Animation Script

Chapter 1: Introduction

If you were assigned the task to collect individuals from every living species on Earth, how would you do it? Well, for starters, don't quit your day job. Or you might want to consider staying in school, because this task would be completely impossible. Not just for you alone, but if every person on the planet worked in unison to gather members from every living species, the task would still not get done. Why is this?

Not only do we not know all species on Earth, we have absolutely no idea *how many* species there are on Earth. We don't even have a good estimate. Every time a team of biologists goes into, say a tropical jungle, they wind up cataloguing hundreds of new species of insects. This happens every year. But those are organisms that we can see with the naked eye. What about all the microorganisms out there? Viruses?! We still haven't decided if they are within the confines of life. They have their own entire taxonomic system! Scientists have discovered about 2 million living species, but their estimates for the total number of species living on Earth range anywhere from 3 -100 million. So, where did all these species come from? They didn't just pop into existence out of nowhere, at least we've never seen that happen.

This is what we DO know: DNA is a shared trait of all life and, within a population, not only do gene frequencies change, but DNA recombines and mutates from generation to generation. Interestingly enough, this is the very definition of <u>Evolution</u>: that is, change in the genetic material (DNA) of a population of organisms from one generation to the next. *This is a fact*. There is no scientific debate on whether or not Evolution exists. It does exist: genetic change in a population from generation to generation does occur.

We also know why Evolution doesn't expand populations limitlessly in all directions; Evolution works through mechanisms, such as Natural Selection. More on that later... But, does evolution cause new species to arise from older species? Again, this is what we do know: the fossil record, DNA and protein analysis, comparative embryology, and all the homologies (or shared traits between species) show that new species do arise from older species. Of course, this can take thousands, sometimes millions, of years in a process called speciation.

Evolution is the cause for all the variation of life on Earth. Without it there would be no reason for you to have Biology class. Biology would be meaningless. In fact, the class wouldn't even exist. There wouldn't be chairs, or desks, or walls. This very animation would cease to be, along with my voice, because... *you* would not exist, either.

Chapter 2: The Fossil Record

So, where did we get this idea of Evolution? Charles Darwin gave us an explanation for how evolution works, but where did HE first get the idea? Well, you're standing on it.

The Earth's surface is composed of layers of rock. And some of that is sedimentary rock, in other words, rock formed from sediment. Now, if you had to guess, which layer do you think would be the oldest layer in this sedimentary rock? Well, it's the layer on the bottom. Think of a sand bottle, in which you pour one color of sand that settles to the bottom. We're depositing "sediment" here. Then you add another color of sand, which settles on top of the first color. In general, this is how the sedimentary rock of the Earth's surface is arranged, with older layers on the bottom and newer layers on top.

The data which support this concept is gathered using a technology called <u>radiometric dating</u> (radioactive carbon dating is one such technique). If they take a sample of rock from one of these layers... there will be radioactive atoms in that sample, which have been releasing particles over time. This is called decay. And using the rate of decay, scientists can measure the amount of certain elements to deduce the age of the rock sample. Radiometric dating has shown that the Earth is about 4 ½ billion years old, and in sedimentary rock, the oldest layers are generally on the bottom, with the newer layers on top.

And just like the rocks in the Earth's surface, certain fossils are found in corresponding layers. If we focus on the tiny branch of Evolution that is our own vertebrate lineage, this is what we find in the fossil record. In the oldest rocks on the bottom, we find only life forms without a head. On top of that we find everything with a head. On top of that we find everything with a head, jaws, and paired appendages. On top of that we find everything with a head, jaws, and paired apendages that walk on land. On top of that we find everything with a head, jaws, paired apendages that walk on land, and hair. And on top of that we find everything with a head, jaws, paired apendages that walk on land with 2 legs, hair, and a well developed brain.

