Your Inner Fish

INTRODUCTION

BRIEF BIOGRAPHY OF NEIL SHUBIN

Neil Shubin earned his Ph.D. in organismic and evolutionary biology from Harvard in 1987. In 2006, Shubin and his team found the fossil *Tiktaalik roseae*, an important intermediary form between fish and land animals. This discovery catapulted Shubin into the public eye, as he was named ABC News' "person of the week," gave several interviews about the fossil, and wrote *Your Inner Fish* to help educate the public about scientific topics. Since then, Shubin helped produce a television show under the same name to bring contemporary science topics into the classroom. Shubin was elected into the National Academy of Sciences in 2011, and he now works as a professor at the University of Chicago, focusing his research on limb development. Shubin has published numerous articles in scientific journals regarding his research on fossils like *Tiktaalik*, the embryonic development of salamanders, and gene expression in fish fins. He published his second popular science book in 2013, titled *The Universe Within*, that traces elements' paths from stars to fossils.

HISTORICAL CONTEXT

The theory of evolution is often credited to Charles Darwin, based on his research about animals in the Galapagos in 1858. Though Darwin's version of evolution (closer to what is now known as natural selection) is now widely accepted, the specific mechanics of how a species would evolve or adapt enough to be deemed a distinctly new species are still in question. The debate over evolution has been a controversial subject in America, with new opposition to the idea in the 20th and 21st centuries. With evolution, science seems to come into conflict with the religious belief in creationism or "Intelligent Design"—the idea that God created each animal fully formed, rather than there being a long process of mutation and adaptation to the environment. The National Academy of Sciences voted to accept evolution as scientifically sound and begin teaching it in schools in 1998. For decades, scientists focused on finding the mythical "missing link" that proves that species evolved from shared ancestral forms. Contemporary scientists look less towards individual links and more towards shared evolutionary pathways, by going back to the fossil record and the genetic information of modern-day animals. In 2006, Shubin and his team of paleontologists found the fossil *Tiktaalik roseae*, which offered a possible intermediary form between fish and land animals because of its small primitive legs and flexible neck. The scientific world exploded over whether this was "proof" of evolution.

RELATED LITERARY WORKS

Your Inner Fish seeks to both interest and educate the general public about scientific issues that might otherwise never receive attention, much like books such as Bill Bryson's *A Brief History of Everything* or *The Immortal Life of Henrietta Lacks* by Rebecca Skloot. Two of the most well-known popular science authors were Steven Hawking and Carl Sagan. *Your Inner Fish* specifically deals with the topic of evolution and comparative anatomy, drawing from Charles Darwin's classic *The Origin of Species* to the works of Richard Dawkins.

KEY FACTS

- **Full Title:** Your Inner Fish
- **When Written:** 2006-2008
- **When Published:** January 15, 2008
- **Literary Period:** Contemporary non-fiction, Pop science
- **Genre:** Popular Science, Non-fiction
- **Setting:** Arctic Circle, Philadelphia, Chicago

EXTRA CREDIT

Small-screen treatment. *Your Inner Fish* has also been made into a TV series on the PBS network, delving deeper into the evolutionary ancestry of humans through the lens of the *Tiktaalik fossil* and genetic experiments.

Paleontology from home. The University of Chicago maintains a website about the fossil *Tiktaalik roseae* that helps people see the anatomical structures of this fossil. Visitors to the website can fully explore both the fish and amphibian features of this ancient creature. The website can be found at tiktaalik.uchicago.edu.

PLOT SUMMARY

Neil Shubin, the author and narrator, opens the book with a story about his experience teaching a human anatomy course at the University of Chicago, even though his degree and research has been primarily in paleontology. The summer after he taught this course, he discovered a fossil fish from 375 million years ago that reframes the transition between fish and land animals. Fossils are the only way to see the past of every animal alive today and understand the development of the human body.

In the summer, Shubin goes to rocky cliffs of the Arctic Circle to look for fossils. The ancient fish he finds—when they are from the right period during the transition between water and land creatures—give valuable insights into the early stages of human skull, neck, and limb development. The fossil record generally follows a progression from the oldest fossils in the deepest rock layers to the most recent fossils in the higher layers. Based on the layers where fish and amphibians have been found, Shubin should look for rocks that are 375 million years old if he wants to find fossils of animals that bridge the divide between water creatures and land creatures.

Shubin starts looking in his hometown of Philadelphia, Pennsylvania with one of his paleontology students, Ted Daeschler. They find a small shoulder bone of a hynerpeton, an early amphibian from the Devonian Period whose fossils have also been found in Alaska and the Yukon. Shubin and Daeschler began looking to mount an Arctic expedition to a region of the Canadian Arctic that has similar rocks to Pennsylvania. A field expedition to the Arctic presents many logistical challenges, but Shubin, Daeschler, and Farish A. Jenkins lead a team through these tough conditions. In 2004, Steve Gatesy, a member of Shubin's team, finds a fossil fish of a species that has never been seen before. Over the next two years, Shubin and his team examine the fossil and find that it straddles the barrier between water animals and land animals. Shubin and the team decide to name the specimen **Tiktaalik roseae**.

Chapter Two focuses on hands, one of the most complex anatomical structures in the entire animal kingdom, and a hallmark of the human species. In the 1800s, the anatomist Richard Owens found that all land animal limbs have the same basic bone structure as the human arm, even if the limb looks radically different on the surface. Most fish have a very different structure in their fins, but certain fish have a very simple limb structure that matches land animals. Fossil preparators Fred Mullison and Bob Masek discovered that *Tiktaalik* is one of these fish. Eventually, fish descended from *Tiktaalik* probably moved out of the water altogether and became the first amphibians.

Shubin then moves to discussing genes and embryonic development of hands. Randy Dahn researches shark and skate embryos, looking for the genes that control protein production to form a fin to better understand the genetic information that directs fin and limb development in all animals. Limbs grow during the third to eighth week after conception, with a small bud of tissue called the zone of polarizing activity (ZPA) at the extreme tip of the end controlling all development. Researchers looking further into how the ZPA works found that there are more genes, called hedgehog genes, that control the development across the front-to-back axis of the whole body. These genes are almost identical in animals as different as flies, frogs, and mice. Dahn proved that the same genes are active in sharks and skates, though these fish have radically different limb-like structures than land animals. Genes therefore connect all living creatures.

Chapter Four highlights teeth, a special area of research for paleontologists because the hard material teeth are made of is especially likely to become fossils. The type of teeth an animal has also tells scientists much about that animal's lifestyle because teeth determine what kind of food an animal can eat. Mammalian teeth are far more complex than reptilian teeth. Shubin explains that he first became interested in fossil finding by finding early mammalian teeth. It took a lot of work for Shubin to learn to identify possible fossil sites in the field, but with the help of his advisor Jenkins, and expert fossil hunters Bill Amaral and Chuck Schaff, Shubin was finally able to find tiny mammalian teeth in the Arizona desert. Bill and Chuck later accompany Shubin on an expedition to Nova Scotia and find a reptilian jawbone that has mammalian style teeth, showing the developmental path from reptiles to mammals.

Shubin then introduces the complex human head, full of nerves that seem to follow insane paths. Four nerves in particular have a circuitous route through the body that stems from the development of human ancestors. As an embryo, the human head is a collection of four blobs, called arches. The different body systems, such as the inner ear and the throat, formed out of these four arches correspond to where those tricky nerves go. Shark embryos have these same arches and their nerves follow the same pattern, with the exception of the ear. Looking for the origins of the human head in worms that have a primitive backbone, the same arches form cartilage rods that help the worm filter water through its body.

From the head, Shubin moves to explaining the entire human body plan. Many animals have the same basic body plan with a front-back, left-right, and top-bottom axis. Shubin saw these similarities in his thesis work on embryonic limbs. The three germ layers that turn into all the anatomical structures of humans are also responsible for the same body systems in all other complex animals. The first germ layer, ectoderm, creates structures on the outside of the body, like skin. Mesoderm create middle structures like the skeleton. Endoderm creates structures on the inside of the body such as the organs. Scientists over the years did incredible work to find out how each layer knows what to become, eventually discovering the Organizer gene in DNA that controls an animal's body plan. Called Hox genes, these genes are found in every animal with a body. The more Hox genes an animal has, the more complex its body plan will be.

It seems like humans have simply added on to a recipe for bodybuilding that started all the way back in single-celled microbes. To count as a "body," a collection of cells has to work together to make a greater whole and have a division of labor among the cells. There is a fine balance of communication between the cells of a body that arose from the earliest animals with bodies, all the way back in the Precambrian Era. These primitive bodies were made out of the connective glue that holds human body cells together and lets them communicate. Structural molecules in the bones are especially important for allowing the whole body to work together. Even sponges, animals with the most primitive bodies of all, have most of the cell connection, communication, and scaffolding systems that humans have. Going even further back in evolutionary history, it seems the first bodies were formed by single-celled microbes that resemble the cells of sponges. They probably formed together to avoid being eaten by larger microbes, and were able to stick together because oxygen levels on the Earth were finally high enough to support a "body" of cells that needed more food.

Chapter eight focuses on the development of the human nose. Smell is one of the most primitive senses, with millions of odor molecules that bond to individualized chemical receptors in the human brain. While ancient jawless fish have relatively few chemical receptors in their brains, modern fish, amphibians, reptiles, and mammals each add on more receptors until reaching the incredible number of smells that the average mammal can detect. Yet though humans have the same receptors for smell that other mammals have, some have been rendered useless by generations of mutations because we are more dependent on our sense of sight.

Moving on to vision, fossils of eyes are rarely found because they are soft tissue that is not usually preserved. So scientists look to the vast range of eye types found in modern organisms. The human eye uses the same basic light gathering molecules (called opsins) that are found in invertebrates. The two types of eyes in vertebrates and invertebrates are made up of the same components. There is even a worm that has both kinds of eyes. After studying flies born with a mutation that caused them not to have eyes, scientists realized that the same gene controls eye production in almost all animals.

In Chapter Ten, Shubin examines the human ear, which gets far more complicated on the inside than it seems on the outside. Two of the three human ear bones seem to have developed bones that form part of the jaw in reptiles and fish. This hypothesis was somewhat confirmed by the discovery of "mammal-like reptiles" that have very small jawbones that recede back towards the reptilian ear. In *Tiktaalik*, Shubin can see the upper jaw support bone that became the ear bone in reptiles after the transition to land animals. The inner ear is very connected to the eyes, providing humans with a sense of balance. The antecedent to that organ is found in the neuromasts of fish, who need a way to feel the current going past their bodies. This connection between eyes and ears is upheld by genetic research that has identified two genes responsible for forming the inner ear—which are also partly involved in the eyes of primitive animals like jellyfish.

Putting all of this together, Shubin goes back over all the ways that the human body carries the history of life on Earth in its various anatomical structures. Returning to the biological "law of everything," Shubin explains that every living thing in the world has parents. This means that scientists can trace the development of anatomical structures (descent by modification) by figuring out how different species are "related" through common ancestors. The deep similarities among all animals then become more and more unique as subsets of animals that have the most in common show exactly when in the history of life groups such as reptiles, amphibians, mammals, and finally humans became distinct from one another. The biological record also gives hints about why certain illnesses and injuries are prevalent in humans. Knee injuries, obesity, hiccups, hernias, and mitochondrial diseases all point to the ways that human bodies repurpose body systems from other animals. Shubin ends the book looking towards the future, as scientists continue to unravel where the human body came from, and where it might develop in the future.

CHARACTERS

MAJOR CHARACTERS

Neil Shubin – The author and narrator of the book. Shubin is a paleontologist who studies fossils looking for information about evolutionary development. In the book, he primarily focuses on the Devonian period from 420 million years ago to 358 million years ago, looking for fossils that show the link between fish and land animals. He is credited with the 2006 discovery of the fossil **Tiktaalik roseae**, which marks a transitional stage between fish and amphibians, as it is a fish with primitive limbs. Shubin has written numerous scientific papers on the development of limbs in salamanders and the genes that control limb development.

Sir Richard Owen – The leading anatomist in the mid-1800s, who gathered and classified thousands of animal specimens from Africa, contributed to the discovery of fossils in England, and pioneered the field of comparative anatomy with his study of exotic creatures. Owen saw the essential similarity of animal limbs as a sign of Divine Order in creation.

MINOR CHARACTERS

Ted Daeschler – Shubin's student and partner in Pennsylvania who worked with him to find fossils near Pennsylvania highways. Daeschler found the fossil Hynerpeton that catalyzed their trip to the Arctic circle to look for more fossils from the Devonian period.

Jenny Clack – A colleague of Shubin's at Cambridge University and a fellow paleontologist who studied the fins of ancient fish and pinpointed the development of limbs meant for swimming.

Dr. Farish A. Jenkins, Jr. – Shubin's graduate advisor at Harvard who joined the expedition to the Arctic to look for Devonian fossils.

Jason Down – A student on Shubin's first Arctic expedition who found the first fossil bone fragments at the Arctic fossil site at Ellesmere Island.

Steve Gatesy – One of Shubin's colleagues who found a fish with a flat head on the Arctic expedition. This fish was later named **Tiktaalik** and became one of the best examples of the water-land transition discovered to date.

Sir Charles Bell – A Scottish surgeon who wrote the most important book on the anatomy of the human hand.

Charles Darwin – A scientist and natural biologist in the 1800s who studied new species in the Galapagos and started the theory of evolution by hypothesizing common ancestors for modern animals as an explanation for similar anatomical structures across different species.

Fred Mullison – A fossil preparator in Philadelphia who helped uncover the fin of the **Tiktaalik** fossil.

Bob Masek – A fossil preparator at the University of Chicago who helped uncover a "wrist bone" in the fossil **Tiktaalik**.

Randy Dahn – A researcher in Shubin's lab at the University of Chicago who performed experiments on the limb regions of shark and skate embryos.

Chuck Schaff – An experienced paleontologist and fossil finder who worked with Farish Jenkins. Schaff taught Shubin how to find fossils by carefully looking for any difference in mineral quality in the Arizona desert.

Bill Amaral – An experienced paleontologist and fossil finder who worked with Farish Jenkins and joined Shubin's fossil expedition to Nova Scotia. He found a key fossil containing teeth showing evidence of occlusion.

Paul Olsen – A leading fossil finder who worked at Columbia University and joined Shubin's fossil expedition to Nova Scotia.

Karl Ernst von Baer – A natural philosopher (now known as biologist) in the 1800s who first studied chicken embryos and found the three germ layers common to all embryos.

Hans Spemann – A German embryologist in the early 20th century who studied how cells differentiate in the embryo to become a body.

Hilde Mangold – A researcher in Spemann's lab who found the Organizer tissue, a patch of cells that sends messages to other cells in order to build the proper body plan. Her research went un-credited for years, and led to Spemann's Nobel prize.

Cliff Tabin, Andy MacMahon, and Phil Ingham – A group of researchers who independently became interested in the genetic body plans of flies, then collaborated to find the hedgehog gene that directs the front-to-back axis in flies.

Reginald Sprigg – An Australian mining geologist who found Precambrian fossils of strange impressions of disk, ribbons, and fronds. These "Sprigg's creatures" were later discovered to be the earliest creatures with bodies on Earth.

Martin Glaessner – An Austrian who lived in Australia in the mid-1960s and identified odd fossils found in Namibia, Africa, and Australia ("Sprigg's creatures") as fossils of the oldest creatures with bodies from the Precambrian era.

Nicole King – A researcher at the University of California at Berkeley who studied the DNA of choanoflagellates, single-celled organisms, to find the most basic versions of the genes of an animal that builds a body out of multiple cells.

Linda Buck and Richard Axel – Scientists who in 1991 found the genes that control the human sense of smell, comprising 3% of the entire human genome. They won the Nobel Prize in 2004.

Detlev Arendt – A scientist who studied the eyes of worms in 2001 and found a species of worm that has both normal invertebrate type eyes and a primitive version of vertebrate type eyes.

Mildred Hoge – The discoverer of the "eyeless" gene in fruit flies.

Walter Gehring – The leader of a team that investigated the "eyeless" gene in flies and was able to manipulate the DNA sequence of flies to grow eyes all over the flies' bodies.

Karl Reichert – A scientist in 1837 who studied the embryos of mammals and reptiles to find that the jaw bones of reptiles correspond to the ear bones of mammals.

Ernst Gaupp – A German anatomist who used Reichert's research to argue that the mammalian ear evolved from the reptilian jaw.

Nathaniel Shubin – Neil Shubin's son, who was 8 at the time this book was written.

TERMS

Arches The four bulges in a vertebrate embryo that form the head and throat of the animal. These four arches coordinate with four complicated nerves in the adult animal, and are found to create the same structures in animals as different as fish and humans.

Blastocyst The small ball of cells that is the embryo from the first couple days after conception to about three weeks after conception. The blastocyst attaches to the uterus wall of the embryo's mother, then begins to develop into the three germ layers that will form the entire body of the animal.

Choanoflagellate Close microbe relatives of simple bodied organisms like placazoans. Choanoflagellates provide a link between single-celled microbes and primitive organisms with bodies, as they have some of the properties of both kinds of life form.

Collagen The main structural protein found in between the cells of bone and skin. Collagen is strong when it is pulled, giving skin its elasticity and bone its flexibility.

Conodont Strange, spiky "shell" fossils with high levels of hydroxyapatite in their bone structure that confused paleontologists when they were first found. Eventually, a fossil impression of a jawless fish was found with conodonts in its mouth, revealing that conodonts were the first teeth.

Descent with modification The process through which evolution is thought to happen. Descent with modification means that children inherit most of their physical traits and body systems from their parents, but that small changes (modifications) might happen in some children due to mistakes or miscopies in the children's genetic code. If enough of these changes build up and completely change the physical traits of the children, a new species is formed. Through descent with modification, animal species can share many common traits (inherited from parents) while gaining unique traits (modifications due to mutations in DNA code).

Devonian Period The geologic period of the fossil record from 420 million-years-ago to 358 million-years-ago, commonly known as the age of the fishes. During this time period, complex fish developed, including many species that are still alive today. In the later Devonian years, animals that could survive on land began to appear. The time period is named for Devon, England, the first site where rocks of this age were studied.

"Eyeless" gene (Pax 6) The gene found by **Mildred Hoge** in the early 1900s and studied by **Walter Gehring** in flies. Pax 6 switches on eye formation in all animals with the complex vertebrate style eye.

Facial nerve One of the more complicated nerves in the human head, along with the trigimenal nerve. The facial nerve serves all the facial muscles and other muscles in the ear, which develop from the second arch in the human embryo.

Hedgehog gene and sonic hedgehog gene The gene found by **Cliff Tabin, Andy MacMahon, and Phil Ingham** that controls the body segments of flies so that the fly body forms properly with a head in front, body in the middle, and wings on the back. The version of this gene that controls the proper formation of limbs in chickens is called "sonic hedgehog" (named after the video game character Sonic the Hedgehog). All animals with limbs and bodies have a version of the hedgehog gene that keeps the body forming in proper alignment and proportions.

Hox gene A gene found in any animal with a body that helps control the body orientation and body plan of the animal. The more complex the animal's body is, the more Hox genes the animal has. The Organizer seems to control which Hox genes are active in which cells so that each cell performs its proper role in the body plan.

Hydroxyapatite A mineral made partially of calcium that gives teeth and bones their strength.

Hynerpeton A small amphibious animal that lived in the Late Devonian Period, about 360 million years ago. *Hynerpeton* walked on four legs and most likely lived in lakes and large river mouths and was able to spend long periods of time out of the water. **Shubin** and **Daechler** found a *Hynerpeton* fossil in Pennsylvania, prompting an expedition to find more fossils of the earliest limbed animals.

Malleus and incus Two of the three bones of the mammalian inner ear, along with the stapes. The malleus and incus develop from the first arch of the mammalian embryo, and correspond to two of the jaw bones that develop from the second arch in reptilian embryos.

Neuromast The sensory organ in fish that allows fish to be aware of the movement, speed, and direction of the water currents around the fish's body. Neuromasts are similar to the mammalian inner ear that gives land animals a sense of balance.

Occlusion The exact fit between the teeth of the upper law and the lower jaw in mammals, unlike reptilian teeth that do not touch each other when the reptile bites down. Occlusion allows mammals to grind down food more efficiently and eat more diverse food types.

Opsin The protein in the eye that signals to the brain that light has entered the light-sensing molecules. Different opsins allow animals to have black and white or color vision, but all opsins perform the same function of sending a chemical messenger up to the cells in the brain. All organisms able to sense light, including bacteria, have opsins.

Organizer A patch of tissue in the blastocyst that includes tissue from all three germ layers and seems to direct the body orientation, proportions, and growth for the entire body of the embryo. The organizer was discovered by **Hilde Mangold**, but **Hans Spemann** received the credit for its discovery after Mangold's early death. The discovery of Hox genes helped explain how the Organizer functions and controls the cells of the body.

