossil record to modern species. Patterns of change and levels of complexity are observable through the history of cetacean evolution covered by this unit, meeting MS-LS-2 standards.

Bibliography

Coyne, Jerry A. *Why Evolution Is True*. New York, NY: Viking, 2009.

Freeman, Scott, and Jon C. Herron. *Evolutionary Analysis*. Upper Saddle River, NJ: Prentice-Hall, 1998.

Futuyma, Douglas J. "Chapter 4." *Evolution*. Sunderland, MA: Sinauer Associates, 2005. N. pag. Print. Fundamental information about geology and rock strata.

Liu, Joseph. "Public's Views on Human Evolution." Pew Research Centers Religion Public Life Project RSS. 2013. Accessed July 19, 2016. http://www.pewforum.org/2013/12/30/publics-views-on-human-evolution/. Frames the public thinking around evolution topics.

"Rodhocetus." Rodhocetus. Accessed July 19, 2016. http://www.prehistoric-wildlife.com/species/r/rodhocetus.html.

"The Evolution of Whales." The Evolution of Whales. Accessed July 19, 2016. http://evolution.berkeley.edu/evolibrary/article/evograms_03. Provides commentary on how intermediate steps in whale evolution lived.

"The First Whale: Pakicetus." The First Whale: Pakicetus. Accessed July 19, 2016. http://www.amnh.org/explore/news-blogs/on-exhibit-posts/the-first-whale-pakicetus/. Provides information about the discovery of Pakicetus and its distinctive whale like features.

"Vestigial Structures." Zoology of Professor Struthers. 2003. Accessed July 19, 2016. http://www.abdn.ac.uk/zoohons/struthers/hind_limbs.hti.

"Whale Evolution and Adaptation." Whale Evolution. Accessed July 19, 2016. http://stories.anmm.gov.au/whale-evolution/. Provides an overview of whale evolution.

Zimmer, Carl. *Evolution: The Triumph of an Idea*. New York: HarperCollins, 2001. Explains the scientific landscape prior to Darwin's mid 19th century expedition and publications.

Endnotes

---

1. Liu, Joseph. "Public's Views on Human Evolution." Pew Research Centers Religion Public Life Project RSS. 2013. Accessed July 16, 2016. http://www.pewforum.org/2013/12/30/publics-views-on-human-evolution/
2. Zimmer, Carl. Evolution: The Triumph of an Idea. New York: HarperCollins, 2001.
3. Ibid
4. Ibid
5. Ibid
6. Fatima, Douglas J. "Chapter 4." *Evolution*. Sunderland, MA: Sinauer Associates, 2005. N. pag. Print.
7. Ibid
8. Zimmer, Carl. Evolution: The Triumph of an Idea. New York: HarperCollins, 2001.
9. Ibid
10. Freeman, Scott, and Jon C. Herron. *Evolutionary Analysis*. Upper Saddle River, NJ: Prentice-Hall, 1998.
11. Ibid
12. Zimmer, Carl. Evolution: The Triumph of an Idea. New York: HarperCollins, 2001
13. Ibid
14. Ibid
15. Ibid
16. Freeman, Scott, and Jon C. Herron. *Evolutionary Analysis*. Upper Saddle River, NJ: Prentice-Hall, 1998.
17. Zimmer, Carl. Evolution: The Triumph of an Idea. New York: HarperCollins, 2001. 8
18. Futuyma, Douglas J. "Chapter 4." *Evolution*. Sunderland, MA: Sinauer Associates, 2005. Print.
19. Coyne, Jerry A. *Why Evolution Is True*. 2009.
20. Ibid
21. Ibid
22. Ibid

23. Ibid
24. Ibid
25. "Whale Evolution and Adaptation." Whale Evolution. Accessed July 17, 2016. http://stories.anmm.gov.au/whale-evolution/.
26. Ibid
27. Ibid
28. Whale Evolution and Adaptation." Whale Evolution. Accessed July 17, 2016. http://stories.anmm.gov.au/whale-evolution/. Provides an overview of whale evolution.
29. "The First Whale: Pakicetus." AMNH. Accessed July 18, 2016. http://www.amnh.org/explore/news-blogs/on-exhibit-posts/the-first-whale-pakicetus/.
30. Ibid
31. Ibid
32. "The Evolution of Whales." The Evolution of Whales. Accessed July 18, 2016. http://evolution.berkeley.edu/evolibrary/article/evograms_03.
33. Ibid
34. Ibid
35. Coyne, Jerry A. *Why Evolution Is True*. 2009.
36. “Rodhocetus.” http://www.prehistoric-wildlife.com/species/r/rodhocetus.html
37. "Whale Evolution." AMNH. Accessed July 18, 2016. http://www.amnh.org/exhibitions/whales-giants-of-the-deep/whale-evolution/.
38. Coyne, Jerry A. *Why Evolution Is True*. 2009.
39. "Vestigial Structures." The Zoology of Professor Struthers. 2003. Accessed July 18, 2016. http://www.abdn.ac.uk/zoohons/struthers/hind_limbs.hti.