This fossil record supports evolution because it shows how adaptations expand upon preexisting structures over time. This is NOT how things were *destined* to evolve; it's just how they *did* evolve. Evolution is not goal oriented. So in case you're feeling on top of it all, keep in mind that these ancestral species split into millions of other lineages, which evolved into all the species alive today. Now Evolution does not support the idea that any species is "superior" to any other species. So, we are not like the highest rung of a ladder. There's no ladder and there's no chain of being. We are only one tiny little branch on an ever expanding tree of life. Instead, you can think of these other living species as our very distant cousins, who are equally adapted to their respective environments.

Now, tectonic shifts (think massive earthquakes, volcanic eruptions, continental drift) have, in specific areas, disrupted the layers. But geologists can still discern the pattern of rocks. And remember, they can use radiometric dating to confirm the identity of the layer. This is how scientists are able to create vast and intricate geological maps, which evolutionary biologists can then use to find certain fossils. For instance, if they are searching for dinosaur fossils they will know in which layer to look. However, if they were looking for human fossils they wouldn't find any in this layer because the rocks are too old, and humans had not evolved yet. Rather, they would know to look in newer rocks to find human fossils.

In a sense, the entire field of Evolution is like a giant jigsaw puzzle. We've put enough pieces together to know it's there, but there are many pieces that have yet to be found.

Chapter 3: Mechanisms

So, how does Evolution work? First of all, Evolution works on populations, not individuals. So if you work out and get really fit, socialize and make a bunch of friends, and study really hard and get very smart, are you "evolving"? Are you "adapting" to your environment? You might maximize your genetic potential to become a sharper, better looking giraffe. But in terms of Evolution, the answer is no because you, an individual, do not evolve or adapt. *Populations evolve and populations adapt over generations*.

Now, a <u>population</u> is a localized group of individuals that belong to the same biological species. This means they can interbreed and produce fertile offspring. Also, populations are kind of a relative concept (meaning it depends on what you're looking at and how closely you're zooming in). You might be comparing 2 giraffe populations within one region in Africa. Or, you could be comparing all the giraffes in that region with all the giraffes in another region. Or, you might even be observing all the interbreeding giraffes in Africa, and comparing them to a population of an entirely different species, like: the population of *Homo sapiens* in your city, country or planet.

But how do populations evolve and adapt? Well there are a few ways. Let's say we have a population of giraffes, with some males and some females. The females are watching the males eat leaves off a tree. And in this activity, we can see some variation in traits. Specifically, there's variation in neck length. In fact, we see 3 different phenotypes of neck length in the males. James has a very long neck and can easily reach the nutrient rich leaves on the tree tops. Sam has an average length neck and can get just enough leaves to get by. Ben, however, has a very short neck and can barely get a leaf. This means, that in this environment, James is the fittest individual for getting enough nutritious leaves to live long enough to reproduce. So, this kind of competition (in this case, for food) is one environmental factor in something called natural selection.

Natural selection is the differential success in the reproduction of different phenotypes (like the 3 giraffes) resulting from the interaction of the organisms with their environment. Now natural selection causes the population to *adapt*, because the next generation will likely look more like James, with longer necks. Another type of natural selection is called sexual selection. Sexual selection is natural selection for mating success. There's intersexual selection, where members of one sex are choosy for members of the opposite sex. And then there's intrasexual selection, or competition among members of one sex.

But, not all factors in an environment favor the reproductive success of one particular phenotype. Predation is another factor in natural selection, and often in nature, it can go against sexual selection. While Sam's babies might not have the long necks that James' babies would've had, they'll be less noticeable to predators. And at least they'll have more sex appeal than Ben's babies. So, with predation, this is how the population might adapt. Natural Selection is a balancing of many different environmental factors with many different physical traits of organisms. But natural selection is just one way populations evolve.

Gene flow refers to the genetic additions or subtractions from a population resulting from the movement of fertile individuals or gametes. Gene flow is another way a population can evolve. But gene flow alone rarely causes a population to adapt. But wait, let's not forget about genetic drift.

Genetic drift is a change in the gene pool of a population that takes place strictly by random chance alone. So in the case of meteor shower… (kaboom!). Also unlike natural selection, it does not cause a population to adapt. The next generation will NOT be more adapted to meteors falling on them. That was just a random event that changed our population's gene pool.