Pax 2 The gene responsible for forming the inner ear in vertebrate animals.

Placazoan One of the most primitive creatures with a body, placazoans were discovered when they developed on the walls of an aquarium in the 1880s. Though they are flat plate shaped disks that only have four different types of cells, placazoans show the division of labor between cells to qualify as an actual multi-cellular body. Some cells take care of movement while others handle digestion of food. Placazoans have never been observed in a natural habitat.

Polychaete Primitive worms with bristles on their body. **Detlev Arendt** studied these invertebrate worms to find that they have a primitive version of the complex eye found in vertebrate creatures.

Precambrian Era All geologic time before 600 million-years-ago. It was originally thought that this time period held no complex organisms with bodies, until Sprigg's creatures, the earliest known organisms with true bodies, were re-dated by Martin Glaessner to be from the Precambrian era.

Proteoglycan A protein found in between the cells of healthy cartilage that soaks up water in bristle-like branches so that the proteoglycan can cushion the cartilage cells, and they can withstand compression force and bounce back to their original shape.

Stapes One of the three bones of the mammalian inner ear, along with the malleus and incus. The stapes is the smallest bone of the inner ear—and the only bone of the inner ear in reptiles—and develops from the second arch of the mammalian embryo. The stapes corresponds to the large upper jaw bone in fish.

Trigimenal nerve One of the more complicated nerves in the human head, along with the facial nerve. The trigimenal nerve serves all the structures that develop from the first arch of the human embryo, including the jaw and muscles in the ear.

Trithledont Small to medium size reptiles from the late Triassic to Jurassic periods (around 200 million-years-ago) that show a mammalian style jaw with signs of occlusion between the teeth. The teeth are reptilian in shape and size, but scrape against each other instead of not touching each other like normal reptilian teeth.

Zone of Polarizing Activity (ZPA) The small zone at the extreme end of an embryo's limb bud, where all of the activity of building the limb takes place.

THEMES

In LitCharts literature guides, each theme gets its own color-coded icon. These icons make it easy to track where the themes occur most prominently throughout the work. If you don't have a color printer, you can still use the icons to track themes in black and white.

SIMILARITIES BETWEEN ALL ANIMALS

The main project of *Your Inner Fish* is outlining the similarities among all animals, even those that look entirely different. Shubin focuses on the human body, comparing human anatomy to the anatomy of fish and other animals and arguing for ways that human anatomy may have developed from these other structures through evolution. These shared features may not be immediately noticeable, but can be traced through study of the fossil record and genetic research. In comparing humans and fish, Shubin brings in fossils of intermediate stages between fish and land animals – such as **Tiktaalik roseae**, a fish with primitive limbs – explaining how the body structures of fish are primitive versions of the body structures of humans that have been modified for life on land.

Genetic information also supports the similarities between animals, as in the genes for eyes that are similar across flies, mice, and humans even though each of these animals have eyes that look incredibly different on the outside.

Using comparative anatomy and genetics, scientists have been able to isolate many genetic mutations and study their affects in different animals such as mice or flies. Once a gene is thoroughly understood, scientists can then apply those findings to the human genome, often helping genetic illnesses or predicting genetic defects. While Shubin avoids speculating on a deeper meaning to these connections between all life on Earth, he does point to the ways these similarities can allow for scientific and medical research that improves the quality of human lives.

HISTORY OF LIFE

Your Inner Fish follows the path of life on Earth as it has developed and changed over time. Following the adaptations in a process called "descent with modification" is one way that scientists figure out where humans fit in among all life on Earth. From the basic law that every living thing on Earth had parents, scientists can build a family tree that traces the development of life from humans all the way back to single-celled organisms. The relationships between different species reflect how many anatomical features those two species share, and how long ago those two species separated to become distinct species. Using this tree, scientists can see when the "human" branch split away from the "primate" branch, then move back to see when primates split from other mammals, when mammals split from reptiles, reptiles from amphibians, and amphibians from fish. Shubin's work in paleontology helps fill in some of the gaps on this family tree of life, especially the groundbreaking discovery of a fish fossil called **Tiktaalik** that appears to be an intermediate creature in the transition from fish to amphibians, because it has anatomical features of fish and the limbs of an (underdeveloped) amphibian. *Tiktaalik* is thus an important ancestor to all land animals and therefore humans.

Shubin suggests that understanding how life has changed so far makes it easier to understand why things happen in the present and what might happen in the future. Many human body structures are holdovers from parts of human anatomy that came from earlier ancestors, who used that structure for a different purpose. As the species "human" emerged and adapted existing structures to new functions, some illnesses and injuries became more common, as when the knee is stressed by humans walking on two legs, or problems in the veins increasing due to the recent end of an active lifestyle. Looking at the history of each body part or body system can also help us better understand how complex organs like the eye work, so that we can better understand how illness or injury occurs and better treat those issues. With more information about the specific ancestral animals that human anatomy came from and how those structures have changed over the history of life on Earth, we might be able to solve some of the issues that stem from humanity's history of adaptations.

UNDERSTANDING COMPLEX CONCEPTS THROUGH SIMPLE ANALOGIES

After noting the similarities between different animal species, Shubin explains how studying the anatomy of simple animals can provide a tool to understand how the anatomy of complex animals works. This approach takes advantage of the ways that these animals are similar as a starting point to focus on the ways that species differ. Shubin uses the anatomy of relatively "simple" animals such as fish, sponges, or bacteria to make it easier to understand what is going on in the more "complex" animals like primates and humans. He then further breaks down the complicated human anatomy by organizing the book into chapters on different parts (teeth, heads, ears, eyes, hands, etc.), tightly focusing on just one part at a time make it easier to see how the entire body comes together in the end. Shubin follows the complex functions of each of these organs or body parts through the "simple" versions of these anatomical structures to make it easier to see why such complicated systems developed the way they did. For example, the complex human eye uses the same light gathering molecules (opsin) as bacteria do. Scientists can run experiments on bacteria to better understand how opsin works that would be impossible to do on a human eye due to all the variables in human vision. Then scientists can apply what they now know about bacterial opsin to human opsin and have a clearer picture of what the human eye is actually doing. Simple animals are a gateway towards studying the more complex animals, because the complex animals utilize many of the parts of simple animals and add to their body structures instead of creating completely different systems.

Aside from using simple animals to make it easier to understand complex animals, Shubin also uses simple analogies to help people understand complex concepts. As *Your Inner Fish* is a scientific book written for the general public, Shubin uses many tools to help ensure that the average person can easily grasp the sometimes-heavy scientific topics that he has made his life's work. For example, Shubin illustrates the concept of descent with modification through a family of clowns who only gain one new trait in each child, simplifying the idea of human generations that change multiple things from parent to child. Yet though he simplifies complex concepts to make them easier to understand at first, Shubin does not advocate for reducing complex concepts to their simplest roots and leaving it at that. Once he has simplified the concept and explained it thoroughly, he adds the layers of complexity back. These simple analogies or illustrations are a tool to help the larger public get interested in these topics and attain a basic understanding. Shubin then expresses the hope that his readers will continue to learn more about these scientific concepts, and he includes a large list of resources for further reading that go deeper into complicated topics of genetic research or medical issues.

SCIENTIFIC DISCOVERY

As Shubin explains the significance of discoveries like the fossil **Tiktaalik** or the fly genome project, he also celebrates the journeys that humans take to make these discoveries. Shubin intersperses his writing with episodes of his expeditions to the Arctic or other fossil fields and describes the work that goes into finding just one fossil. This makes the journey to finding the fossil as important and exciting as the discovery itself. Shubin also gives short backstories about the historical scientists that made important strides for the scientific community as a whole. These men and women made important contributions to the work of modern scientists, even if their scientific work seemed useless at the time. For example, Randy Dahn's work manipulating the genetic information of shark embryos might not be that useful in and of itself, but Dahn's discovery that shark embryos use the same process to develop their fins that humans use to develop their hands points to the possibility that human hands developed from an ancestral shark-like fin over thousands of centuries. Furthermore, Dahn's experiments on shark and skate embryos helped other scientists figure out how to better address genetic defects in humans who did not develop functional hands.

This theme thus emphasizes the idea that all scientific work is collaborative in some sense, as the scientists of today build on the discoveries of earlier scientists. Layers of past knowledge and discovery pave the way for future scientists to make even greater discoveries, some of which could benefit the entire human race. Shubin's book honors and recognizes all human discovery and points out how valuable this type of work is for all humanity, even if the applications of a specific discovery are not immediately obvious.

SYMBOLS

Symbols appear in **teal text** throughout the Summary and Analysis sections of this LitChart.

TIKTAALIK ROSEAE

This fossil fish (named with an Eastern Canadian Inuit word) was found in 2006 in a fossil site off the coast of Canada near the Arctic Circle. Neil Shubin and his team, who discovered the 375-million-year-old fossil (from the Devonian Period), studied its anatomy and discovered that the fish showed primitive "legs" with the same basic bone structure that eventually formed the limbs of land animals and mammals.

Tiktaalik also had a flexible neck that allowed it to turn its head without turning its whole body. Both of these anatomical structures, coupled with the fish's likely lifestyle in shallow stream beds close to land during the crucial time period when land animals started to develop, made *Tiktaalik* a good candidate for an intermediary stage between fish and land animals.

While popular culture might call *Tiktaalik* fish a "missing link" between fish and mammals, Shubin actually rejects this term. Firstly, the fish is no longer "missing," as it has been found, and it is not so much a singular link as one stage that life on Earth went through. *Tiktaalik* points to the ways that all animals are "linked" by their developmental history – some animals are just farther along on their specific developmental path. *Tiktaalik* represents the shared ancestry between all land animals, though modern species may look completely unrelated on the surface. Shubin uses the fish as a symbol of what human scientific inquiry can accomplish, making discoveries that change how we think about the history of humanity and all life on Earth.

QUOTES

Note: all page numbers for the quotes below refer to the Vintage Books edition of *Your Inner Fish* published in 2009.

Chapter 1 Quotes

How can a walk through the zoo help us predict where we should look in the rocks to find important fossils? A zoo offers a great variety of creatures that are all distinct in many ways. But let's not focus on what makes them distinct; to pull off our prediction, we need to focus on what different creatures share. We can then use the features common to all species to identify groups of creatures with similar traits.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 7

Explanation and Analysis

Shubin starts the book from a perspective that ties together all of the various animals that live in the zoo, no matter how different these animals might seem on the surface. These comparisons help Shubin make groups for animals that share certain traits. First of all, everything at the zoo shares the fact that it has a body. While that might seem like a useless thing to point out, the fact that all animals really have bodies is truly amazing given the amount of living things on Earth that do *not* have bodies, and the amount of time during which life on Earth was comprised only of single-celled organisms that did not have bodies. This fact allows scientists to predict a common ancestor for all creatures with a body, as bodies must have come from somewhere. Moving to a smaller group, a certain number of animals in the zoo have four legs. Though a chicken's wings and a lizard's legs may have little in common, chickens and lizards are both part of a group called tetrapods: animals that have four limbs. The first animal with four legs must be younger than the first animal with a body, so paleontologists like Shubin then know to look for the first animal fossil with a body in older rocks than they should look for the first animal with four legs, as the group of animals with four legs is smaller and must have split off more recently than the group of animals that have a body.

It took us six years to find it, but this fossil confirmed a prediction of paleontology: not only was the new fish an intermediate between two different kinds of animal, but we had found it also in the right time period in earth's history and in the right ancient environment. The answer came from 375-million-year-old rocks, formed in ancient streams.

Related Characters: Neil Shubin (speaker)

Related Themes:

Related Symbols:

Page Number: 24

Explanation and Analysis

Shubin's book explains the history of human life through the somewhat surprising lens of a fish fossil found in the Canadian Arctic from rocks 375 million years old. This fish fossil, later named *Tiktaalik roseae*, shows one of the first primitive versions of legs with all of the bones that humans have in our limbs. As amazing as this discovery is on its own, it is even more significant to paleontologists like Shubin, because it confirms the predictions they had made about the fossil record and supports the logical progression of life on Earth that Shubin and his team had hypothesized based on previous observations. The fossil record shows only fish in rocks 385 million years old, and fully formed amphibians capable of living on land in rocks 365 million years old, meaning that the transition from water to land had to happen around 375 million years old. Shubin also guessed from previous limb analyses that the first limbs developed to help animals swim, not walk. *Tiktaalik*'s lifestyle in shallow streams, as evidenced by the type of sedimentary rock in which the fossil was found, validates this idea and furthermore places early limbed fish close to land where the transition to actually living on land seems more likely. Shubin and his colleagues spent six years looking for this fish fossil, and were rewarded with a fossil that answers many questions about how life moved from water to land, and also fits into the framework that paleontologists have built about the history and development of all life on Earth.

I can do a similar analysis for the wrists, ribs, ears, and other parts of our skeleton—all these features can be traced back to a fish like this. This fossil is just as much a part of our history as the African hominids, such as Australopithecus afarensis, the famous "Lucy." Seeing Lucy, we can understand our history as highly advanced primates. Seeing Tiktaalik is seeing our history as fish.

Related Characters: Neil Shubin (speaker)

Related Themes:

Related Symbols:

Page Number: 26-27

Explanation and Analysis

Tiktaalik, the fish fossil found by Shubin and his team in 2006, helps show the first animals to develop true legs. As humans also have legs, this fish is an important ancestor during the transition between water-dwelling creatures with no legs and land-dwelling creatures who depend on legs. Similarly, the famous "Lucy" was a skeleton that shows a transitional stage between the great apes and true human beings. Lucy tells scientists about how humans developed to be unique from apes, and the type of lifestyle they had that eventually led to the animal that we think of as modern humans, *homo sapiens*. *Tiktaalik* goes even further back in the long history of life on Earth, revealing how the first primitive limbs developed and giving insights as to why limbs might have become useful for animals. *Tiktaalik* is thus an ancestral cousin to all animals that walk on land using limbs. *Tiktaalik* paves the way for human life just as much as animals like Lucy did, even if *Tiktaalik* lived much further back in history.

Chapter 2 Quotes

Some fish, then, had structures like those in a limb. Owen's archetype was not a divine and eternal part of all life. It had a history, and that history was to be found in Devonian age rocks…

Related Characters: Neil Shubin (speaker), Sir Richard Owen

Related Themes:

Page Number: 33

Explanation and Analysis

Shubin focuses on the process that create the anatomical structures we see in animals today. For Shubin, explanations that involve "divine" intervention do not adequately interpret the vast array of similarities among all species of life on Earth. Rather than all species springing into being as fully formed versions of distinct animals, the specific physical traits of each animal are linked to each other through the development of life, as one species adapts and changes to become a new species due to environmental pressures. Unlike Richard Owen, the 19th century biologist who first catalogued the similarities in limbs, Shubin looks for a more logical progression in animals than an unchanging creation of divine origins. Limbs are not a gift from a higher power that was granted one day—they are the result of thousands of generations of animals who gradually lived lives where having limb-like structures was more beneficial than not having limb-like structures. This long series of changing limb structures is documented in the fossil record, beginning in the Devonian Age Rocks (from 420-358 million years old) that Shubin studies.

Do the facts of our ancient history mean that humans are not special or unique among living creatures? Of course not. In fact, knowing something about the deep origins of humanity only adds to the remarkable fact of our existence: all of our extraordinary capabilities arose from basic components that evolved in ancient fish and other creatures. From common parts came a very unique construction. We are not separate from the rest of the living world; we are part of it down to our bones and, as we will see shortly, even our genes.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 43

Explanation and Analysis

The similarities between animals actually enhance Shubin's appreciation of how special human life is. The truly remarkable thing about life on Earth is that all life is connected. As the surface of the animal primarily displays what is unique about them, genes are actually one of the best places to see the ways that animals are all the same. Humans have the same genes as some mammals, and the same genetic building blocks (DNA sequences) that come together at the foundation of all life. A fish may seem much simpler than (or altogether different from) a human, but the fish's genes already have the start of every amazing thing that humans can do. Humans can use these ancient genes for new purposes – including the scientific capabilities to study these similarities at all.

Chapter 3 Quotes

His experiments may seem to be a bizarre way to spend the better part of a year, let alone for a young scientist to launch a promising scientific career. Why sharks? Why a form of vitamin A?
To make sense of these experiments, we need to step back and look at what we hope they might explain. What we are really getting at in this chapter is the recipe, written in our DNA, that builds our bodies from a single egg.

Related Characters: Neil Shubin (speaker), Randy Dahn

Related Themes:

Page Number: 44

Explanation and Analysis

Shubin explores the work of Randy Dahn, a researcher at the University of Chicago who dedicated his time and resources to studying the effects of vitamin A on the development of shark fins. As Shubin acknowledges, this seems like a potential waste of a very smart young man. Sharks are not all that important to the average human, and research on sharks might not seem like it will benefit humankind. For those who believe that the point of science is to improve human lives, Dahn's experiments appear useless. Yet Shubin points out that research on sharks can actually be very profitable to humans due to the fundamental genetic and developmental similarities between sharks and humans, and so Dahn's work on sharks can be applied to the development of human limbs later on down the line. Shubin does not really address the ethical question of whether sharks should be used to benefit humans, focusing only on the good that scientific experiments on animal embryos can do for human health and to improve the human condition.

Experiment after experiment on creatures as different as mice, sharks, and flies shows us that the lessons of Sonic hedgehog are very general. All appendages, whether they are fins or limbs, are built by similar kinds of genes. What does this mean for … the transition of fish fins into limbs? It means that this great evolutionary transformation did not involve the origin of new DNA: much of the shift likely involved using ancient genes, such as those involved in shark fin development, in new ways to make limbs with fingers and toes.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 58

Explanation and Analysis

Sonic hedgehog, the slightly silly name for the gene that controls body development and limb development in all animals, shows that the same genetic information can make a fin or an arm depending on what animal embryo the gene is a part of. Genetic codes such as the DNA sequence that controls the growth of a limb point to how similar animals are underneath the surface. Fins and arms look nothing alike, but they have the same DNA in the embryonic stage.

As well as highlighting the fundamental similarity between all animals, this gene also reveals part of the history that brought life on Earth to this point. Shubin reinforces evidence that animals with fins appeared before animals with limbs, and then focuses on the transition between fins and limbs. If the sonic hedgehog gene can be repurposed from making a fin to a limb, then genes could also be repurposed for all kinds of structures and uses. This showcases the adaptability of life on Earth, as animals continue to change to achieve the best life in their specific environment. Adaptations like limbs for land animals do not require entirely new genes; these changes just require using old genes in revolutionary ways.

Chapter 4 Quotes

❝❝ The power of those moments was something I'll never forget. Here, cracking rocks in the dirt, I was discovering objects that could change the way people think. That juxtaposition between the most child-like, even humbling, activities and one of the great human intellectual aspirations has never been lost on me.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 67

Explanation and Analysis

As a graduate student, Shubin started hunting for fossils in the field by looking for the tiny teeth of early mammals. These "objects that could change the way people think" are the teeth that show signs of occlusion – the precise fit between teeth that marks the specialized motion of mammalian chewing instead of the ripping and shredding of reptilian chewing. These teeth help shape Shubin's opinion of humanity's place in the world. Humans are not "better" or more developed than all other animals—they are just made up of parts that first appeared in very small primitive animals.

Even the practice of finding fossils keeps Shubin from taking the human condition too seriously. Fossil work takes him digging in the dirt, a "child-like" activity, as he says, in order to make his living. Shubin celebrates the impulses behind scientific discovery, as well as the actual discoveries that he and his colleagues make.

❝❝ ...in teeth, mammary glands, and feathers, we find a similar theme. The biological processes that make these different organs are versions of the same thing. When you see these deep similarities among different organs and bodies, you begin to recognize that the diverse inhabitants of our world are just variations on a theme.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 80

Explanation and Analysis

As Shubin explains the biological processes that form human teeth, he compares this mechanism to the development of feathers and mammary glands. Though these three organ systems are incredibly different, both in form and function, they form in the same way during the embryonic stage of the organism. Each of these different anatomical structures are made out of two layers of tissue that fold around each other to make one complex body system with many types of specialized cells. Shubin hypothesizes that this process first developed to make teeth, as teeth are found very early in the fossil record, and it was then tweaked to make the other structures as things like feathers and mammary glands became useful to animals. Over and over again, Shubin highlights that animals do not invent entirely new structures to cope with new environmental pressures. Organisms on Earth reuse and repurpose old anatomical structures and processes, maintaining the "deep similarities" inside different species even if their outward appearances seem radically different.

Chapter 5 Quotes

❝❝ If you want to understand the wiring and plumbing in my building, you have to understand its history, how it was renovated for each new generation of scientists. My head has a long history also, and that history explains complicated nerves like the trigeminal and the facial.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 86

Explanation and Analysis

Shubin explains the path of cranial nerves using the analogy of wiring and plumbing in an old building. Like electrical wires or plumbing distribute electricity and water throughout a building, the cranial nerves deliver electrical impulses from the brain to muscles and bones in the head to tell them what to do. These nerves, especially the trigimenal and the facial, have circuitous paths through the various structures of the human head that seem to make no sense. Shubin expects that the human body would naturally want to form the easiest pathways for the nerves through the head to save on energy, like a good plumber or electrician would run the wires of a house so that every room was connected in the most efficient and shortest path. However, a plumber who is working to update a building that already has a system of plumbing would be constrained by the previous pipes and might be forced to run new pipes in a way that is not the most intuitive or the most efficient. In order to achieve the new purpose, as technology or plumbing advances, the plumber has to rework the old system in a way that would never happen if the new purpose had been in mind from the start. Likewise, the human head is not built new from scratch, but actually develops out of the same process that fish use to develop their heads. That means that the nerves of the human head follow paths that were first made for fish heads, but are now asked to serve muscles that never existed in a fish. To accommodate these new demands, the old nerves find odd ways to connect to every muscle that develops from the same area of the embryo as they do. It may not be the path that makes the most sense at first glance, but it is the path that made the most sense at each new stage of the head from fish to human.

❝❝ What I've just given you is one of the big tricks for understanding the most complicated cranial nerves and large portions of the head. When you think trigeminal nerve, think first arch. Facial nerve, second arch.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 87

Explanation and Analysis

In this chapter focusing on the mechanisms of the human head, Shubin unpacks two nerves that are often very difficult for anatomy students to master. The trigimenal nerve and the facial nerve are two nerves in the head that connect to multiple seemingly random muscles in the face and ears. Furthermore, the two nerves overlap and cross each other, making them redundant for a job that could more easily be done by just one nerve. Shubin looks back at the embryonic version of the human head, a more simplified construct before all the aspects of the human head have developed. Like fish and sharks, human embryos have four blobs in the head called arches. These arches contain the cells that become many structures in the head. The first arch becomes the exact same muscles and bones in the face that the trigimenal nerve connects to in mature humans. The second arch becomes the muscles and bones in the face and ear that are connected to the facial nerve. One of Shubin's main goals throughout the book is to simplify the long and complicated history of human anatomy into easily understandable paths. In the development of the human head, Shubin is able to simplify the complicated nerve system in the human head by looking to the human embryo and the cranial nerves in fish.

Chapter 6 Quotes

❝❝ As they looked at embryos, they found something fundamental: all organs in the chicken can be traced to one of three layers of tissue in the developing embryo. These three layers became known as the germ layers. They achieved almost legendary status, which they retain even to this day.

Related Characters: Neil Shubin (speaker), Karl Ernst von Baer

Related Themes:

Page Number: 99

Explanation and Analysis

Shubin investigates the body plans of many different animals in this chapter, noting how the early stages of species as different as mice, chickens, lizards, and humans all share the same germ layers at the very beginning stages of development. First found in chickens by Karl Ernst von Baer and his students, these layers appear a few days after conception and direct the development of every single part of the body that the mature chicken will have. This first similarity ties all the various body systems of a chicken, from brain to bones, to one of these three layers. They are ordered from inside to outside as the endoderm, which forms all the inner structures of an animal, the mesoderm, which develops into middle structures like bones, and the ectoderm, which forms the outer structures like skin.

As amazing as it is that these three simple cell layers can become a full animal, the truly remarkable thing about the germ layers is that they are found in every complex animal that forms a blastocyst after conception, and that the three different layers develop the exact same structures in the mature animal. While a chicken's skin and feathers may look very different from a lizard's scales, they both come from the ectoderm of their respective embryos. Even the human body, which seems so different from the other animals at first glance, is exactly the same at this early embryonic stage. The "legendary" status of the germ layers survives because it holds true for so many animals and gives so much information about the eventual structures that an animal will have. Looking at the embryo in this form, it is easy to see how Shubin connects all animals to the same anatomical beginnings.

Mangold had discovered a small patch of tissue that was able to direct other cells to form an entire body plan. The tiny, incredibly important patch of tissue containing all this information was to be known as the Organizer… Today, many scientists consider Mangold's work to be the single most important experiment in the history of embryology.

Related Characters: Neil Shubin (speaker), Hans Spemann, Hilde Mangold

Related Themes:

Page Number: 106

Explanation and Analysis

Hilde Mangold, a student of Hans Spemann, took Spemann's work on embryonic cells one step further to find the patch of tissue that tells event he three germ layers how to form. This Organizer is a minuscule region of the early embryo, found 1 to 3 days after conception depending on the organism, that sends the directions to every single other cell that the embryo will produce to ensure that the embryo develops into a properly formed and proportioned mature body. Mangold isolated the Organizer patch, which includes pieces of each of the three germ layers that will later control the development of the inner, middle, and outer body systems of an animal, and transplanted this Organizer patch onto an embryo of another species. The embryo developed with a fully formed salamander body attached to its back, proving that the Organizer has all the information necessary to create a full body.

Mangold's work was significant both because of the patch of tissue that she found and her physical skill in surgically operating on tiny salamander embryos so that she could remove the Organizer and attach it to another embryo in a way that the embryo was still viable. This surgery at a cellular level required immense precision, and yet was unable to clarify how the Organizer actually works. Mangold's ground-breaking discovery opened the door for later scientists to pick this work back up once genetic experiments became possible. Mangold's foundation allowed genetic research to pinpoint exactly how the Organizer directs other cells, making a huge leap in the study of embryology.

Chapter 7 Quotes

Take the entire 4.5-billion-year history of the earth and scale it down to a single year, with January 1st being the origin of the earth and midnight on December 31st being the present. Until June, the only organisms were single-celled microbes, such as algae, bacteria, and amoebae. The first animal with a head did not appear until October. The first human appears on December 31st. We, like all the animals and plants that have ever lived, are recent crashers at the party of life on earth.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 119-120

Explanation and Analysis

The history of life on earth is incredibly long, and Shubin works in time periods hundreds of millions of years ago when investigating the animals that eventually developed into the ancestors of humans. Shubin uses the analogy of a year-long calendar to make these time periods easier to visualize. Though human history seems long to us, and life spans are only a small fraction of the thousands of years of known human activity on Earth, the emergence of humans on Earth is truly miniscule in light of the long, long history of all life on Earth. It is easy to be human-centric when considering the history of the world, but that focus would ignore 364 days of the Earth "year." For nearly half the year (meaning nearly 2 billion years), the only life on Earth was single-celled. After that, it took 4 months (about 1,500,00 years) for single-celled organisms to gradually develop into an animal that has a head. It is then another 3 months (1,125,000 years) before the animal with a head develops into a human. Coming from that perspective, the entire lifetime of a single human is not even worth registering on this calendar. Though it is obviously important to continue to study human anatomy, this long history means that there is a lot to learn from studying simple creatures, as they were the only creatures on Earth for very long stretches of time. A new perspective on the history of all life on Earth justifies the amount of time that Shubin spends on primitive animals in this book.

Chapter 8 Quotes

Fossils and the geological record remain a very powerful source of evidence about the past; nothing else reveals the actual environments and transitional structures that existed during the history of life. As we've seen, DNA is an extraordinarily powerful window into life's history and the formation of bodies and organs. Its role is particularly important where the fossil record is silent.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 139

Explanation and Analysis

As a paleontologist, Shubin recognizes that the fossil record can tell scientists a lot about the history of life on Earth, but it can't give all the information required. Fossils are rare, hard to find, and there is no guarantee that all the transitional structures of a species were preserved in the right conditions for study. Shubin was incredibly lucky to find an almost intact skeleton for his major find, the *Tiktaalik* fish fossil that shows primitive legs as a transitional stage between water animals and land animals. To fill in the gaps in the fossil record where no fossils have been found yet, scientists turn to the genetic information that has been passed down from different species over millennia. Using DNA to answer these questions points to both the collaborative nature of scientific discovery – turning to another field of study to supplement Shubin's original interest in paleontology – and the line of descent that runs through all creatures. DNA is useful because the versions of specific genes in organisms that are more primitive, such as bacteria or microbes, show the "original" state of a gene that can be compared to the multiple versions found in more complex animals, moving through flies, amphibians, reptiles, mice, and even humans, to see where the changes and adaptations have been made to the genes over time. Shubin brings both these areas of study together in his book to give a more complete vision of the history of life on Earth.

If you compare the odor genes of a mammal with the handful of odor genes in a jawless fish, the "extra" genes in mammals are all variations on a theme... This means that our large number of odor genes arose by many rounds of duplication of the small number of genes present in primitive species.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 145-146

Explanation and Analysis

As Shubin catalogues the many similarities between animals of different species, he delves into the genetic information of these animals to help explain how the structures developed in each. Focusing just on the sense of smell, Shubin traces the odor genes of jawless fish to the far more complex sense of smell found in mammals. At the genetic level, jawless fish have relatively few genes that control odor perception, while mammals have a thousand or more of these genes. It logically follows that the organism with more genes dedicated to a sense of smell would have a better ability to discriminate between different odors.

Shubin then turns to how mammals would have gotten so many odor genes. As these genes are so similar, it seems that the ancestors of mammals continually copied the simple odor genes and made small "errors" each time that helped the animal key into new odors that the previous generation could not detect. This copy and mutate system helped the animals who had a better sense of smell find more food and avoid predators, favoring animals who copied and mutated more genes in order to discriminate among even more scents. Mammals' superior sense of smell did not necessitate inventing new genes for smell, just tiny changes and duplications of the genes that jawless fish already had. Though mammals and fish seem to have different senses of smell at first glance, they actually use the exact same system at the genetic level.

Chapter 9 Quotes

Our eyes have a history as organs, but so do eyes' constituent parts, the cells and tissues, and so do the genes that make those parts. Once we identify these multiple layers of history in our organs, we understand that we are simply a mosaic of bits and pieces found in virtually everything else on the planet.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 149

Explanation and Analysis

The history of life on Earth has many levels. Shubin focuses on the history of entire animals by breaking them down into simple parts – the organs of the animals that give each chapter a theme. Within the eye-themed chapter, Shubin breaks the organ down further into the parts that make up the eye, so that the pathway from simple, primitive animals to complex animals becomes obvious. The opsins in the eye that detect light were first developed in invertebrates, and the path that opsins take to reach cells' nuclei is found in bacteria. The processes and proteins that are essential for human eyesight are found all the way back in bacteria – the first living creatures from the earliest history of life on Earth. By breaking down the eye into small parts, Shubin can better find the connections between humans and bacteria, even though bacteria seem to be the furthest thing from the human body. Similar stories can be told about almost every other body system that humans have, as Shubin does for the ears, nose, limbs, body plans, and other body systems over the course of the book.

Gehring's lab found they could use the mouse gene to trigger the formation of an extra fly eye anywhere: on the back, on a wing, near the mouth. What Gehring had found was a master switch for eye development that was virtually the same in a mouse and a fly. This gene, Pax 6, initiated a complex chain reaction of gene activity that ultimately led to a new fly eye.

Related Characters: Neil Shubin (speaker), Walter Gehring

Related Themes:

Page Number: 156

Explanation and Analysis

With the rise of genetic experimentation, scientists like Walter Gerhing are better able to isolated the DNA sequences that direct the formation of different body systems. Gehring did many experiments on flies to isolate the gene that directs eye development, called Pax 6, and then found that this same gene was responsible for eye development in most animals that had the same complex camera-type eye as most highly developed vertebrate animals. Though fly eyes, mouse eyes, and even human eyes look incredibly different, they all have the same gene that starts the eye-building process in the embryo. Shubin glosses over this process a little by leaving it as a "complex chain reaction of gene activity," so that his book is as accessible as possible to the general public. Though Shubin leaves complicated eye development at its most simple explanation, he focuses on the significant discovery that the initial gene is shared by many different animals. The production of eyes in general can then be traced back to a common ancestor that first had the primitive version of the Pax 6 gene that is found in all of these creatures.

Chapter 10 Quotes

As he describes the ear-jaw comparison, his prose departs from the normally staid description of nineteenth-century anatomy to express shock, even wonderment, at this discovery. The conclusion was inescapable: the same gill arch that formed part of the jaw of a reptile formed ear bones in mammals. Reichert proposed a notion that even he could barely believe - that parts of the ears of mammals are the same thing as parts of the jaws of reptiles.

Related Characters: Neil Shubin (speaker), Karl Reichert

Related Themes:

Page Number: 160

Explanation and Analysis

Shubin celebrates the amazing moment of making a significant scientific discovery by detailing the moment that Karl Reichert relates his conclusions about the development of mammalian ear bones from reptilian jaw bones. Though this discovery might not have much significance in the everyday lives of people, it has huge ramifications for the origin of species. If Reichert can prove that a part of mammalian anatomy, specifically the malleus and incus bones in the middle ear, is directly related to reptilian anatomy, then the hypothesis that mammals descended from reptiles can be validated. At the time, Reichert does not have enough information to fully prove his hypothesis, but his findings allow other scientists to look for the intermediate stages that prove the relationship between mammals and reptiles. Using that information may lead to a deeper understanding of the human body, by tracing certain body systems (like the inner ear) back to these reptilian roots.

Jellyfish do not have either Pax 6 or Pax 2: they arose before those genes hit the scene. But in the box jellyfish's genes we see something remarkable. The gene that forms the eyes is not Pax 6, as we'd expect, but a sort of mosaic that has the structure of both Pax 6 and Pax 2. In other words, this gene looks like a primitive version of other animals' Pax 6 and Pax 2.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 172

Explanation and Analysis

As Shubin explains the history and development of the human eye, he examines the genes that control the production of the eye in embryos. This gene, called Pax 6, is found in many other animals – even those that don't have the same type of eye as humans. Jellyfish are some of the simplest animals on the planet, and likely developed between 700 and 500 million years ago. This means they developed before many fine tuned organs fully adapted. Yet remarkably, the box jellyfish genome includes a primitive version of the Pax 6 gene that seems to be mixed with the Pax 2 gene that controls eye production in many complex animals such as mammals. The conjoined Pax 6 and Pax 2 gene in box jellyfish suggests that the two different genes actually come from one shared source. The connection between these two genes explains why many birth defects or mutations that affect the eyes in humans also affect the inner ear. With that knowledge, doctors can be better prepared to treat children with conditions that damage the eyes by looking for problems in the inner ear as well. The jellyfish gene, and its similarity to the human gene, help modern scientists see how different organs in humans might actually be closely related in their primitive versions.

Chapter 11 Quotes

❝❞ This law is so profound that most of us take it completely for granted. Yet it is the starting point for almost everything we do in paleontology, developmental biology, and genetics. This biological "law of everything" is that every living thing on the planet had parents.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 174

Explanation and Analysis

As Shubin has written the history and development of the human body, he has constantly looked for ways to simplify complex concepts so that they are easy to explain. In this final chapter, he distills all of biological inheritance to the simple law that "every living thing… had parents." This law of everything first points out a major similarity between all living organisms. The most important thing that all organisms receive from their parents is their genome. During early embryonic development, organisms get the genetic information that tells a creature how to build, regulate, and maintain their specific body from their parents, meaning that the genetic information is copied for the new child. During the copying process, mistakes or misprints can occur, explaining how new traits might arise that are not seen in either parent. These mutations ensure that the population as a whole can adapt to their environment by favoring mutations that help an animal survive.

The genetic information that children inherit from their parents also allows biologists to recreate the family tree of life on Earth, by going back through the genomes of animals and analyzing the relationship between two species based on how much genetic information they have in common. Two related species copied from a shared parent or grandparent somewhere back in their lineage, then gradually became distinct as the small mutations in each generation built up. The fossil record can help fill in the gaps of intermediate stages that occurred as the two species steadily branched off from this parent. Knowing that every living thing has parents, and every new gene has to come from some original copy, paleontologists can look for fossils or a living primitive parent that show how a new body system developed. This one simple law brings order to a process that would otherwise devolve in the chaos of the many varieties of species on Earth.

❝❞ Replace this family circus with real features - genetic mutations and the body changes that they encode - and you have a lineage that can be identified by biological features. If descent with modification works this way, then our family trees have a signature in their basic structure... Obviously, the real world is more complex than our simple hypothetical example. Reconstructing family trees can be difficult if traits arise many different times in a family… or if traits do not have a genetic basis and arise as the result of changes in diet or other environmental conditions.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 177

Explanation and Analysis

Shubin illustrates the concept of descent with modification using a family circus made up of clowns. The clown family adds on one new trait per generation, so that Shubin can tell which generations are most closely related by checking how many traits each generation has in common. The generation with curly hair, big feet, and a red nose are more closely related to the generation that has big feet and a red nose than they are to the generation that has only a red nose. Shubin then applies that concept to the real circumstances of decent with modification with actual humans – where far more than one trait may change with each generation. Other factors also complicate Shubin's simple model, as he acknowledges the effects that the environment has on the outward traits of organisms. Yet the simple model is still a sufficient explanation of descent with modification that can then be used to puzzle together the tricky layers of relationships that humans have with each other, or that the human species has with other species. Comparing humans to any mammalian species will bring up more physical characteristics in common than comparing humans to a reptilian species, meaning that humans are more closely related to other mammals than they are to reptiles. Though these trees have numerous branches and may need to be reassessed many times to properly fit all the observed data, the basic principle of descent with modification holds true enough that scientists can use this knowledge to make predictions about missing places in the family tree and how related animal species are.

Our humanity comes at a cost. For the exceptional combination of things we do - talk, think, grasp, and walk on two legs - we pay a price. This is an inevitable result of the tree of life inside us.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 185

Explanation and Analysis

After Shubin explains how human anatomy can be traced from the physical characteristics of primitive creatures such as fish, amphibians, or even single-celled bacteria, he turns to examining the ways that this long history of descent with modification can actually cause problems for human health. The human lifestyle puts pressures on the shared body systems that no other species requires, as primitive creatures do not have the same complex functions unique to human life. Because the human body attempts to do these new things with a body that originally developed for more primitive functions, problems crop up as the body systems are adapted to new ways of moving or working. Injuries such as knee displacement point to the changes that human habits make to limbs that originally were not meant to support the stress that walking on two legs puts on these joints. Talking creates difficulties for the throat muscles, as they have to be flexible enough to move for the incredible range of speech sounds that humans uniquely produce, but rigid enough to hold breathing passages open. The trade-off for human abilities is that the body systems that support them have to carry different loads than the original environmental conditions that created these body systems in the distant history of life on Earth.

These are not esoteric discoveries made on obscure and unimportant creatures. These discoveries on yeast, flies, worms, and, yes, fish tell us about how our own bodies work, the causes of many of the diseases we suffer, and ways we can develop tools to make our lives longer and healthier.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 198

Explanation and Analysis

Shubin has focused much of the book on animals that are not normally deemed important to human health. Yet because the body systems of humans developed from the physical characteristics and genetic information carried within these simple animals, scientists who study these unglamorous creatures can actually make significant discoveries that address human concerns of health and well-being. The fundamental similarities between all living things on Earth mean that many of the complicated systems that keep human beings alive actually began their development in simple, ancient organisms like yeast or fruit flies. There are even benefits to studying these smaller creatures because scientists can perform experiments that would be impossible to do on humans for practical or ethical reasons. Biologists who study so-called "obscure and unimportant creatures" are not wasting their time or resources, but indirectly contributing to the larger body of knowledge that all scientists share. The more that the scientific community as a whole learns about the development of life on Earth, the better they can address diseases and injuries that specifically affect the quality of human life.

Apollo 8 was a product of the essential optimism that fuels the best science. It exemplifies how the unknown should not be a source of suspicion, fear, or retreat to superstition, but motivation to continue asking questions and seeking answers. Just as the space program changed the way we look at the moon, paleontology and genetics are changing the way we view ourselves.

Related Characters: Neil Shubin (speaker)

Related Themes:

Page Number: 200

Explanation and Analysis

One of Shubin's main goals in the book is opening up the scientific community to all the people who might read his book. He details the wonder and excitement that can come from new discoveries, such as the findings made possible by the space exploration program that sent Apollo 8 into space to give humans a new perspective on the entire Earth. Shubin believes in constantly pushing forward for the sake of answering new questions to find things that might benefit mankind. Shubin's specific area of expertise is in the fossil record and embryonic development that explains how human bodies came to be the way they are. The more that paleontologists and geneticists learn, the better Shubin believes we will be able to solve health problems, lifestyle issues, and environmental pressures that can be difficult for humans today. *Your Inner Fish* glorifies the attempts that generations of scientists have made to examine these issues as much as it celebrates the scientific findings themselves, hoping to inspire more people to join in the effort to understand the human body through the connections to other organisms in the past and present.

SUMMARY AND ANALYSIS

The color-coded icons under each analysis entry make it easy to track where the themes occur most prominently throughout the work. Each icon corresponds to one of the themes explained in the Themes section of this LitChart.