Oh, I almost forgot. There's one more cause for evolution, and it's something that farmers and ranchers and animal breeders do for a living. Artificial Selection is the selective breeding of domesticated plants and animals to encourage the occurrence of desirable traits. In other words, in artificial selection we are the environment and we select the individuals who will make it to the next generation. You see these individuals when you cruise the produce section at the grocery store or your local pet shop. But do populations which evolve through artificial selection adapt? Take your little puppy and put him out in the Alaskan arctic and he probably won't fit in so well. Plop him on a sofa in front of a warm fireplace, however, and he will seem perfectly adapted. So yeah, sure, they adapt to us and the environments we create.

We’ll come back to the giraffes in a little bit, but for now, let’s go into the laboratory so we can manipulate the environment to observe changes in a population under the microscope.

In the lab…

Let’s say we have a population of microscopic, multicellular organisms. When we look more closely at their trait for surface area to volume ratio, we discover that there are 3 different phenotypes. So let’s discuss the different types. One has a low SA/V ratio. In other words, the outer surface is about as small as it can get for this volume. The type beside it has the same surface area, but its volume has decreased, so it has a higher SA/V ratio. The last one, with a deep invagination, has the most surface area per volume, and therefore the largest SA/V ratio. And because our population has this *variation* of traits, we say it has *genetic variation*. Look around your classroom; it’s a population. Does anyone look exactly the same? (Unless your class has identical twins, probably not) So the population of your classroom has genetic variation, just like this one. This variation can be plotted on a distribution curve, so we can see that most of our population has an average SA/V ratio. But few individuals have a very low or a very high SA/V ratio. So, now that we’ve analyzed our 3 phenotypes for this trait, and placed them on a distribution curve, let’s see what happens with selective pressures from an environment. Choose an environment. You can release food, biotoxin, both food and biotoxin at the same time, or a predator.

The food is a positive, life-sustaining environmental factor for our population. Which type seems to be the most adapted to getting food? The one with the highest SA/V ratio will have a higher chance of getting enough food because of its larger SA. So, which type would likely be the most successful in reproducing offspring in this environment? Yes, the type that is most adapted to getting food will have a better chance of living long enough and having the energy to reproduce more, and more successfully. Now what do you think will happen to our distribution curve in the next generation? It shifts more towards the individuals with the highest SA/V ratio because they were the best at getting food, and therefore could reproduce more. This is a kind of natural selection called <u>directional selection</u>. In this case the “direction” is towards the phenotype with the highest SA/V ratio.

The biotoxin is a harmful molecule produced by another organism in this environment. If an individual in our population gets too much biotoxin, it will die. So, what organism is most susceptible to the biotoxin? The one with the highest SA/V ratio will likely be most affected by the biotoxin. But which one will be the most reproductively successful? Well, since the one with the lowest SA/V ratio receives less, it is safest from the biotoxin. Therefore, in this environment, it is more likely to survive to reproduce. So, in the next generation there will be more individuals with a lower SA/V ratio. So, what happens to our distribution curve in the next generation? It shifts towards the individuals with the lowest SA/V ratio to reflect that there are more of them being reproduced in this environment. This kind of natural selection is called directional selection. In this case, the "direction" is towards the type with the lowest SA/V ratio.

Releasing both the food and biotoxin, a positive and negative stimulus, respectively, at the same time, will create a more complex environment. So, what type is the most adaptive to this environment? It's hard to say, and in real life there are often an incredible number of environmental factors, each balancing the benefits and costs of an individual's traits. But perhaps we find that the type with the average SA/V ratio gets just enough food and avoids the biotoxin just enough to survive, so that in this environment, we find it to be the most reproductively successful. But what do you think will happen to our distribution curve in the next generation? In this environment, our distribution curve will spike in the middle and be reduced on both sides, showing that in the next generation our population will have even more individuals with an average SA/V ratio. This type of natural selection is called <u>stabilizing selection</u>. Think of this as selecting for the most "stabile" or "balanced" set of traits, in between the 2 extremes.