CHAPTER 1: FINDING YOUR INNER FISH

Preface. Neil Shubin describes how he taught a human anatomy course at the University of Chicago, though his degree was in paleontology and his specialty was fish. Yet Shubin's knowledge of other animals gave him the opportunity to explain complex human anatomy in terms of simpler animal anatomy. The second year he taught the course, Shubin found a fossil fish from the period of transition between water animals and land animals, and this discovery reframed how he thought about the human body.

From the start, Shubin highlights how knowledge of animals can help anyone who wants to study the human body, as humans are so similar to other animals underneath the surface. As a paleontologist and a developmental biologist, Shubin takes a long view of the history of the human body and looks for the historical ancestors to humans, starting from the first animals that even lived on land.

Shubin has now spent many summers in the Arctic looking for fossil fish. Fossils are the only way to see what life was like on Earth in the distant past, and therefore are a key part of understanding how life developed into human life. These fish give fundamental clues to understanding the human body.

Shubin draws connections from the ancient fossils to contemporary humans, though other scientists might think that fossils are a dead area of science. From Shubin's perspective, understanding the origin of humans is important to understanding modern anatomy.

Digging Fossils – Seeing Ourselves. On Ellesmere Island, with a latitude of 80 degrees north, Shubin finds a fossil fish with a flat head. He is in the Arctic because the Arctic region is one of the best places to reliably find fossils. With new technology that allows paleontologists to scan potential field sites before digging, fossils are in some ways easier to find than they once were. But fossils are so fragile that digging them out by hand is still laborious, time-consuming work – often in harsh terrain and weather conditions.

A flat head is important because it suggests that the fish probably lived in shallow water, an important move from living in deep water to living on land. The details that Shubin provides about his location on Ellesmere Island make the search for this fossil more engaging than a simple list of the facts. Shubin emphasizes the time and care that goes into finding fossils in these Arctic conditions, as well as the significance of finding the fossil itself.

Fossil sites depend on three things: rocks of the right age, rock types that can preserve fossils, and rocks that are exposed on the surface. To look for fossils from the transition between water animals to land animals, Shubin has to find rocks that are older than 365 million years old. Luckily, the arrangement of rock layers on Earth leaves a relatively stable timeline with the oldest rocks on the bottom and more recent rocks on top. Earthquakes and fault shifts can disturb this pattern, but there is usually enough evidence to put the timeline back together.

The order of the fossil layers helps paleontologists like Shubin predict the location of certain fossils if they know approximately which age the fossils they are looking for were formed. Shubin does not explain how paleontologists know the age of the rocks, but methods of radiometric dating first started in 1907 have proven reliable in setting base layer ages for volcanic rock, from which paleontologists can extrapolate the ages of sedimentary rocks found above and below these radioactive dated volcanic layers.

Fossils inside the rock layers also follow the progression of oldest on bottom to youngest on top, starting with jellyfish-type creatures, moving through various animals with skeletons, all the way to humans. Looking at a zoo from today can actually help paleontologists predict what type of animal will be in each age of rock layer. They do this by focusing on the traits that animals share.

Since the rocks are layered with oldest on bottom to youngest on top, it makes sense that the fossils formed within that rock would also follow that pattern. Shubin also makes the assumption that the animals with the "simplest" body plan are the oldest, as these simple traits had to develop before more complicated animals could arise.

Everything in the zoo has a head and two eyes. A subset adds limbs. The next subset adds another feature. The more unique a subset is, the younger it is. Thus Shubin expects to find fossils with a head and two eyes in rock layers below fossils with a head, two eyes, and limbs. By analyzing thousands of animal characteristics and species, paleontologists have formed a catalogue of what age rock holds which type of fossils.

The assumption that "simple" animals are older follows the ideas of descent with modification that Shubin will pick up again in Chapter 11. The idea is that as time goes on, life on Earth grows more complicated by adding more features to animals. While all of this history might not be expressed in the animal physically, the evidence of these types of group progressions are seen in the genetic information of animals.

For the first fossils with limbs, the rock layer comes from the critical time period from 380 million years ago to 365 million years ago. 360-million-years-old rocks already show diverse life forms that look like modern day amphibians (frogs and salamanders). Shubin decided to focus on 375-million-years-old rocks to maximize his chances of finding fossils of the first creatures with limbs.

Since only fossils of fish are found at rock layers 385 million years old, and fossils of land animals with limbs are found in rocks 365 million years old, the natural conclusion is that the transition between water and land animals happened in the time period in between. The fact that these calculations are made in terms of millions of years highlights the long, drawn-out process of change in life on Earth.

The best type of rock for finding fossils is sedimentary rock, as volcanic and metamorphic rocks form in conditions too violent to allow fragile fossils to stay intact. Sedimentary rocks all over the world show that the geography and climate of Earth has changed significantly over time, with oceans or tropical rainforests where there are now mountains and deserts.

Sedimentary rock forms by pressing small rocks, pebbles, and sand together with enough force that the rocks fuse into a solid layer. Any bones caught between these small rocks will also be pressed down and the spaces in between the organism's cells are filled in with mineral-rich water that hardens into a rock-like structure. Sedimentary rock typically forms in stream beds or areas with water, showing that water on Earth was once distributed much differently than it is now.

The last step for choosing a fossil site is finding a layer of sedimentary rocks of the right age that is not covered by human settlements. These three factors are almost always easier to find in deserts. However, it is very expensive to mount a full fossil-finding expedition to a desert like the Gobi or the Arctic.

The desert winds help wear away rock, exposing possible fossils, and paleontologists have an easier time digging in deserts because cities are not usually built in areas with so little water. Yet these factors also mean that the expedition itself takes more work and planning.

Shubin starts his fossil-finding expedition researching the origin of limbs in his hometown of Philadelphia. The Catskill Formation of Pennsylvania actually holds rocks from the Late Devonian Period that contain valuable fish specimens. Shubin and one of his students, Ted Daeschler, check sites of exposed rock recently blasted by the Pennsylvania Department of Transportation to make new roads. They are rewarded with a shoulder bone from a hynerpeton, a small amphibian.

The Devonian Period was the geologic age from 420 million to 358 million years ago. This time period is also called Age of Fishes, due to the many deep water predators that "ruled" the oceans and the apparent lack of many significant land creatures until the late Devonian. Shubin and Daeschler display the ingenuity of scientists on a budget, letting the PDOT do the heavy blasting work for them and then looking for fossils in the newly uncovered rock. A hynerpeton has a very primitive limb, showing that Shubin and Daeschler are close to the origin of limbs.

With one new fossil found, Shubin and Daeschler are ready for more. Looking at a geology textbook, they notice that rocks from the Devonian Period are also in the Alaskan Yukon (which has already been well-studied), the coast of Greenland (where Jenny Clack found an early creature with limbs), and the Canadian Arctic—which has rocks almost identical to the rocks in Pennsylvania. Shubin and Daeschler decide to go to Canada because it has not yet been explored by vertebrate paleontologists.

The rocks from the Devonian period show that Arctic areas such as Greenland and Alaska were once temperate forests with streams fit for small amphibians like hynerpeton. Shubin and Daeschler decide to maximize the cost of mounting a fossil expedition by going to an area that has not yet been covered, in the hopes that they will find new fossils. The success in other Devonian areas is a huge clue that Shubin will not be wasting his time or money in the Canadian Arctic.

An expedition to the Arctic comes with many dangers, including the local wildlife, unpredictable weather, and the limited ability to carry supplies when the team is airlifted to dig sites. Furthermore, Shubin and his team can only go to the Arctic during the summer. Shubin brings in Dr. Farish Jenkins, his graduate advisor from Harvard, who has years of experience leading expeditions in similar conditions in Greenland.

Shubin again focuses on the work of fossil finding, showing that this science is not an easy task even when all the theoretical and academic factors fall into place. Shubin builds on the knowledge of an older and more experienced paleontologist to help ensure that his expedition will be successful.

Shubin spends the first few weeks at the dig site worrying about polar bears. The Arctic landscape is vast and empty, making the search for fossils less than four feet long even more improbable. In 1999, Shubin and his team find plenty of fish fossils from deep water, but none of the shallow-water fish they need to start looking for the transition to land-living animals.

Even though Shubin has planned his expedition carefully, finding fossils isn't a guarantee. There is a certain amount of luck involved for even the most meticulous and careful fossil finders. And even when Shubin is successful, his fossils might not reveal anything that is not already well-studied.

In 2000, Shubin and his team move their dig site east to Ellesmere Island. There, a college undergraduate named Jason Downs is late returning to camp one night. Just as the senior members of the team are ready to mount a search party for Downs, Downs returns to camp with his pockets full of fossil fragments. The whole team heads out to the river bed where Downs identified these fossils, and they spend several days identifying the exact rock layer that might hide intact fossil fish skeletons. They eventually find intact skeletons, but the fish are all of species that have already been documented.

Jason Downs represents the many levels of the scientific community that are valuable at a dig site. Though Downs may not have all the experience and knowledge that Shubin or the older professors have, his contributions are still important. Even though the fish fossils they found were already catalogued, finding something is better than nothing in terms of continuing to receive funding for these Arctic missions. Had Downs not found these fish, Shubin and his team might not have been able to justify another trip to Ellesmere Island.

In 2004, Shubin and his team make one last expensive trip to the Arctic. Finally, Shubin finds a fish fossil fragment with a jaw that suggests the fish had a flat head. Then another team member, Steve Gatesy, finds a full fish skeleton with the same flat jaw. Over the next two months, fossil preparators meticulously expose this fossil from the rock, discovering that it is an intermediate between fish and land animals. This fish fossil has scales like a true fish, but a neck, flat head, and small limbs like a land animal.

Though Shubin was the lead paleontologist on this mission, he makes sure that his book recognizes the many scientists, like Steve Gatesy, who contributed to the amazing find. This fish is special because it blends traits that previously appeared only in animals that live solely in water with traits that appear in animals that live in land and water. It is an indirect ancestor of all animals that now live on land, as it paved the way for body systems that facilitate limb development for motion on land.

This fish find is a huge success for the idea that there is a transitional stage between fish and amphibians at the 375-million-year time period. Shubin, Daeschler, and Jenkins decide to thank the Inuit people for allowing them to work in the Nunavut territory by giving the fish fossil a name that reflects the Inuit heritage. The Inuit Committee of head elders suggests Siksagiaq or Tiktaalik. Shubin decides on **Tiktaalik**, which means large freshwater fish.

Shubin also highlights the contributions of people who are not members of the scientific or academic community by honoring the Inuit people with the name of the fossil. The Inuit also made this discovery possible by allowing Shubin and his team to excavate this land at all. Tiktaalik was the winner partly because it was easier to say, another sign that Shubin wants this discovery to be as accessible to the average person as possible.

Tiktaalik's discovery is a huge news story in 2006, but Shubin is most affected by a moment in his son's preschool class. Shubin takes the *Tiktaalik* fossil to his son Nathaniel's show-and-tell. When one child asks if the fossil is a fish or a crocodile, another child responds that it can be both. More than bridging the gap between fish and reptiles, *Tiktaalik* offers insight into all the body structures that land animals share.

It is easy to put animals in strict categories, and often those categories help the average person understand different animals. Yet Tiktaalik is easier to understand when people embrace the similarities it has to both fish and amphibians instead of trying to force it into one box or another. Tiktaalik's primitive legs also offer a blueprint to understanding the various limbs of all land creatures.

Tiktaalik shows human's history as fish the same way that the famous "Lucy" (an early human ancestor discovered in Ethiopia) shows human's history as highly advanced primates. Human anatomy is the result of millennia of small shifts in the bone structure of all animals. These shifts can be seen in the fossil record, as well as in genes and DNA.

Tiktaalik is a much older fossil than Lucy, and seems much further removed from human anatomy than Lucy does. Yet Shubin stresses that Tiktaalik is just as important in the entire story of human development, because Lucy never would have developed if fish like Tiktaalik had not paved the way for animals to live on land.

CHAPTER 2: GETTING A GRIP

When Shubin did his first human medical dissection, he was unbothered by the creepiness of working on a person until he had to focus on the hand. The hand is the most quintessentially human feature, and one of the most complex parts of the human body in terms of bones, muscles and tendons. Sir Charles Bell, a Scottish surgeon in the early 1800s, took this complexity as evidence of a divine creator.

Shubin explains that his desire to study animals stems from a desire to understand all life, including the human body. The complexity of the human hand leads some, like Bell, to believe that the human body never could have developed by "accident," as some detractors of evolution have argued.

Sir Richard Owen, one of the most famous anatomists of the 1800s, also believed in a divine order within bodies. Owen catalogued thousands of animal specimens, and realized that almost all of the animals with limbs had the same bone structure: one bone that connects to two bones, followed by lots of small bone blobs and finally the digits (fingers or toes). The shape and size of these bones changes radically, but the underlying blueprint remains. Charles Darwin took this similarity further to suggest that all animals with limbs shared a common ancestor that gave them this limb structure, going all the way back to fish fins.

Though Shubin acknowledges that men like Bell and Owens had reasons to believe in the possibility of divine creation, he puts far more emphasis on the idea that the basic similarities between many animals make it likely that the different species we have today developed from one common ancestor. In Owen's case, the similar bone structure between all limbs is a huge similarity between all animals.

Seeing the Fish. Fish fins look nothing like limbs, being mostly made up of webbing with four bones arranged in a line. Yet the lungfish, a fish that has lungs, actually has a single bone that attaches the four fin bones to the fish's shoulder. Another fish from the Devonian period, *Esuthenopteron*, goes even farther, with one bone connecting to two bones in the fin.

Fish fins are an excellent example of Shubin's point that all animals are fundamentally similar, because fins and limbs look nothing alike on the surface. Yet some fins seem to transition into the same bone structure that human limbs have, suggesting that the fish that are most similar to land animals (those that have lungs) are the ones that started to develop land limbs. Shubin acknowledges that it is still a long way from these primitive fin-limbs to true limbs, but rationalizes that there are millions of years in which these fin-limbs could evolve.

Swedish Paleontologist Gunnar Säve-Söderbergh found a "missing link" fossil from the Devonian Period in expeditions between 1929 and 1934. This fish fossil, *Ichthyostega soderberghi*, has a land animal neck and back with fully developed fingers and toes on its fin-limbs. Another Säve-Söderbergh fossil remained a mystery until 1988, when Jenny Clack analyzed the limb as a flipper. This appendage, with fully-formed wrist and finger bones, suggests that the earliest limbs developed for the purpose of swimming instead of walking.

A "missing link" is the popular term for a fossil or animal that seems to fill in a gap between two distinct sets of animals, such as fish and amphibians. Shubin rejects this term, however, as the link would no longer be missing once it is found, of course, and there also has to be more than one singular link to show the many transitional stages animals go through to arrive at the distinct animal species now living. Clack's work is another example of how scientists can build on the work of previous generations in order to make greater discoveries.

Finding Fish Fingers and Wrists. In 1995, Daeschler and Shubin find an isolated fin fossil in a Pennsylvania highway construction zone. The fin has the "standard" bone structure of a limb, even though the fin has all the webbing and scales of a normal fish. This fin looks as if it is a good candidate for the origin of limbs, but Daeschler and Shubin need a full skeleton.

On the surface, Shubin and Daeschler's fossil looks like a fish, but the bones are in some ways similar to a human – another example of how human developmental history is actually tied up in fish. Yet a fin in isolation does little good for Shubin, as one fin cannot fully explain the animal's lifestyle, and it is easy to misinterpret a fossil fragment. Without a full skeleton, Shubin and Daeschler may be wrong about the bone structure they think this fin has.

Shubin and his team bring back three chunks of Devonian rock from their 2004 expedition to the Canadian Arctic. Fossil preparators Fred Mullison and Bob Masek work on these chunks for the next two months, gradually uncovering intact skeletons of flat-headed fish that have human style wrists in their fins. One of these fish, another **Tiktaalik**, seems to have a limb that is part fin and part limb. *Tiktaalik* would have lived during the exact time period of the transition between water and land animals.

The importance of Tiktaalik is not only that it has the limb structure that suggests a movement towards limbs from fins, but also it is the right age. If Tiktaalik were much younger than 375 million, Shubin's team would have just found another example of a strange amphibian, instead of the origin of limbs. If it were much older than 375 million, Shubin and his team would have to revise the expected predictions about when animals moved out of the sea, or explain why fish needed limbs if they did not live close to land.

Now that they have uncovered **Tiktaalik**'s wrist, Shubin and his team analyze the most likely function of this limb. Due to the structure of *Tiktaalik*'s joints, it seems that the limb was designed to allow the fish to do "push-ups" off the shallow stream bed and maneuver around rocks. *Tiktaalik* probably lived in a shallow rocky environment to avoid larger predators in the deep river water.

Shubin's explanation for the limb relies on Tiktaalik living in a shallow stream bed, which is an educated guess considering the rocks that Tiktaalik was found in, but is not a proven fact. All fossil analysis includes some level of doubt because many specifics of the environment are unknown. Shubin also guesses at the muscles his fossil most likely had, as these details are not fossilized Here is another area where similarities between animals can help biologists, as Shubin can make assumptions based on what animals with similar bone structure alive today do with their limbs. The things we have observed in animal behavior today can be applied even to ancient fish.

It is a long journey from **Tiktaalik**'s "push-ups" to the range of complicated motions and movements humans can do with their wrists. But the blueprint for the human skeleton already existed within this fish, and would later become refined through amphibians and reptile species from 250 million years ago. Shubin sees this especially in the ability to rotate the thumb relative to the elbow. Humans can do this because our elbow joint is a ball-and-socket fit that lets the radius bone in our lower arm rotate around the humerus bone in our upper arm. *Tiktaalik*'s upper arm bone already has a primitive version of this joint, which becomes more defined in amphibians and reptiles.

Shubin does not underestimate the amount of time and miniscule changes in successive generations that are necessary to go from Tiktaalik's very primitive wrist to the highly specialized human wrist, but he does understate the difference somewhat. Though Tiktaalik may have the beginnings of the ball-and-socket joint that lets humans rotate their thumb, a groove and elongated bump are very different from a fully realized joint. Shubin doesn't detail the long process and the many survival motivations that benefitted animals that had more developed limbs.

Another key anatomical structure for humans is our kneecap. Our knees and elbows bend in opposite directions, allowing us to walk on two legs. In the womb, human fetus limbs face the same direction, much like a primitive fish like *Euthenopteron*. The knees and elbows then rotate as the legs project under our body instead of to the side – thanks to the bow-shaped pelvis and deep hip sockets. This feature, unique to humans and bipedal primates, is another reminder that all of the extraordinary things the human body does came from the humble structural anatomy of a fish.

In a rare move for a book that highlights the similarities between all animals, Shubin focuses on something that makes humans different from other animals. By explaining the bone structure that allows only primates and humans to walk upright, Shubin ensures that he is not glossing over factual difference to further his argument. However, Shubin does not back up his explanation of the bones with the reasons behind the changes that allowed humans and primates to walk upright, leaving this analysis somewhat less convincing than other portions of the book that delve into the complicated history of a certain body structure.

CHAPTER 3: HANDY GENES

While Shubin and his team dig up fish fossil bones, Randy Dahn at the research lab at the University of Chicago looks at the embryos of sharks and skates (a smaller cousin of a shark. Dahn is investigating the affects of Vitamin A on limb development in sharks, hoping to explain part of the way that our DNA directs body cells to form a functional body. Dahn's experiments look to compare the DNA "recipe" for shark fins to the "recipe" for human hands.

Dahn's work points both to the ways that animal bodies are similar enough that sharks can stand in for humans, and the ways that scientific research builds on the past and looks towards the future. Dahn does not expect to change the world with his research, but the information about shark development he finds may be useful for other scientists looking at human hands.

Experiments on DNA fill in an important gap that fossil study can't address, as fossils are rare and cannot be manipulated to change specific variables or answer certain questions. Dahn wants to prove that the genes for fish fins and human hands are virtually identical by manipulating shark embryos to make part of the fin look like a hand.

Aside from the bones that Shubin compared between fins and limbs, the genetic code that builds these structures may prove to be very similar. If the directions for building limbs and fins are the same, it is more likely that fins and limbs share the same developmental path in the history of life.

Though the human body is made up of hundreds of different kinds of cells, every cell in an individual human's body has the exact same DNA in its center. Different organ cells develop differently because only certain genes are active in each cell. Understanding what switches a gene on or off in a particular cell helps explain what genes are involved in specific body systems. Isolating the genetic differences between the code for a fin and the code for a hand gives Shubin likely places to look for a switch that allowed an animal like **Tiktaalik** to start making the bones for a hand instead of a fin.

Though Shubin set up the argument that fins and limbs have the same basic genetic directions, a key part of Dahn's research is actually looking for differences between hands and fins. These small changes will point to the ways that the "basic" fin recipe may have turned into a more complex limb. Even if fins and limbs do not have the exact same genetic code, finding that they share some information would be evidence that limbs developed from fins.

Making Hands. Hands have three dimensions: top to bottom, pinky side to thumb side, and base to tip. Shubin looks for the genes that make a pinky look different from a thumb as a "key" to the genetic recipe that controls hands. In the embryo, limbs develop from the third to eighth week after conception. First, tiny buds extend from the body, then form into little paddles. The tips of these paddles are the millions of cells that will become the limb's skeleton nerves and muscles. Scientists study limbs that have gone wrong because it is easier to identify genetic mutations that differ from the "normal" DNA recipe.

Comparisons between DNA continue to be important, as Shubin explains how Dahn compares not only fin and limb DNA, but normal limb and mutated limb DNA to look for what is the same and what is different. Places of difference point to structures unique to that specific animal, while places of similarity suggest a shared past between all of these structures. From a very simple paddle, complicated limbs form.

To study embryonic limbs, scientists need an organism that is big enough to see and manipulate and that has readily available, fairly cheap embryos. In the 1940s and 50s, chicken eggs were the perfect candidate. Edgar Zwilling and John Saunders, two scientists that studied embryos, cut into chicken embryos and surgically removed small patches of tissue in the limbs to see what would happen. They discovered that a small zone of tissue is responsible for the development of the entire limb. Removing it at different times in the embryo's life stops limb development at different junctures.

Scientific research always has to contend with what is practical for the time period and the location as well as what will best fit the question that scientists like Zwilling and Saunders want to investigate. Shubin does not address any ethical concerns that might arise from surgically experimenting on embryos of any species, though chicken eggs are easy for most people to approve of sacrificing for scientific good. The small patch of tissue that Zwilling and Saunders found is another example of simple starts that can blossom into huge results, as Shubin explains throughout his book.

Mary Gasseling, a member of John Saunder's embryo lab, transplanted limb tissue to different places on the limb to see how manipulating the place affects limb development. Taking a small patch of tissue from the "pinky" side of the limb bud and transplanting it to the "thumb" side early in development actually causes the embryo to develop a limb with a full duplicate set of digits, arranged as a mirror image of the normal set. Injecting vitamin A into the chicken egg during development produces the same result. The patch of tissue that controls limb development was named the zone of polarizing activity (ZPA).

Gasseling continues Saunder's experiments and builds on them in another example of collaborative scientific work. His experiments help clarify the complicated process of building a hand, as Shubin breaks down the many factors at play in the work of the ZPA. While the ZPA is not wholly responsible for building an entire hand, it is the initiator of hand development. This small patch of tissue yields huge results in the mature animal.

The ZPA controls the formation of fingers and toes by controlling the concentration (amount) of a certain molecule in the cells that will become the limb. The cells closest to the ZPA have a high concentration of the unknown molecule and respond by making a pinky finger. The cells farther away from the ZPA have a low concentration of the molecule and respond by making a thumb. The cells in between have varying concentrations of the molecule that correspond to making the second, third, and fourth fingers.

Shubin makes the complex process of digit formation very simple by focusing only on the ZPA and the concentration of molecules, even though there are many other genes and protein interactions at work. This is a good basic understanding that lets the average person grasp enough of limb development for the purposes of Shubin's book, and learn more if they are interested.

The DNA Recipe. In the 1990s, scientists were better able to look for the molecular mechanisms that the ZPA uses to differentiate fingers. Cliff Tabin, Andy MacMahon, and Phil Ingham decided to look at flies for the answer. Genetic experiments in the 1980s had already mapped out the gene activity that guides fly development from front to back, with different genes active in the front head than the back wings. Tabin, MacMahon, and Ingham identified another gene that controlled the body regions of the fly.

The fact that Tabin, MacMahon, and Ingham can look at flies for a process originally found in chickens again points to the underlying similarities between all creatures. Yet Tabin's group must modify their research to the fly's body instead of its limbs, as fly limbs do not have different digits. The process of differentiating body segments is very similar to the development of different digits in a limb.

Tabin, MacMahon, and Ingham named the gene that controls differentiating body segments in flies the hedgehog gene, because flies that have a faulty hedgehog gene look like little bristly hedgehogs. In chickens, this gene is called "sonic hedgehog" (named after the video game character). Sonic hedgehog is only active in the ZPA of chicken embryo limbs. After experiments that confirmed that hedgehog does the same limb production in flies, chickens, and mice, Dahn began to look for a sonic hedgehog gene activity in sharks.

Though chickens also have different body segments, it seems that the specific "sonic hedgehog" gene is only active in chicken limbs, whereas a more general version of the gene has a much larger role in the fly body plan. Yet Shubin does not explicitly say that flies developed before chickens in this case, or use this as evidence for a shared developmental path, only commenting on the similarities between flies and chickens as they are now.

Sharks and their smaller cousins, skates, have embryos in eggs that are remarkably similar to chicken eggs, with some adaptations for life in water. Looking for sonic hedgehog activity in skate embryos would prove that this basic recipe for limb development goes far further back than just land animals in the history of life on earth, as the earliest shark fossils are dated to 400 million years ago. Sharks and humans are distantly related, and obviously look very different on the surface. Shark bones are even made out of a different material than human bones. All of these differences make it even more useful to use sharks to see if sonic hedgehog is unique to limbed animals or if it is active in all animals with appendages.

The comparison between skate sonic hedgehog and chicken sonic hedgehog is much cleaner than the earlier comparison between chicken limbs and fly bodies, because these experiments are considering the same body structure and the same specialized limb version of the hedgehog gene. If the gene is the same in such different appendages, the similarities between sharks and chickens would be deep enough to suggest a developmental path from water creatures like sharks to land creatures like chickens.

Dahn started by looking for the sonic hedgehog gene in shark embryos. Once he found that sonic hedgehog was indeed present, he started to run through all the experiments that Tabin's team had done on chicken eggs. In each instance, the shark fin reacted the same way as chicken limbs – to the point of producing a duplicate fin when the shark ZPA was treated with Vitamin A.

Dahn basically reenacts the earlier experiments on chickens, building on this earlier research that explained how limbs developed and pushing it to help find the origin of limbs. The fact that the shark ZPA shows the same signs as the chicken ZPA supports the idea that fins and limbs are fundamentally the same structure.

Dahn went further to see if the shark ZPA could be influenced with the protein that the sonic hedgehog gene produces in mice. Normally, the rods in a shark's fin are all the same. When Dahn inserted the mouse sonic hedgehog protein, the rods of the shark fin developed to be different sizes and shapes from each other, just like mouse fingers do.

Dahn's experiment was a success, based on the goal that Shubin stated earlier in the chapter of developing fins into hands. Dahn was able to introduce genetic material from a mouse, have it be accepted by a shark (proving that genetic material is similar enough across these two species to even have effects) and force the shark fin to develop like a limb with differentiated fingers.

Dahn's experiments prove that all appendages, whether fins or limbs, develop the same way from the same basic DNA recipe. Shubin argues that this means the transition from fins to limbs did not involve any new DNA, but simply using the ancient genes for fin-making in new ways. Ultimately, experiments on flies, chickens, mice, and sharks show the similarity between all animals with appendages and give insight to the genes responsible for the development of human limbs.

Shubin focuses on the significance of tying fins and limbs together with the same genetic recipe. While this is certainly evidence that supports connections between all animals, Shubin does not fully explain why certain species would begin using the DNA that allowed them to build fins for another purpose—a question that has more to do with environment than with fossils and DNA.

CHAPTER 4: TEETH EVERYWHERE

Though teeth might not be the most glamorous anatomical structure, looking at teeth is an integral part of learning about the lifestyle of an animal because teeth tell scientists what an animal most likely eats. For humans, we have a mix of blade-like teeth for cutting meat and flat teeth for grinding plant or meat material. Our upper and lower jaws also fit together precisely (a fit called occlusion) to break up food with maximal efficiency.

Teeth are a fountain of information for paleontologists that must rely on very little physical evidence to make conjectures about the entire ecosystem of the past. From the simple knowledge of how an animal eats, Shubin can reconstruct a complex picture about how and where that animal lived.

Teeth are one of the most common finds for paleontologists, because an easily-preserved hard mineral called hydroxyapatite makes up much of the outer layer of the tooth. Teeth are especially helpful for mammal fossils, as mammal species have distinctive teeth. While reptiles all have similar teeth that they replace many times over their lifetime, mammals have teeth that occlude and are only replaced once. During the time period from 225-million to 195-million years ago, paleontologists see a progression from dog-sized reptiles with fairly simple teeth to small animals with mammal-type teeth that fit together inside a smaller jaw.

Mammals have relatively complex teeth that are specialized for each species. From the basic template of reptile teeth, mammal teeth seem to develop in ways that let that mammal get the most nutrition and survive in their environment. Based on the fossil record, there seems to be a direct line from reptiles with simple teeth to mammals with more complex teeth.

Shubin began studying these early mammals at Harvard, under Farish A. Jenkins, Jr., who specializes in looking for the fossils of early mammals. With the help of expert fossil finders Bill Amaral and Chuck Schaff, Shubin learned how to spot the distinctive signs of bone in the ground. At first, this was incredibly difficult for Shubin. Schaff, a traditional "cowboy" type despite his New York upbringing, showed Shubin how to search for fossils without wasting effort.

Shubin directly learns from the experience and expertise of other scientists who help him learn how to find fossils. Shubin previously acknowledged the element of luck involved in finding fossils, but here he honors the skill and years of study that men like Jenkins and Schaff have put in to their lives as fossil hunters.

Once Shubin is able to see the bone in the midst of desert rocks, he realizes there are fundamental rules to fossil hunting. Rule one: go to rocks that seem most likely to have fossils, based on geological search images or past experience of productive sites. Rule two: don't follow in the footsteps of other fossil hunters, but search new terrain. Rule three: Only one person looking for fossils per area of the site. The more Shubin practiced looking for fossils, the easier it got to identify fossil from rock in all sorts of terrain and lighting conditions.

Though the process of finding fossils may have seemed random or chaotic to Shubin at first, here he simplifies the process into 3 straightforward rules. Shubin's rules break down the huge task of sweeping an entire desert landscape for fossils into more manageable chunks. Just as Shubin looks for simplicity and order in the fossil record, he also looks for simplicity and order in the search for the fossils themselves.

Jenkins' site in the Arizona desert was full of tiny animals with bones no more than an inch or two long. Their teeth were even smaller, but Shubin was fascinated by the signs of occlusion in tiny mammals 190 million years old. It gave him a humbling perspective on the development of complex human anatomy.

The specialized fit of these tiny teeth allows Shubin to draw a line from these early mammals to human life today. The development of human complexity is even more incredible when Shubin understands where mammals started.

Back in school after working with Jenkins all summer, Shubin decides to lead his own expedition. With limited funds, Shubin needs somewhere fairly accessible, yet with the right type and age of rocks. With the help of Paul Olsen, a professor at Columbia University, Shubin settles on a swath of 200-million-year-old rocks in Nova Scotia, Canada. Amaral and Schaff come along for a two-week dig.

The theoretical concerns of where Shubin will find the most useful fossils are balanced by the practical concerns of funding. Shubin brings in another person on the journey to find early mammalian fossils, further proving that science is always collaborative.

Back in Boston, Amaral works as the fossil preparator for the rocks that Shubin's team found in Nova Scotia. He uncovers a tiny reptile jaw from an animal called a trithledont that shows signs of wear on the cusps of the teeth – evidence of occlusion. Shubin is incredibly impressed with Amaral's find and learns that some of the most important discoveries actually occur once paleontologists leave the field.

Though trithledonts are reptiles in most of their physical characteristics, they have a mammalian jaw – marking them as an intermediate stage between reptiles and mammals, just as the Tiktaalik was an intermediate between water animals and land animals.

Shubin returns to Nova Scotia in the summer of 1985, hoping to find more trithledont fossils, but is disappointed to find that the dig site from the previous year is now weathered away from the tide. Still, Shubin and his team decide to investigate nearby rocks on the beach. One day, Shubin and Amaral get stuck on a spit of volcanic rock because the high tide blocks their path back to the base camp. Though volcanic rock was previously thought to be too hot to support fossil preservation, Amaral notices a whole area of small fossil fragments.

Fossil finding depends on much more than careful research, as Shubin cannot control the environment where he has to find his fossils. Yet that lack of control can also lead to strokes of luck, such as Amaral's accidental find in volcanic rock that no fossil hunter ever would have checked according to the accepted norms and regulations of fossil finding.

Shubin and Amaral dig out the volcanic rock site, finding that there are patches of sandstone that protected the fossils from the volcanic heat. They find several more trithledonts, which provide valuable clues to the progression from reptilian teeth to mammalian teeth. Though trithledonts do not have true occlusion, their upper and lower teeth scrape against each other like scissors, showing an intermediary step to the fit of the mammalian jaw. After trithledonts, the fossil record shows an explosion of new mammal species that have many different kinds of teeth specialized for different kinds of chewing to expand their possible food sources.

Sandstone is a sedimentary rock, the perfect type for finding fossils. The trithledonts that Shubin and his team find there show the long time frame for development of species. It would be ridiculous to assume that new body structures could pop up in a matter of generations. The changes that most benefit the animals, such as teeth that increase the number of food sources available to an animal, are the ones that remain and continue to develop.

Teeth and Bones – the Hard Stuff. The most immediately special feature of teeth is how hard they are compared to other organs. The mineral that makes the outermost layer of teeth extra-hard, hydroxyapatite, is also found in lower concentrations in bones and the inner layers of the teeth. This mineral distinguishes human hardness from the hard exoskeletons of other animals. Shubin then turns to investigating where hydroxyapatite came from.

Hydroxyapatite is found in both bones and teeth, bringing together two different body systems with a fundamental similarity even if they look different on the outside. This mineral also shows a progression from the exoskeletons of insects or crustaceans to the inner hard skeletons of more complicated creatures like mammals.

The most common fossils from the ancient oceans are conodonts, first discovered in the 1830s by Russian biologist Christian Pander. Conodonts are small, shelly organisms covered in spikes that have been found on every continent on Earth. At first, no one knew what conodonts actually were. Finally, a professor of paleontology at the University of Edinburgh found a slab of rock in university storage that showed a primitive jawless fish with the distinct impression of conodonts in its mouth. Conodonts are teeth.

The fossil record is incredibly useful, but also includes huge gaps. The case of conodonts is one area where fossils actually confused scientists because they did not yet have all the information. Yet through generations of study, building on work from past scientists, these questions can be answered. Conodonts are now so well catalogued that they are used as index fossils: fossils which help paleontologists pinpoint the specific geologic age of the rocks they are looking at.

Part of the struggle in identifying conodonts as teeth was that the teeth were the only hard part of these ancient jawless fishes' bodies, and were therefore the only part of the jawless fish that was preserved as a fossil. These fish most likely developed teeth in order to break through the hard exoskeletons of potential prey. Once animals developed hydroxyapatite-rich teeth, the mechanism for creating hard structures out of hydroxyapatite then became a method of protection. Fish called ostracoderms actually have a disk-like shield of bone covering their head that is entirely made of the tissue that human teeth are made of.

Using one simple mineral, animals can do many complicated things depending on what will help them most. Animals who are on the high end of the predator-prey chain need teeth that increase their ability to eat other animals. Animals lower in the predator-prey hierarchy need protection from more dangerous creatures. The same type of body structures can be used in many different ways.

Teeth, Glands, and Feathers. Teeth are also special due to their specific method of development. Teeth are made of two layers of tissue that fold together, with the outer layer becoming the enamel and the inner layer becoming the dentine and pulp of the tooth. This two-layer process is also used in the development of all body structures that form within skin, such as scales, fur, hair, or feathers. Shubin compares the process to a new assembly line process; once teeth were developed, animals reused the same system for creating teeth to create many different body parts. This underlying process links organs as different as feathers, teeth, or even mammary glands.

Shubin uses the development of teeth to show two things – first, that a complicated structure like a tooth can come from a relatively simple method of folding together two tissues, and secondly, that this process is the same between many different body systems across many various animals. The feathers, teeth, or mammary glands that come from this process develop in birds, mammals, and reptiles, showing that these different species must have shared an ancestor in the past from which they all inherited this process.

Shubin recaps what the book has argued so far, tracing how the same organ can be found in many different creatures. Chapter 1 focused on finding versions of human organs in ancient rocks. Chapter 2 compared the bones of fish and humans, while Chapter 3 looked at the genetic similarities in the development of those bones. Chapter 4 highlights teeth to once again show the deep similarities between different body parts and animals.

Shubin's recap simplifies even his own book, helping break up the many different points that he is trying to make so that they will be easily understood. The recap also unifies these separate chapters with the common theme of following one organ (hands, teeth, etc.) in many animals.

CHAPTER 5: GETTING AHEAD

As a graduate student, Shubin had to study the nerves of the human body for an anatomy final. Two of these cranial nerves (nerves in the head) have a very complicated path through the body that becomes much simpler if one knows anything about shark anatomy. The jumble of human nerves is actually a simple plan in fish.

By using the simple nervous system of the fish, Shubin can make it easier to understand the very complicated human nervous system. This works because Shubin argues that the human nervous system is a specialized development from the basic template of the fish nervous system.

The Inner Chaos of the Head. Head anatomy is difficult to study because the human head is encased in the bone box of the skull. Skulls have three parts: plates covering the brain, a platform block that holds the brain up, and rods in the jaw, throat, and ear. The skull is also three-dimensional, with compartments for different organs that make it harder to visualize how everything fits together.

The human head is complicated because it is so specialized. The twisting paths of the bones and nerves have developed to allow humans to eat, breathe, and talk. The human brain is also much larger than the brains of many other animals, requiring a different skull shape than almost every other species.

There are twelve cranial nerves in the human head. Some of these have simple paths to just one organ or muscle in the body, like those that attach to the eye (optic nerve) or ear (acoustic nerve). But four of the cranial nerves have complex functions that take them in "random" paths throughout the head with many different branches. The trigeminal nerve and facial nerve are especially difficult to pin down.

Shubin constantly looks for simple order in his studies, even with nerves that seem impossible to simplify due to their complex development. Shubin works from the assumption that there is always a simple order to every biological system if one goes back far enough.

The trigeminal nerve has to do with controlling the muscles that humans chew with and small muscles in the ear, as well as sensations in the skin of the face and the teeth. The facial nerve controls the muscles involved in facial expressions as well as more small muscles in the ear. At first, it seems like these two nerves serve the same function, even crisscrossing over each other at times. Yet Shubin illustrates the sense of these nerves by describing the plumbing of an old building. In order to update old plumbing to modern functions, it is sometimes necessary to "jury-rig" the old pipes and wires to accommodate new needs. Shubin applies the same concept to the history of the nerves in the human head.

Shubin uses the analogy of a building's plumbing to explain why the human cranial nerves are so difficult to trace. Like a building that has to carry new pipes as technology improves, the nerves of animal bodies must change as new demands are placed on the nervous system. Humans place huge demands on the cranial nerves, especially given the huge range of expressions that humans have that more "simple" animals like fish do not. It makes sense that a nervous system originally meant for fish would have to make some odd changes when used in a human body.

The Essence in Embryos. At the embryonic stage, the human head is just a big glob of cells. At three weeks, four blobs begin to form around the area that will be the throat. These blobs, called arches, will become different tissues for the head. Cells from the first arch become the upper and lower jaws, and two of the ear bones. The second arch becomes the third ear bone and the muscles in the face. The third develops into bones, muscles, and nerves in the throat, and the fourth arch becomes the deepest parts of the throat, including the larynx.

Even something as complicated as the human head starts out as a simple blob, looking back in the human's developmental history. The further back he goes in developmental history, the easier it is for Shubin to see the basic pattern that controls the animal's anatomy. This holds true for both the development of an individual animal from embryo to maturity and the history of all life, starting with single-celled organisms.

Looking at the arches provides a neat trick to understanding the cranial nerves. The trigeminal nerve serves all the body systems formed by the first arch. The facial nerve follows the path of the second arch. The same pattern holds true for the nerves associated with the third and fourth arches.

Here, Shubin clarifies the complicated nerves by reducing the nerves to the arches that they come from. Shubin never fully explains what the trigeminal and facial nerves do, but he gives enough information that readers can have a basic understanding that will serve as a foundation for those who would like to delve further.

Shubin also relates the head to the body, following the insight of the German writer Johannes Goethe in the 1800s, who saw that the skull is made up of many vertebrae fused together. Looking at each vertebra as a distinct segment of the human body allows anatomists to see the nerves that are associated with each body system exit the spinal cord in a specific place according to their segment. The same segmental organization exists in the head, but can only be seen at the embryonic stage when the human head is not so complicated.

Shubin follows in the footsteps of Goethe, building on previous work to make even better conclusions for science. Goethe saw that skulls and vertebra were basically the same thing – showing the similarity between unique body systems that marks Shubin's approach to the book.

Our Inner Shark. The arches of the human head look very similar to the gill slits of sharks and fish, but human "gills" are sealed by the plates of the skull before most human babies are born. However, each arch is responsible for many of the same body systems in both sharks and humans. The first arch makes jaw bones for both species, with the only difference being that the human first arch also develops into ear bones. The second arch handles inner ear muscles and throat muscles for humans, while in sharks the second arch creates bones that support the upper jaw. The third and fourth arches focus on gill movement in sharks, while in humans they supply the muscles that allow us to swallow and talk. Mapping these systems on a shark head and a human head creates blueprints that look remarkably similar.

The arches of the human embryo – the simple antecedent to a mature human body – are connected to the gills of fish, which Shubin sees as a simple version of complex animals like mammals. Though fish may be just as specialized for their environment as mammals are, Shubin argues that the body systems of fish are really basic versions of all the structures that are so complicated in humans. And the systems that each arch produces in both fish and humans connects these two separate species.

Gill Arch Genes. The first three weeks after conception are a very active time for the arches, with many genes turned on and off as brain tissue begins to develop and specific regions become different from each other. Each arch has a different set of Hox genes active that tell that arch what to become. If a scientist manipulates the Hox genes in a specific arch, it is possible to change the identity of that arch. Experiments on the Hox genes in the arches of frogs were able to create frogs with two "first" arches that developed two jawbones as the frog embryos matured.

The ability to trick a second arch into becoming a first arch, as scientist did in frogs, shows that all arches are basically the same things. Shubin will delve deeper into Hox genes in Chapter 6, but the genes themselves are helpful in showing how the arches can start from similar blob shapes and turn into such varied body systems in the adult animals.

Tracing Heads: From Headless Wonders to our Headed Ancestors. Shubin extends the comparison of human heads to shark and frog heads, then further to worm "heads." Though worms are invertebrates, a specific worm, Amphioxus, has a notochord that acts like a primitive version of a backbone. Though amphioxus has no head, 500-million-year-old fossil impressions of amphioxus bodies have gill arches. This basic structure of the human head stretches all the way back to ancient worms.

Worms are the simplest creature with a "front" even though they don't actually have heads. These very simple creatures already have the same basic arches that will later develop into the entire complicated human head. Shubin shows how humans are similar even to worms, though worms have nothing in common with humans at first glance.

CHAPTER 6: THE BEST-LAID (BODY) PLANS

Human bodies are packages of two trillion cells assembled in a very specific way. Almost all animals with bodies have a similar body plan with a front/back, top/bottom, and left/right. Generally, the head goes in front in the direction that the animal moves. For very primitive animals, like jellyfish, it is a bit harder to compare body plans. On the surface, animals like jellyfish only have a top and bottom.

No matter the different size or shape of an animal's body, Shubin reinforces their basic similarity by focusing only on the axis of symmetry that run through bodies and none of the superficial features.

The Common Plan: Comparing Embryos. Shubin started to become really interested in studying fish and amphibians when he looked at embryos. He was amazed by the transformation that fish, amphibians, and chickens made after starting from embryos that looked so similar. Back in the 1800s, a biologist named Karl Ernst von Baer came to the same realization about embryos, and pushed further to find that all the organs in a developing embryo can be traced back to three distinct tissue layers (called germ layers). Von Baer found that all the embryos he could check had the same three tissue layers.

When looking at embryos, the basic version of the adult animal that the embryo will become, the basic similarity between all animals is much easier to see. The germ layers, even simpler than embryos, are shared by all animals. Shubin goes to the simplest versions possible to make it easier to find the things that animals have in common.

Shubin explains what happens to the "embryo" after conception. For the first few days, the embryo is just a spherical clump of cells called a blastocyst. The blastocyst implants to the wall of the mother's uterus and cells start to rapidly divide. Tissues fold around each other to form a tube within a tube that stays a fundamental part of the human body – the stomach and intestinal system within the body.

The basic structure of the human body is already present in its simplest form a few days after conception. As a blastocyst, the complicated digestive tract is just a tube within the body – an image that helps clarify the digestive system even when Shubin brings back the nuanced structure of the human body.

Von Baer's three germ layers are named for their position in the blastocyst. The ectoderm is the outer layer that forms the outside of the body (skin) and the nerves. The middle layer is the mesoderm, which becomes the tissue between the skin and the gut, such as skeleton and muscles. The inner layer is the endoderm, which forms the inner systems of the body such as the digestive tract and glands. For a large portion of an embryo's life, all animals with a backbone have the same three germ layers.

Like the arches in the human head that correspond to specific head structures, the layers of the blastocyst give a simple way to think of the many various body structures in a mature animal. The logical order of the layers provides an easy way to think of the inside, middle, and outside of an animal.

The deep similarity between these animal embryos contradicts another theory that animal embryos go through the species' evolutionary path while in the womb. Under that framework, a human embryo would be compared to an adult fish or lizard. However, von Baer's approach (comparing embryos to other embryos) is ultimately more useful because it allows Shubin to investigate the mechanisms that might drive evolution in the first place. To do that, Shubin turns to the question of how the cells' embryonic bodies "know" what type of cell they should become in the adult body.

Comparing embryos to embryos makes sense because it cuts out some of the variables that come from comparing animals at different stages of life. If all embryos are fundamentally the same, then the specific environmental pressures or competitions that force each species to become specialized must work at some level after *the basic embryo stage. Knowing what type of cell to become means that embryonic cells must have some sort of instructions that outline what the animal has to be like in order to survive in its particular environmental niche.*

Experimenting with Embryos. In 1903, German embryologist Hans Spemann investigated body-building cells in the embryo, focusing on whether all the cells in an embryo had the information to build a full body or if each cell only had a specific piece of the body-building plan. Spemann pinched apart a newt embryo (using a piece of his infant daughter's hair) to make two separate clumps of embryonic cells. The two clumps each formed an identical newt, showing that early embryonic cells have the capacity to build an entire body.

At very early stages of life, all the cells in an embryo have the full plan to become a complete body. Spemann's experiment highlights the often mundane concerns of scientific exploration, such as what material Spemann can use for splitting a miniscule embryo. Shubin is able to extrapolate the information Spemann found in newts to all animals because Shubin has already set up a precedent for treating all embryos as the same.

In 1920, Hilde Mangold, a student in Spemann's lab, took that research further. Mangold was able to cut off miniscule pieces of tissue from newt embryos that contained cells from all three developing germ layers. She then transplanted that piece of tissue to the embryo of another species and found that the patch of tissue actually made a full newt body on the back of the other embryo. Mangold called the patch of tissue she transplanted the Organizer.

Mangold represents another generation of students who built on the findings of previous scientists to make truly amazing discoveries. Both Mangold's academic prowess and her skillful physical dexterity helped her pursue groundbreaking experiments. The Organizer focuses all of the many complicated processes that make a full body into one small patch of tissue – possibly the simplest beginnings possible.

Around the same time period, another German biologist came up with a way to label cells so that the cells could be traced through the embryo to their final positions in the fully matured fetus. We can now make a map that shows where all the adult organs of an animal begin in the embryo. The Organizer somehow directs each clump of cells in the embryo to become the correct body plan for that animal.

Color-coding the cells in an embryo makes a much simpler map for an entire body, showing that body systems that may seem different actually come from the same groups of cells in the embryo. The Organizer acts as the "directions" that Shubin was looking for at the start of this chapter, when he asked how cells "know" what to become.

Of Flies and Men. To continue the work of early embryologists like von Baer or Mangold, modern embryologists now look at the genetic makeup of embryos. Studying genetic mutations in flies that cause the flies to have organs or body parts in the wrong place can actually provide insight to the body plan genes of humans. By painstakingly cataloguing the chromosomal differences between normal flies and mutated flies, scientists can pinpoint where the mutation happens in the fly's genome. Most wonderfully, the genes that control the body segments of the fly lie next to each other in the same order as the fly's body plan.

Now that technology has improved past the somewhat primitive methods of early embryologists (who had to do surgery on individual embryos by hand), scientists are in the position to make incredible leaps based on the foundation that these earlier scientists provided. Genetic research has been a huge boon to many different areas of biological research, especially when full genomes such as the fly genome are catalogued.

The challenge is then to identify what is actually causing these body plan genes to mutate. Mike Levine, Bill McGinnis, and Tom Kauffman isolated a short stretch of DNA code in each body plan gene that they looked at, finding that this sequence was almost the same in each species they looked at. The sequence is called a homeobox, and the gene that includes a homeobox sequence is a Hox gene. Every animal with a body has some version of these Hox genes.

Mutations in genetic sequences happen when one letter of the DNA code is replaced with a different letter, as the genetic information from both parents forms one new set of genes for the child organism. The homeobox sequences of DNA that appear in every animal with a body are powerful evidence that the bodies of animals come from common ancestors and develop differently over time.

Animals with more complex bodies have more Hox genes, but every Hox gene is a different version of the basic Hox gene template. This similarity leads to the idea that these Hox genes were just duplicated with few changes as animals became more and more developed over evolutionary history.

Mutations actually become more likely as more copies are made (as when a person might copy a letter wrong when rewriting a document), leading to an easy explanation for the small changes in Hox genes across species.

DNA and the Organizer. After Spemann and Mangold found the Organizer, the patch of tissue was mostly abandoned by researchers because no one could figure out exactly how it worked. The discovery of Hox genes in the 1980s brought the Organizer back to the foreground. Eddie De Robertis, a professor at UCLA, looked at Hox genes in frogs, finding that a specific Hox gene was always active in the patch of tissue that contains the frog embryo's Organizer.

Success in scientific research often comes down to whether the technology to run experiments is available or not. Scientists have to constantly revisit the work of the past to see what they can add to as each discovery leads to others. The discovery of Hox genes had huge ramifications for the organizer because Hox genes offer a way for the organizer to give instructions to specific cells.

Another researcher, Richard Harland at Berkeley, found a gene called "Noggin" that works like an Organizer gene, telling the embryo where to make a head. Many genes like Noggin interact to form the entire body of an animal. A gene called BMP-4 tells cells to make the bottom or belly side of an animal. It was found to be present in all cells that don't have Noggin active. It seems that Noggin actually blocks BMP-4, simply telling the cells where Noggin is active not to be bottom cells and defaulting them into top cells.

At first, scientists thought that Noggin switched on in cells to form a head for the animal. Further research proved that the truth was more complicated, as Noggin actually turns off the gene that makes cells the bottom of an animal. Here is one place where Shubin must recognize the complexity of animal body formation instead of explaining a concept through the simplest means. Yet the fact that "top cell" is a default for all body cells before Noggin and BMP-4 do their work is another testament to the underlying similarity of all the cells that allow bodies to be so complex.

An Inner Sea Anemone. Moving away from the relatively easy comparison between humans, frogs, and fish, Shubin turns to jellyfish. Animals like jellyfish do not have a front/back axis, using one hole to both intake food and expel waste. Looking at sea anemones is a good way to reframe the lack of a head-to-anus line in these animals. Sea anemones have primitive versions of some of the genes that control the head-to-anus line in humans. Furthermore, anemones also have a "left" and "right" side that becomes distinctive once an anemone is cut open. The axis of the anemone is just hidden from plain view.

Shubin considers comparisons between humans frogs, and fish easy because these animals at least all have heads, spines, limbs or appendages, and body systems that act in similar ways (as in the nervous system). Jellyfish are more primitive creatures, meaning they developed earlier in the history of life before many complex body systems were possible or necessary. Sea anemones, however, show that animals that seem as simple as jellyfish might actually be complex – and therefore more similar to humans, frogs, and fish – in ways that are difficult to see at first.

Sea anemones have a version of the Noggin gene that created the bottom of frogs. Scientists injected sea anemone Noggin into a frog and found that the anemone Noggin was able to perform the same function in the frog. It seems that all animals with bodies draw from the same basic recipe, like a recipe for a cake that has been tweaked as it has been passed down generations.

It's significant that scientists took DNA from the less complex animal (the anemone) and introduced it to the more complex animal (the frog), as Shubin's account theorizes that the frog DNA actually came from thousands of mutations to the anemone DNA. A frog using anemone DNA is just using a primitive version of its own DNA, based on the developmental history of life on Earth.

CHAPTER 7: ADVENTURES IN BODYBUILDING

In graduate school, Shubin studied how the cells of a salamander or frog come together to make bones, by staining the cells with dyes that turn bone red and cartilage blue. Shubin found that specific clumps inside the limb bud of the embryo became bones. Somehow, the cells are able to communicate and attach to one another in order to make specific materials. Shubin asks how the cells "know" how to come together to make a body at all.

Shubin's bone experiments showed similar results for both frogs and salamanders, another reminder of the fundamental similarity between animals. Like Shubin's earlier question about how cells know where they are supposed to end up in the body, he now asks how cells that start off identical can become different things in order to benefit the body as a whole.

Habeas Corpus: Show Me the Body. Mats of bacteria or groups of skin cells are not enough to be called a body, though they are also clumps of cells that work together. To be a body, all the cells in a clump have to work together and have a specific portion of the body that keeps the entire clump alive. In a body, some clumps of cells are specialized for different kinds of labor, such as hearts, brains, or stomachs.

Bacterial cells are all the same, and are all self-sufficient. Cells in a body have different functions and must trade materials between each other in order to survive. Shubin stays vague on these points to give readers a basic understanding of bodies without getting too bogged down in details.

Yet despite the interdependence in a body, some cells in the body can die off and be replaced in a way that keeps the entire body working seamlessly. Diseases like cancer happen when some body cells don't know when to die, or when to stop growing. This balance means that cells had to learn how to work together. At some point in the history of life, cells developed a mechanism for doing revolutionary things like communicating, sticking together, and trading proteins.

Cells that can't stop growing usually develop into tumors, large clumps of a certain type of cell that start pushing into places they shouldn't normally grow in the body. These tumors are cancerous when there is no signal for the cells to ever die or ever stop multiplying, which can obviously be disastrous for the body as a whole. Bacterial mats actually do work together in primitive ways by sticking together, but the key difference in true bodies is the communication and transmission of proteins from cell to cell.

Digging Up Bodies. For most of the Earth's history, life was only single-celled organisms. If all of the Earth's history were reduced to one year, single-cell organisms would be the only life until June. Animals with heads appear only in October, and humans do not develop until December 31. Fossils of the earliest organisms with bodies were actually found in the 1920s and 30s, but paleontologists did not know what they were looking at. These bodies just looked like disks and plates.

Shubin has been working with huge numbers for the time periods in this book. Using the analogy of a calendar makes these enormous eras much easier for the average person to imagine. It also reframes the significance of humans in the history of life. Human bodies are amazing, but we owe everything to the primitive bodies of the first organisms.

In 1947, Reginald Sprigg found many rocks with impressions of disks, ribbons, and fronds in the Australian outback. Most paleontologists gave them little thought because it was thought that the rocks came from the young Cambrian era when animals already had bodies. In the 1960s, however, Martin Glaessner proved that these rocks were actually 15-20 million years older than originally thought. These rocks actually held the impressions of the some of the earliest bodies ever formed.

Dating rocks layers is not easy, but it is hugely important for the fossil record. Glaessner relied on the incredibly detailed dating of British rocks due to the British Geological Survey to date a frond found in Britain to the Precambrian Era. This frond looked so similar to Sprigg's fronds that it is almost certain that Sprigg's creatures are also Precambrian. The most likely date for these creatures is the Ediacaran Era (635-542 million years ago).

Sprigg's rocks show that multi-celled organisms with some sort of bodily symmetry and body system specialization had appeared by 600 million years ago. The rocks also show trace pathways of movement, showing that these early bodied creatures were able to move in ways different from the movement of bacterial mats. Now that Sprigg's rocks show when the first bodies developed, Shubin turns to how and why bodies would happen.

The creatures from Sprigg's rocks do have true bodies, but their body plans and construction of bodies largely died off in the Cambrian era. During this time period, many of the primitive versions of body plans that still exist in animals today appeared. It seems that the Sprigg's creatures' body plans were functional for a time, but were not the best way to ensure an organisms' survival in the environment of the Cambrian.

Our Own Body of Evidence. Though humans may seem to have nothing in common with the early Precambrian bodies, those early bodies were actually made out of the very material that allows human body cells to stick together. In the human body, this biological "glue" is a complicated mix of molecules that differs depending on the organ that it is holding together (e.g. an eye or a muscle). Without these molecules, bodies would not even be possible.

The material of these Precambrian bodies suggests that there is one default "stick together" protein that was then specialized in human organs, the same way previous chapters have traced one "original" organ structure that became specialized in different species.

Shubin now dives into how bone tissue is connected, as bones are essential to keeping the human body moving and functional. Bones are like a bridge made of steel or cables—only as strong as its building blocks. Yet bones also have to be slightly bendable so that the human body can move and withstand force. The specific balance of strength and flexibility in the human skeleton is what allows humans to run, just as a frog's skeleton is specialized for jumping.

Shubin's comparison of bones to bridges helps create a visual for the strength and flexibility required by the human body due to human movement. Organisms like trees can be much stronger because they move much less. Frog skeletons, as Shubin brings up, are specialized for jumping, in that they are proportioned differently. This helps explain the concept of limb differentiation from Chapter 2, where all animals had the same blueprint for the limb bones but changed the size of each bone based on their particular body needs.

Looking at the bones under a microscope reveals the molecular structure that gives bones their strength. Some cells are tightly packed together while others are separated. Where cells are separated, minerals such as hydroxyapatite help give bones strength when they are compressed. In the gaps, a ropelike bundle of fibers called collagen gives bones strength when the collagen is pulled.

Though hydroxyapatite and collagen each have complex constructions of their own, Shubin associates them with bricks and rope to give readers an easy mental picture of how bones can be strong under different types of stress.

Cartilage behaves differently than bone, as a much softer material that bends when force is applied and then springs back to its original shape (when healthy). At a molecular level, cartilage has much more space between its cells, with lots of collagen filling in and an incredibly specialized molecule called a proteoglycan that can fill up with water to cushion the cartilage cells to withstand force. Like bone, the material between the actual cartilage cells gives the cartilage most of its distinctive properties. Even when different body systems have the same materials in between the cells, the ratios of different materials can change how the cells behave.

The theme of basic similarity with small differences based on function is seen again in the distinctive material between cells. Cartilage and bone are actually very similar, except for the amount of collagen, hydroxyapatite, and proteoglycan in between their cells. The human body can use the same materials in different amounts to create body systems that address different structural needs.

Moving back to the earliest bodies, almost all animals with a body seem to have collagen and proteoglycans in between their body cells. The earliest creatures with bodies would have had to make these materials in some way. Furthermore, the earliest bodies would have had to find a way to stick cells together and communicate in between cells.

Human bodies are linked to these early bodies because they presumably inherited collagen and proteoglycan from these bodies. Yet Shubin does not explain how paleontologists know what proteins these bodies were made of, as the soft proteins cannot be fossilized.

Starting with how cells stick together, there are many different methods for connecting cells. Bone cells attach like a rivet with a molecule that binds to the outside of two cells. Some of these molecular rivets are able to selectively bond only to certain cells, helping to organize which kinds of cells belong in specific places in the body and keep cells of the same type close to each other.

Shubin continues to use construction analogies for the skeletal system, as it is much easier to visualize connections like rivets than to memorize exactly how a molecule "sticks" to different cells. These rivets also help answer Shubin's question in Chapter 6 about how cells "know" where to be in the body. If they are connected by the correct rivets, cells don't necessarily need to know where to be in relation to the entire body.

Cellular communication is another important issue, as cells have to know when to divide or die in order to keep the whole body healthy. Cells send molecules back and forth to each other that transmit certain messages. A molecule will attach to the outside of a cell, setting off a chain reaction of molecules in the cell until the message reaches the cell's nucleus. Shubin hopes to find the first bodies where these mechanisms of cell attachment and communication were in place.

Shubin does not fully explain how the molecular message affects the cell, as a basic understanding of this system is enough to follow how cellular communication might have come from early Precambrian bodies. The most significant aspect is the path that the molecule takes from the outside of the cell to the nucleus, the center of the cell that houses the cell's DNA and directs all cellular functions.

Bodybuilding for Blobs. In the 1880s, workers at an aquarium found a living mass of goo on the glass walls of the fish tanks. This blob is now known as a placazoan, a very simple creature with only four different types of cells in its plate-shaped body. Yet though placazoans are simple, they do have the necessary features of a real body – namely division of labor among the different parts of the body. Placazoans also have rivet connection and cell communication tools between cells.

Placazoans have actually never been observed in a habitat other than an aquarium or a lab, making it incredibly tricky to pinpoint when organisms like placazoans first developed on Earth. Due to their extreme simplicity, it is likely that placazoans are incredibly old. Attempts to classify the age of placazoans based on their genome places them between sponges and animals with three germ layers.

Going even further back, sponges have bodies that are simpler than placazoans. The "body" of a sponge is actually a non-living silica complex with collagen interspersed. In 1894, H.V.P. Wilson, the first professor of biology at the University of North Carolina, found that sponges could even properly put themselves back together if their bodies were dispersed through a sieve.

There was debate among biologists over whether sponges truly counted as animals due to their largely non-living body cells and experiments like Wilson's that seemed to prove that the sponge's body cells were not interdependent for survival. Sponges are now widely accepted as the simplest animals because they do have specialization in some cells, communicate between cells, and have a form of sexual reproduction that mixes genetic information from multiple sponges to create a new generation (as well as the asexual cloning that bacteria use to reproduce).

It is the cells within the sponge that make sponges truly interesting. Special cells shaped like goblets direct water through the sponge while tiny "arms" branching off from these cells catch food particles for the sponge. The goblet cells also have flagellum (like tiny cellular legs) that can beat in tandem to move a current of water through the sponge. From this, we can see that sponges have a very primitive version of the organization of labor in the human body.

The cell specialization in sponges is not actually complete, as some cells in the sponge can change their function based on the sponge's needs, whereas the cell specialization in the human body cannot be reversed. Yet the cells of the sponge have to communicate with one another to change, strengthening the importance of communication between cells in a true body.

Placazoans and sponges are as simple as bodies can get. To find out anything more, Shubin must turn to single-celled microbes. For years, scientists assumed that the genetic information of microbes would be completely different from animals with bodies, as these cells have none of the adhesion or communication abilities that body cells have. Yet Nicole King changed that by studying choanoflagellates, the closest microbe relatives of placazoans and sponges.

King's work on choanoflagellates is another example of how scientific theories must constantly adapt to new discoveries as technology improves biologists' ability to study the genetic information of animals as well as their physical and behavioral characteristics.

Choanoflagellates look like tiny versions of the goblet cells in sponges, but their DNA is actually more similar to microbes. Choanoflagellates then form a link between single-celled microbes and organisms with bodies like sponges. Choanoflagellates also have the molecules that could be used for cell adhesion or cell communication. Expanding her research on microbes, King then found primitive versions of collagen and proteoglycan on the surfaces of different microbes that specialize in invading and infecting other cells.

Microbes simply do not express any adhesion or communication skills outwardly, but they do have the ability to potentially do those things. Like Tiktaalik forms a bridge between water and land animals by mixing the DNA and physical characteristics of these two separate groups, choanoflagellates link together microbes and multicellular creatures.

A Perfect Storm in the Origin of Bodies. With King's research, it seems that the building blocks for bodies were in place long before bodies actually appeared. The actual timing depends on many factors. One theory for the development of bodies is that microbes banded together to avoid being eaten by bigger microbes. Molecules that microbes use to catch prey could potentially turn into the molecule that stick cells together in the body.

The developmental path of life on Earth must always take into account environmental pressures. Shubin works from the assumption that no living creature is going to expend energy needlessly, and therefore will not waste effort creating a body if there is no external reason that having a body would be more useful than the energy-saving lifestyle of not having a body.

Researchers did an experiment to support the predator explanation for body formation. After cultivating a single-celled alga for thousands of generations, biologists introduced a predator that caught and ate single-celled microbes. The alga clumped together, finally stabilizing into groups of eight cells that were big enough not to get caught but small enough that each cell could still get enough light to survive.

This experiment essentially simplifies a primitive microbe ecosystem down to one predator and one prey. Multiplying the body-forming reaction of this one strain of small microbes helps explain why many different types of bodies might have arisen in the Precambrian Era, as different strains of microbes might have been more comfortable with a different number of cells in their "body."

If predators are a viable explanation for the emergence of bodies, we must look to other factors to explain why bodies took so long to develop. The ancient environment was much harsher than our current environment, and bodies are hard to maintain. Collagen especially requires a lot of oxygen, meaning that cells would have needed a huge surplus of oxygen to even consider producing that molecule. A billion years ago, Earth's oxygen levels spiked, possibly giving microbes the extra resources they needed to begin forming the building blocks for bodies.

As Shubin has to carefully plan his fossil finding expeditions based on his amount of funding and which sites are the most accessible as well as the most theoretically useful, microbes had to balance the cost of making oxygen rich proteins like collagen with their "funds" of oxygen and the usefulness of having a body in their particular environment. As with the journey of scientific discovery, timing is also key to bringing these factors together.

Shubin now has the "when": 600 million years ago, the "how": adhering together through molecular rivets and communicating with molecular messengers, and the "why": bodies are big enough to allow microbes to avoid predators. When the environment reached high enough oxygen levels for microbes to put all of these tools into practice, bodies developed and life on Earth changed forever.

Shubin reduces the complicated mix of factors that led to the formation of bodies to three simple reasons. All bodies can then be described as variations on the theme of these early bodies, as life continued to specialize to fit into niche environments.

CHAPTER 8: MAKING SCENTS

In the 1980s, molecular biologists revolutionized the approach to anatomy and developmental biology, so much so that some molecular biologists suggested that their research would replace "dead end" disciplines like paleontology. Yet Shubin explains that the fossil record is still a valuable source of evidence, working with DNA records to fill in the gaps of information.

The progress of science cannot forget the past and look only to future projects, as Shubin has shown multiple times in the book so far. In Shubin's eyes, the best way to further scientific knowledge is to build up from and collaborate with these "old" disciplines rather than just replace them.

Shubin explains how to extract DNA from a plant, blending together the tissues, adding salt, dish soap, and meat tenderizer, then letting the mixture separate until a white goop forms on top. This white goop holds the DNA, which scientists then analyze and compare among many different species.

Shubin gives easy instructions that the average reader could use to separate DNA in a home kitchen, opening up the study of DNA – a seemingly prohibitively complicated line of research – to anyone with a blender.

One of the most incredible features of DNA is that every cell in the body, whether muscle, bone, or organ, holds all the DNA information for every other cell in the body. For example, locked within each cell is the DNA humans use to detect odors, though those genes are only active in the nasal area. Smell is one of the most ancient abilities of the human body.

DNA is an essential similarity between all the various cells in an organism's body, though the individual cells might look quite different. Shubin chooses to highlight that every cell in the human body holds the DNA for the sense of smell, but he just as easily could have made this argument with any other body system.

Humans can pick out 5,000 to 10,000 different odors, as the brain registers different molecules floating in the air. As we breathe, these odor molecules come into the nose and are trapped in a patch of tissue with millions of nerve cells. The nerve cells bind to the air molecules and send signals to the brain that are read as a specific smell. Each air molecule has a specific receptor that matches that molecule's particular shape. A single smell might involve many different molecules and their respective receptors in the nasal cavity. Fish, reptiles, mammals, and birds all share the same general framework for a sense of smell. Fish, however, must smell molecules in water, not air.

Shubin gives a simple, succinct explanation for the mechanisms that allow humans to have a sense of smell. This basic template is shared by many creatures, another piece of evidence for Shubin's argument that all animals have common traits most likely inherited from a common ancestor. Yet these shared characteristics must always respond to an organism's environment, such as a fish's smell being tuned to water instead of air.

Linda Buck and Richard Axel made a major breakthrough in the sense of smell in 1991 by identifying the genes involved in smell. They started from three assumptions: that human genes for smell would resemble the genes for smell in mice; that these genes would only be active in tissues involved with smell; and that there would be a large number of genes involved in smell (based on the idea that the sheer number of chemical smell receptors would require many genes to produce). Buck and Axel found genes for each of the receptors for odor molecules, representing a full three percent of the entire human genome.

Three percent may sound small, but it is actually a statistically large portion of the human genome. Though the sense of smell as a whole is complicated due to the sheer number of odors a human can identify, Buck and Axel's assumptions were able to cut through the noise and find incredible results. Shubin does not explain how the genes for smell in mice were already known, but it is worth noting that the entire mouse genome has been sequenced, so isolating the genes for smell would be as simple as comparing a "normal" mouse genome to the genome of a mouse who had a dysfunctional sense of smell.

The smell genes are actually an important record of major transitions in the history of life. These genes had to change significantly when animals stopped smelling molecules in water and started smelling molecules in air. In an interesting twist, the most primitive fish still alive on Earth actually have receptors that can handle both water and air molecules. Furthermore, these fish have a relatively small number of odor genes. It seems that as animals became more complex, the sense of smell became more refined.

Shubin does not explain why primitive fish would have had genes capable of identifying odors in air when they lived their entire lives in water. These explanations may come as there is more study on the individual genes of living fish. Starting from this basic template, it seems that animals in water and then on land adapted the same odor genes to their specific environment.

The "extra" odor genes in mammals seem to be copies of the few odor genes in primitive fish. The large number of mammalian odor genes most likely came from thousands of generations of mutations and duplications in the fish's odor genes. Yet, paradoxically, hundreds of odor genes in humans are useless due to mutations that render them ineffectual.

The more a gene is copied, the more likely it is that some mutation will take place. The mutation will then be passed down to the next generation if it is beneficial to the animal and helps the animal have more children. Yet mutations can also be passed down simply if they are not harmful to the animal and don't prevent it from having children.

Dolphins and whales help explain why some of the human odor genes are useless. As mammals, dolphins and whales have the same huge number of odor genes as all mammals that are specialized for air molecules. Yet dolphins and whales use their nasal passages for their breathing blowhole, and none of their odor genes are functional. It seems that, because dolphins and whales do not use their sense of smell, random mutations in the odor genes built up in the population until all of the odor genes were useless.

Dolphins and whales are different from humans in huge ways, but there is a fundamental similarity in our shared classification as mammals. In the developmental path of life, dolphin and whales' mammal characteristics suggest that they are descended from land animals that returned to living solely in water, and then had no more use for a land animal's air-specialized sense of smell.

Similarly, advanced primates (the evolutionary ancestors of humans) began to rely more on their sense of sight to find food and escape predators. Thus, the sense of smell was less important and mutations in the odor genes did not negatively affect individuals. These mutations were then passed down and built up in the population as a whole.

Shubin's argument depends on the idea that humans are descended from advanced primates and therefore inherited their sense of smell while continuing a lifestyle that de-emphasized smell for survival. Shubin doesn't say whether the sense of smell is as specialized as possible in animals, or whether it is still possible that smell-dependent animals could acquire new odor genes through the same copying mechanism that refined the mammalian sense of smell in the first place.

The sense of smell gives a good window to how closely related species are, because the copies of the olfactory genes seems to change each time they are duplicated. The more similar the odor genes are in two species, the more closely related those species are. Human odor genes are most similar to primates, then other mammals, then reptiles, followed by amphibians, and then finally fish.

The odor genes support the path of descent that Shubin originally traced through limbs and other body systems in the first few chapters. The more different sources of evidence that support this lineage, the more likely it is that this proposed developmental path is correct.

CHAPTER 9: VISION

Shubin describes the only time he has ever found a fossilized eye. In a small mineral shop in China, Shubin and his colleague Gao Keqin bought fossils of 160-million-year-old salamanders. Keqin spent considerable time negotiating in Chinese before Shubin was allowed to go into the back room and see a fossil of a larval salamander with its eye intact. Eyes are incredibly rare in the fossil record, as they are made entirely of soft tissue.

Shubin says he "found" a fossilized eye, but this discovery depended more on negotiation and people-skills on the part of Keqin than any fossil finding expertise of Shubin's. Shubin suggests that scientific discovery takes many pathways and always includes some element of luck, especially in circumstances as rare as finding a fossilized eye.

There are many different types of eyes still used by animals alive today. The eyes of invertebrates give an important look into the history of the parts that make up the complex human eye. Shubin compares the eye to a car, where the development of the car as a whole also incudes the development of pieces such as tires and the rubber that tires are made of.

The eye as an entire organ has a developmental path through many different species, but the parts of the eye can be traced even further back to invertebrates. Shubin's car analogy helps clarify how the many simple parts can build on each other, leading to the development of a complex piece of large machinery. Detailing the entire history of a car is difficult, but following the history of one tire is much easier and provides a lot of information about the car as a whole.

Human eyes function like cameras. Light enters the eye and is focused on a screen (the retina) in the back of the eyeball after passing through the lens. Tiny muscles in the eye control the iris, a small opening that controls how much light is allowed to enter the eye, as well as the shape of the lens itself. The retina has two types of light receptors that send signals to the brain. More sensitive receptors see only black and white, while less sensitive receptors see color. All of these cells make up about 70% of the sensory cells in the body, showing how important vision is to humans.

Shubin gives a simple run-through of the function of the human eye, glossing over many of the trickier aspects of sight to give a basic understanding of the entire mechanism. Vision is by far the most important sense to the average human, and the human eye is one of the most fine-tuned sight organs on Earth.

Most animals with a skull have this camera type eye. Other animals have different eyes, from light-detecting patches, to compound eyes in insects, or simple versions of the camera eye. Shubin compares all these different kinds of eyes by studying the molecules that gather light, the tissues in the eye, and the genes that direct eye production.

Though the human eye is incredibly complex, Shubin draws the similarities that human eyes have to other animal eyes through their component parts of. Calling back to the car analogy from earlier in the chapter, Shubin is comparing cars to motorcycles and bicycles by focusing only on tires.

Light-gathering Molecules. The molecule that collects light breaks into two parts when light is absorbed: Vitamin A and a protein called opsin that sends an impulse to the brain. Animals need three different opsins to see in color, and only one to see in black and white. Every animal with the ability to see light uses the same kind of opsin molecule to do so.

In another example of similarity in animals despite perceived difference, there is no grand new mechanism for seeing in color, just more of the same opsin proteins that see in black and white, and that are slightly tweaked for color vision.

Opsins transmit messages by carrying a chemical across the membrane of a cell, then helping the chemical follow a specific twisting path through the cell to the nucleus. This same twisting path is seen in certain molecules in bacteria, tracing the history of vision all the way back to single-cell bacterium.

The path of opsins through cells calls back to Chapter 7 and the mechanisms that cells use to communicate with each other. Opsins just have a more specialized version of this same basic practice. This feature is shared with even the most simple life on Earth that has no real sense of sight.

The development of rich color vision unique to primates (including humans) comes from a change in the gene that makes light receptor molecules. Primates have three of these genes, where other mammals have only two. It seems that primates copied one of these genes, just as mammals copied the odor genes and gained a better sense of smell. A mutation that increased color vision would have benefited primates who could better discriminate between different kinds of fruits and choose the most nutritious. Scientists estimate that color vision arose about 55 million years ago, at which time the fossil record also suggests that forest plants became more diverse.

Again, the mechanism of copying genes with mutation creates a new ability out of old, shared parts. Mutations that change the way an animal's sense works are only passed down to the next generation if they are beneficial to the animal. Shubin explains why better color vision would have been helpful to advanced primates, leaving the door open to whether humans could continue to improve this sense if there were an environmental reason to do so.

Tissues. There are two main types of eye, the invertebrate eye and the vertebrate eye, each using a different method to increase the amount of light-gathering surface area in eye tissue. Invertebrate eyes have many folds in the tissue, while the vertebrate eye has bristles projecting from the surface of the eye. Scientists could not understand how to bridge the gap between the two types of eyes until 2001, when Detlev Arendt studied the eyes of a primitive worm called a polychaete.

Shubin constantly seeks to bring back together groups of species that biologists have deemed separate based on physical traits or outward appearance. Shubin does not explain why one method of gathering more light molecules might be better than another, but the vertebrate eye has more room to improve vision by increasing the number of bristles, whereas invertebrate eyes can only handle a specific number of folds.

Polychaetes are among the simplest living worms, but they have both a true eye and light sensing patches in their nervous system under their skin. Arendt studied these physical structures and the genes that created them, finding that the eye was a normal invertebrate eye but that the light-sensing patches had the opsins normally found in vertebrate eyes. These patches even had primitive versions of the little bristles of vertebrate eyes.

Here, the polychaete worm acts as the "bridge" for vision the same way that Tiktaalik is the bridge for limb formation. Polychaetes bring together vertebrates and invertebrates by combining features of both distinct groups. Significantly, Arendt had to look at both physical structures and genes to see these similarities that were not fully apparent on the surface of the worm.

Genes. In order to understand how eyes that look different can be related, Shubin turns to the genes that create eyes. In the early 1900s Mildred Hoge studied flies with a mutation that gave them no eyes at all. A similar mutation in mice and humans creates individuals missing large chunks of eye tissues. In the 1990s, geneticists found that these mutated flies, mice, and humans had similar DNA sequences on a specific gene. Scientists then began to study this gene, then called "eyeless," through fly populations, to pinpoint how this gene was responsible for forming eyes.

As when studying mutations in hands or body plans helped to isolate genes for limb development or Hox genes for body plans in chapters 3 and 6, geneticists can use the same approach to isolate the genes for vision. Crucially, animals as different as flies, mice, and humans seem to have the same gene for eye development, though the eyes of these animals look quite different.

Walter Gehring isolated the eyeless gene and was able to insert the gene to form eyes all over flies' bodies. Gerhing then used the mouse version of the eyeless gene and was able to insert that genetic code to make an eye on a fly's body. DNA from a mouse was able to make the eye of a fly by acting as the "on" switch for a complex chain of gene activity in fly cells. This same gene, now called Pax 6, is responsible for the development of eyes in any animal that has eyes.

The similarity between the Pax 6 eye gene in many different species is a huge boon to scientific research, as it is much easier to accept experiments on flies that cause mutations in eyes than it is to accept experiments on animals such as mice. Gerhing's study of Pax 6 shows one way that the fundamental similarity between all animals (even flies and humans) can benefit human health care by teaching us how our same genes work.

CHAPTER 10: EARS

Human ears are rather boring on the surface, but the mechanisms that funnel sound into the inner ear act like a complicated Rube Goldberg contraption with multiple differently shaped muscles and bones. There are three main parts to the ear: the external ear visible outside the body, the middle ear with three ear bones, and the inner ear of sensory cells, fluid, and a tissue cushion. The external ear is a relatively new evolutionary development, but the middle and inner ear is connected to the bone structure of sharks.

A Rube Goldberg contraption is built of a long sequence of many pieces that all perform some simple task in order to accomplish one larger goal. In the same way, each of the parts of the three layers of the ear perform simple functions in order to allow the ear as a whole to process sound waves and send a signal to the brain. Our ears may look different from animal ears on the outside, but Shubin again points out inner similarities.

Starting with the ear bones, Shubin recalls from Chapter 5 that two of the ear bones (the malleus and the incus) develop from the first arch in the head and the third bone (the stapes) develops from the second arch. In 1827, German anatomist Karl Reichert studied the gill arches to find that two of the ear bones in mammals corresponded to two jaw bones in reptiles. Ernst Gaupp continued this study in 1910 to interpret Reichart's conclusion to mean that mammals evolved from reptiles over time.

Shubin brings back the arches that form all the structures of the human head, this time looking with more nuance at the complex development of the middle ear bones. Gaupp builds off of Reichert's work in another example of how scientists can work together to make more impactful discoveries than they could alone. Yet Gaupp's theory alone is not enough to prove that mammals evolved from reptiles, because he did not have the intermediary forms that show the jaw bones becoming ear bones.

Gaupp worked only with living creatures, and so had no proof that the malleus and incus bones gradually moved from the jaw in reptiles to the ear in mammals. Richard Owen, the anatomist, then appears again, this time cataloguing small dog-sized reptiles found in South Africa that had oddly mammal-like teeth. In 1913, W.K. Gregory, a paleontologist at the American Museum of Natural History, connected Gaupp's theory to Owen's mammal-like reptiles to find that the reptiles that had the closest to mammal-like features in their teeth also had very small bones in their jaw that shifted back toward the ear. Gregory thus proved that the malleus and incus evolved from reptilian jaw bones.

Though Gaupp saw the similarity between reptilian jaw development and mammalian ear development, it took Owen's specimens and Gregory's insight to cement the theory that these jaw bones gradually became ear bones. This points to Shubin's larger point that one scientist's work is often not enough to make large claims, but that scientists can work together as they each provide a piece of the evidence. Gregory filled in a huge gap in the evolutionary path between reptiles and mammals, one that seemed insurmountable due to the many superficial differences between these species groups.

If the malleus and the incus evolved from the reptilian jaw, Shubin now turns to the development of the stapes. This tiny bone in the middle ear of mammals comes from the second arch, just like the huge bone in the upper jaw of fish and sharks. These two incredibly different bones are even served by the same second-arch nerve in both mammals and fish. The fossil record shows a progression of fish to amphibians that have smaller and smaller jaw bones as these animals began to live on land and needed a way to hear higher frequency sounds in air instead of in water.

There are many developmental similarities between the stapes and the jaw of fish, even though the bones themselves look radically different. Shubin again pushes past the surface to get at the fundamental similarities that connect these anatomical structures. As Tiktaalik's primitive limb fills in a gap of the developmental path of appendages from fins to hands, the fossil record also holds intermediate versions of the jaw bone moving to the ear.

The Inner Ear – Gels Moving and Hairs Bending. The mammalian inner ear has different parts for functions of both hearing and balance. Special cells send hair-like bristles into the gel that fills the inner ear. If the gel moves, the bristles bend and send a signal to the brain that is interpreted as sound, position, or acceleration. Shubin imagines the inner ear like a snow globe with a flexible case that also moves when the snow globe is tipped upside down.

Shubin gives the example of a flexible snow globe to explain the inner ear, because the inner ear is hard to visualize for most people who have never seen this bodily structure.

Human inner ears are even more sensitive because there are rock-like structures on top of the gel membrane that move when the head is tilted. Humans also perceive acceleration through three gel-filled tubes inside the ear that move when the human body accelerates or stops. Both of these position and acceleration mechanisms are also connected to the eye muscles that help keep humans looking in the same direction even when our head tilts or moves.

Shubin builds from the simple version of the inner ear as a snow globe and adds nuance to adequately explain the complexity of this structure specifically in humans. Only then does he introduce the additional sensory capabilities of the human inner ear, so that each piece is easier to understand.

The easiest way to understand this eye-balance connection is to mess with it. If a person drinks too much, the alcohol makes the fluid inside the inner ear tubes less dense and convinces the inner ear that the person is moving. The brain then sends this "we're moving" message to the eyes, causing the eye muscles to twitch. Hangovers are also an effect of the inner ear. Even if the liver removes alcohol from the bloodstream, there is still alcohol in the inner ear that convinces the inner ear that the person is moving even when they are standing still.

As when the function of genes is easiest to understand based on mutations, the function of the inner ear is easiest to understand when it is misfiring. The same basic approaches can be used for many different experimental questions. Shubin then reduces the complex ear-eye connection to the key functions that allow the ear and eye to work together when both the are working properly.

Fish like trout have a primitive version of the human inner ear. Trout hang out in quickly moving eddies in streams, and need a mechanism to sense the motion of the current around their bodies. Small sensory lines run under the trout's skin and send hair-like projections into jelly-filled sacs called neuromasts. When water flows around the fish, the neuromasts change shape and the hairs send an impulse to the fish's brain that tells the fish how fast the water is moving.

Shubin focuses on the neuromast of trout, not explaining that trout also have an inner ear that handle the trout's sense of hearing. The unanswered question here is how the neuromast functions were enveloped into the inner ear in land animals, as Shubin offers no sense of when the first animal with an inner ear capable of sensing acceleration developed.

It's hard to tell whether neuromasts or inner ears developed first, as the inner ear is almost never preserved with fossils. Due to the similarity between neuromasts and inner ears, it is likely that one evolved from the other. What is clear is that animals have developed a better sense of hearing over time, creating a bigger inner ear in mammals than in amphibians and reptiles. The sense of acceleration became more sensitive as well, with only one inner ear tube in ancient jawless fish and three ear tube canals in modern fish and other vertebrates.

Shubin seems to be suggesting that primitive fish might have had the capability to form both inner ears and neuromasts, from which modern animals refined these organs based on which mechanism was most useful to their environment. This is similar to the evidence that primitive fish have mechanisms for smelling molecules in air and water that was later refined for land animals. The ear is another example of a basic template that became more complex over time.

The neurons inside the gel of the ear have an even more ancient history. Neurons in the ear are different from any other neurons in the body, as they have a long "hair" on the outside and remain in a fixed orientation in the body. These neurons have been found in animals that have no heads at all, like the worm amphioxus from Chapter 5.

Recall from Chapter 5 that amphioxus was the example of an animal with a primitive "front" that housed light-sensing organs as a precursor to animals with heads. The fixed orientation of this neuron might have contributed to amphioxus' sense of forward direction, despite amphioxus not having a true ear.

Genetic information also tells the long history of the ear. A gene called Pax 2 seems to control ear formation in both mice and humans, as a mutation in Pax 2 creates an animal with a faulty inner ear. Pax 2 is also active in the neuromasts of fish.

Genetic similarities tie together different species once again. Mice and humans are compared often because scientists have a large body of knowledge about the mouse genome and the human genome after years of using mice as test subjects in labs.

Jellyfish and the Origins of Eyes and Ears. There is a link between the Pax 2 gene for ear formation and the Pax 6 gene we saw in Chapter 9 for eye formation. Box jellyfish are a fairly primitive animal that have over 20 eyes with a full cornea and lens spread all over their bodies. The gene that forms these eyes seems like a primitive version of sequences from both Pax 2 and Pax 6. This link helps explain why many human birth defects affect both the eyes and the inner ear.

The eyes and the inner ear share a developmental path based on this genetic evidence. As when copies were made of odor genes or the genes for color vision, it is likely that a descendent from the box jellyfish produced a copy of the jellyfish's combined Pax 2 and Pax 6 genes that then underwent thousands of generations of mutations until Pax 2 was specialized for ears and Pax 6 for eyes.

CHAPTER 11: THE MEANING OF IT ALL

The Zoo in You. In college, Shubin volunteered at the American Museum of Natural History, where he would listen in on weekly seminars that would often devolve into shouting sessions between biologists about the smallest details of a presentation. At the time, Shubin could not understand why these scholars were so passionate about the names or biological classifications of species, but he now sees how species classification and the description of different animals has huge effects on how scientists compare different species and use that genetic data for purposes as varied as family ancestry, forensic crime scene analysis, and the tracking of familial or inherited diseases.

Though the details of scientific theories about certain animals may seem like useless distinctions that have no bearing on human anatomy, Shubin argues that the many basic similarities between these animals and humans mean that any information about might eventually have use for humans, as in efforts to cure genetic diseases or the ability to track genetic data on crime scenes. It takes many scientists over different generations working on similar issues across many animal species in order to see the full picture of how one scientist's contribution might add to scientific discovery as a whole.

There is one simple law at the heart of all biology: every living thing on the planet had parents (or at least parental genetic information, in the case of cloning). This means that organisms are modified versions of the DNA of their parents. Using this knowledge, Shubin suggests that it is possible to build a family tree of how closely related a room full of individuals might be.

Shubin acknowledges the simple law at the heart of biology, though the details and differences between all the species on Earth quickly make attempts to make a family tree very complicated. By tracing parentage instead of comparing physical structures, biologists can block out a lot of similarities between animals that don't actually have a shared developmental history.

Shubin illustrates this idea of descent with modification using the analogy of a family of clowns. The first generation of clowns has a mutation that gives them a red nose. The second generation has the red nose and a new mutation that gives them huge feet. The third generation has the red nose, floppy feet, and adds orange curly hair. Looking back on this lineage, it is easy to see who is more closely related based on who has more shared features. The first generation and the third generation share only a red nose, while the second and third generations share red noses and huge feet.

For the purposes of this example, it is not important how the clown family gains new traits. In humans, the crossing of genetic information from mother and father creates new combinations that sometimes results in new traits in the offspring. Though Shubin uses traits that can be seen visually for his example, geneticists actually depend more on genetic similarities in people's DNA sequences to determine lineage, as those markers are less likely to be changed by differing environmental influences.

Now replace the "clown features" with actual human traits, and Shubin has a simple model of human genetic descent with modification. The only problem is that humans (and other animals) tend to change more than one trait with each generation. Yet through careful analysis, it is possible to trace this lineage of shared traits all the way through humans back to 3.8-million-year-old pond scum. To do this, Shubin returns to the zoo.

The clown family isolates the thousands of genetic mutations that could happen in a generation of humans to one simple difference, making the process of descent with modification easier to see. Tracing the lineage back to pond scum then depends on using specific genetic markers that geneticists have seen go relatively unchanged through different species.

A (Longer) Walk Through the Zoo. Many human features are shared with other animals, but some animals share more features than others. For example, polar bears and humans have more in common than turtles and humans. Additionally, turtles and humans have more in common than fish and humans. As with the clown family, different subsets of animals seem to add on features just like the generations of clowns added clown traits.

Though the mechanism of descent with modification that Shubin used in his clown example is the same, the time frame for descent with modification actually creating new traits and new species is thousands (or even millions) of years, rather than one generation as in Shubin's simple example.

Using the lineage of shared traits to create a biological family tree predicts that fish and amphibians would be the "grandparents," followed by the "parent" reptiles, then the more recent generation of mammals, and finally the most recent generation of human species. There are many branches of sisters and cousins within that framework, such that it is very hard to trace one clear line back to "The Ancestor" of humans. This family tree also allows biologists to make predictions about which animals should share the most features and have the most similar DNA. If the predictions are backed up by the actual features and genes that biologists observe in animals, then biologists know that their tree is correct.

Shubin has walked through a few of the shared traits that support the tree that flows from fish to humans, including limbs in Chapter 2, odor genes in Chapter 8, and eyes in Chapter 9. The family tree and animal observation itself form a circular feedback loop, as scientists use and observation to build the most likely tree based on available evidence, then use that tree to make predictions, check to see if those predictions hold true in nature, and tweak the tree as new observations come out of these predictions.

Shubin begins to walk through the family tree of the human species, noting the modifications that are made with each generation. At the top is multicellular life: organisms with a body made of many cells. Then comes Bilateria: the group of organisms with body plans that include front/back, top/bottom, and left/right symmetry. Next are vertebrates: all animals with a backbone. The next level is vertebrate tetrapods: animals with four limbs. After that are mammals: tetrapods who have a three-boned middle ear. Finally comes humans: mammals who walk on two legs and have enormous brains.

There are obviously many more factors in the modifications of each species in the generations that Shubin traces from multicellular life to humans, but Shubin focuses on a few key modifications to keep his analysis as clear as possible. These classifications are useful in tracing the history and gradual development of a species, but they are somewhat limiting for intermediate stages such as Tiktaalik that might seem to fit into two categories based on their physical traits and genetic information.

The family tree of the human species is supported by the fossil data, as the first multi-celled fossil is older that the first fossil with a three-boned middle ear. The three-boned middle ear fossil is in turn older than the first fossil that walked on two legs. In some ways, the human body acts like a time capsule, preserving features from ancient animals that reflect how life has changed over time.

Shubin specifically mentions the ways that the fossil record upholds the tree he previously outlined, as he is a paleontologist and the fossil Tiktaalik that inspired this book is one of the fossils that helped cement this lineage. Yet the genetic record also supports this tree, as Shubin has described in previous chapters – showing how many scientific disciplines can come together for the same conclusions.

Why History Makes Us Sick. Shubin says that he once hurt his knee badly, finding out that he had torn his meniscus (one of the ligaments in the knee). There are three ligaments in the knee that are particularly likely to get hurt, due to the fact that knees were not originally developed to support walking on two legs. Shubin compares the human knee to a VW Beetle that has been jury-rigged to accelerate to 150 mph.

As when Shubin walked through the cranial nerves by describing them as plumbing from an old building that needed to be brought up to new codes, the human skeletal system holds evidence of using old structures for new purposes.

Another place that shows the changes humans made to a body plan originally meant for fish is the paths of arteries, nerves, and veins. Some veins loop over organs or switch direction almost randomly within the body. Furthermore, the modern human's sedentary lifestyle exacerbates blood flow problems in a body meant for a short life span full of active movement. Almost every illness humans suffer has a historical component about the past functions of different human body systems.

The nervous system is fairly clear and straightforward in fish, but increases in complication due to the complex history of humans developing their specific body plan from the original blueprint of fish. In an example much closer to our own time period, modern humans are even rewriting the lifestyle and body plan of the first humans by becoming less active with each generation. Shubin applies this broadly to all humans, but of course some communities continue to live in ways that make the best use of the original human body plan.

Our Hunter-Gatherer Past: Obesity, Heart Disease, and Hemorrhoids. Almost every level on the human family tree was an active predator in a different environment. Fast forward to modern human life, and most people have very little physical activity over the course of the day. Four of the top ten modern causes of death—heart diseases, diabetes, obesity, and stroke—arise from the conflict between humanity's genetic wiring for an active lifestyle and the sedate lives we actually lead.

Shubin argues that understanding the original plan for human lives built into our genes can help us live healthier lives by increasing activity that is in line with the ways that human bodies originally worked. This line of thinking is certainly useful for increasing human health in the short-term, yet pushing that idea further suggests that our new sedentary lifestyle is an external pressure that will simply shape the path of future human development to favor those humans who can best handle this sedentary "environment." However, these adaptations will take significant time, and no adaptation can take place within the small number of generations alive on the planet today.

An anthropologist named James Neel looked at the conflict between active wiring and sedate lives through the lens of diet. Neel hypothesized that early humans would have likely had "thrifty genotypes" that could save food as fat when food was plentiful so that the individual could survive long stretches when food was scarce. Now that (many) humans do not have to deal with periods of famine, our genes constantly tell our bodies to save fat that is never used – leading to high rates of obesity when high-fat food is always readily available.

Shubin explains the discovery of the "thrifty genotype," a genetic disposition to saving fat that was useful in human history. There are now studies of medicines or gene therapy that might be able to address the fat storage techniques of individuals with thrifty genes so that their metabolism will not save so much. Understanding the historical adaptations that helped humans in the past allows scientists to see which paths will be most beneficial to human health in the future.

A sedentary lifestyle also affects human blood flow. Walking on two legs makes it harder for blood to flow "uphill" from the feet back to the heart. Our leg muscles help push the blood back up, assisted by little valves that stop the blood from rushing back down due to gravity. If a human does not use the leg muscles, the blood pools in the veins and stresses the valves. When the valves break, painful problems such as varicose veins can restrict blood flow in the legs even more. When people sit too much, blood can also pool around the rectum to form painful hemorrhoids.

The things that make humans unique – such as walking upright – require complex mechanisms that allow a body plan originally meant for another lifestyle to perform these functions. The adaptations that worked for humans who had a specific kind of active lifestyle are not helpful for humans who now have a sedentary lifestyle. This example provides a small glimpse into the environmental pressures that shaped how animal species adapted their body plans to external factors over the history of life on Earth.

Primate Past: Talk is Not Cheap. In order to be able to talk, humans have to deal with the hazards of choking and sleep apnea. Looking back to the gill arches from Chapter 5, the throat muscles that allow humans to talk are a modified version of the gill arches of a fish. When we speak, the muscles of the back of the throat contract to control how rigid or flexible the throat is, making it possible to produce a wide range of speech sounds. Yet this flexibility means that the throat can collapse so much while a human sleeps that no air can pass through, a breathing problem called sleep apnea. Another problem of a human's modified throat is choking, as humans use the throat to swallow, breathe, and talk.

Though human embryos never use their gill arches to breathe, the developmental path that follows humans back to fish means that these gill structures are still in place in the human. Humans did not invent new structures to perform new actions that helped them survive (like talking and verbal communication), they simply repurposed old structures that other animals already had for other reasons. As mutations in genes help isolate the progression of genetic changes, the missteps in human anatomy help Shubin explain the origin of human anatomical adaptations.

Fish and Tadpole Past: Hiccups. Many animals can hiccup, a complicated reflex triggered when the major nerves that control breathing spasm and contract the breathing muscles too fast, and then a flap over the airway closes and makes a "hic" sound. There are two issues at play in the history of hiccups: the nerve spasm and the flap closure.

Hiccups have no real use in modern humans, yet they are a holdover from our evolutionary past. Shubin identifies two key areas for tracing the development of hiccups, making a potentially complicated backstory simple and easy to follow.

The nerve spasm in hiccups comes from our fish history. Most of the time, the human brain coordinates all the breathing muscles in a well-defined rhythmic pattern where the brain stem activates specific nerves that in turn activate specific muscles. This nerve pattern is seen in fish where the major nerves and muscles involved in breathing are fairly close to the brain stem. Yet the human muscles for breathing are much farther away in our chests, meaning that the nerves must travel a long way from the brain stem to the muscles and are vulnerable to an interruption that could cause a spasm.

The fish body and the human body each use the same nervous system, yet demand different functions that put different pressures on this common system. In order to have larger lungs meant for breathing air, the human chest cavity had to expand. The cost of this beneficial adaptation was stretching the nervous system to new lengths. Again, humans can only survive this adaptation because the larger chest cavity is helpful to surviving in our land environment, and the nerve cost is not fatally harmful.

The flap closure of hiccups comes from our amphibian history. Tadpoles use the same pattern of sudden muscle contraction followed by throat flap closure that distinguishes hiccups in humans. Yet in tadpoles, this pattern allows the tadpoles to keep their lungs clear of water and breathe with their gills.

Unlike the adaptation of a larger chest cavity, Shubin does not explain any benefits that this throat mechanism could have for humans, simply using it as evidence of humans' evolutionary lineage through amphibians like frogs.

Shark Past: Hernias. Hernias near the groin are likely a product of repurposing a fish body for human life. In fish, the gonads that hold sperm are near the liver toward the front of the body. In humans, the gonads are much lower in the body, and separated from the main torso in the scrotum so that the temperature of the gonads can be regulated to maximize the health of the sperm. The movement from shark gonads high in the chest to human gonads low in the groin area means that the tubes that carry sperm from the gonads to the penis actually go up toward the human waist, loop back over the pelvis and then travel out through the penis.

Given the assumption that bodies will be as efficient as possible, many pieces of human anatomy don't actually follow that rule on the surface. Shubin already touched on this in his explanation of the cranial nerves in Chapter 5, and he brings it up again by assuming that sperm tubes would be better served by staying closer to the low position of the human gonads. Looking at human bodies through the lens of the evolution and adaptation of many species gives reasons for some strange parts of human anatomy such as the long path of the sperm tubes.

As pre-pubescent children, human male gonads are housed near the human liver, then descend as the male matures. This descent creates a weak spot in the body wall of the torso, as the gonads push down on the body wall like a hand pushing through a sheet of rubber. This weakness in the body wall means that the guts can sometimes escape the body cavity and lie next to the spermatic cord when the guts are pushed by the abdominal muscles. The escape of the guts creates a painful injury called a hernia.

Hernias are an injury that is much more likely in males. Before looking at the developmental path that links human anatomy to fish anatomy, there would have been no viable explanation for why male body walls were so much weaker than female body walls. Given the anatomical blueprint that human bodies work from, the descent of the gonads is the best way to use that fish body for human purposes, even if it leaves males open to injury.

Microbial Past: Mitochondrial Diseases. Mitochondria are important in every single cell of the human body, turning oxygen and sugar into energy for the cell and performing other regulatory functions. Yet tons of things can go wrong inside mitochondria, leading to illness or death. The chemical reactions that mitochondria use to create energy are an ancient process still used by bacteria, meaning that scientists can use bacteria to study mitochondrial diseases that kill humans. By changing the bacterial energy process to match the mutation that is killing humans with faulty mitochondria, scientists can run experiments to keep the bacteria healthy in other ways. This is just one example of how knowing our evolutionary past can lead to scientific insights that help humans live healthier and longer lives.

Scientists cannot easily do experiments on humans to treat fatal illnesses, due to the relatively small pool of human test subjects and the larger issue of ethical problems with experimenting on humans. The fundamental similarities between mitochondria and bacteria mean that scientists can perform the necessary experiments that might actually save human lives in a humane and safe way.

Epilogue. Shubin says that he often takes his children to zoos, museums, and aquariums, a far different perspective than the time he spends in those buildings as a scientist and a professor. Being a visitor there reawakens his wonder at the complex workings of life on earth. At the Museum of Science and Industry in Chicago, Shubin was struck by a display of a battered space capsule. Shubin realized this display was not a replica, but the actual space craft Apollo 8 that took humans to the moon. Shubin tried to explain the momentous significance of this trip to Nathaniel, his son, but Nathaniel was too young to understand what made this space craft so special.

Just as many people might not understand why Dahn devotes his life to the boring work studying shark embryos, or Shubin himself spends his time looking for ancient, outdated fish fossils when he could be doing genetic research, Shubin's son does not see the importance of a space capsule that looks beat-up and dirty. These examples all point to the ways that large leaps in scientific discovery can be made from unglamorous beginnings.

For Shubin, Apollo 8 represents the power of science to explain our universe and the essential human optimism that keeps humans asking questions and seeking answers. Just as Apollo 8 made space and the moon accessible to humans, paleontology and genetics make the distant past and the history of life available for human study. So far, this research has revealed that all life is a constant cycle of recombining and repurposing old materials for new functions. Shubin imagines a future where genetic research and new discoveries in the fossil record can help humans understand the fundamental building blocks of the human body and cure diseases.

Shubin ties together the future of scientific research, both in outer space and on Earth, to the past that has built the foundation for scientists to continue their research. The developmental history of life on Earth illustrates how organisms themselves use this same process of taking existing structures and applying them to new functions or adaptations to a specific environment. The task of scientists is now to bring many fields of research on distinct species together in ways that take advantage of the basic similarities between all living things in order to benefit human health.

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