The predator is a hydra that has adapted to feed on our population. While the hydra can devour any of the phenotypes, it is specifically adapted to eat the most numerous phenotype, which are the ones with the average SA/V ratio. So, which phenotype will show the least reproductive success in this environment? The one in the middle right? Because that's the type the predator is most adapted to eat. And what do you suppose might happen to our distribution curve in the next generation? Well, the individuals with an average SA/V ratio will decrease and the 2 phenotypes at the extremes will reproduce more. So, our curve would look something like this. This is a kind of natural selection called <u>disruptive selection</u>. So, the predator apparently "disrupted" our nice singular curve into 2 smaller curves.

Back to the giraffes…

So... back to our population of giraffes. Little did Patricia and Becky know, and you wouldn't know it from looking at him, but Ben had a few germ cells tucked away that were carrying some really awesome mutations. In fact, you might call them super sperm! You see, while there are many causes of Evolution, there is one cause which rules them all. So what is it that all 4 of these mechanisms need in order to work? Let's think about this. What if we had started out with just a population of only Bens? When they compete, get sexually rejected or eaten by predators, who, if anyone, will survive to mate and reproduce? Ben, right? But he can only reproduce with more Bens (which is kind of problematic). And if more Bens show up from a neighboring population, there won't be much *gene flow*. Nor will *genetic drift* have any real effect if some of the Bens survive whatever random thing happens. And if we wanted to artificially select to breed giraffes from this population, well, you got your choice of Ben... or Ben. We need something to get these mechanisms of Evolution to cause... well... Evolution. What is it?! The answer is genetic variation. Now... what causes this genetic variation? Well, your variation comes in 2 different varieties. You got new combinations of genes and new genes… in other words, sex, which recombines existing genes into new genetic flavors, and mutation, which are little changes in DNA that create new alleles and new genes. So, sexual recombination and mutation create variation, which allow these mechanisms of evolution to work.

Now, here in the forest, some of Ben's sperm, with very rare but awesome mutations, will recombine genetically with Patricia's eggs, to make some really fit offspring. Well, these new guys take off through natural selection, and over many generations they adapt to the forest. With each new generation they get new mutations and sexual recombination, which leads to more variation, which allows natural selection and genetic drift to cause Evolution. We're not around so there's no artificial selection. And Ben and Patricia's population is reproductively isolated from other giraffe populations, such as Gene's. Meaning, no *gene flow* and they're not mating with giraffes from these other populations. When evolution works like this over long periods of time (a matter of hundreds of thousands to millions of years), coupled with <u>reproductive isolation</u>, you get new species. And if you can understand just this much by the time you get to college, you'll be… (awesome).

Chapter 4: Embryology

<u>Embryology</u> is the science which studies the development of embryos, from the fertilization of the ovum to the fetus stage. What does embryology have to do with Evolution? We know that DNA mutations in the germ-line cells (that is, the egg and sperm) cause changes in the development of the offspring. And this changes the <u>morphology</u>, or form and structure, of the adult organism. And over hundreds of millions of years the changes in morphology can gradually become very great. But how does this idea show relationships between the species?

Well, did you know our embryology still has a lot in common with our recent relatives? Like all vertebrates, for instance, go through very similar stages of development. We see the following pattern in all fish, amphibians, reptiles and mammals (including humans). First there comes a fertilized egg which starts off as a *single cell*. That cell divides to form two cells in the *cleavage stage*, and then many cells in a stage called a *morula*. This ball of cells forms a cavity, becoming hollow, and goes through a stage called a *blastula*. The blastula develops a little hole, which in all vertebrates becomes the anus, and forms 3 layers of tissue (called endoderm, mesoderm and ectoderm), thereby becoming a *gastrula*. And then this develops into a little guy with a head, eyes, pharyngeal arches (we'll talk about those later), 4 limbs and a notochord.

So, how is it that our development has so much in common with all these other species? The answer is that the specific genes, in our DNA, which control development, are essentially identical to the genes in these other species. We still have a lot of the same genes with the same developmental functions. These genes include <u>egg polarity genes</u>, <u>segmentation genes</u>, and <u>homeotic genes</u> (or Hox genes). Basically they encode transcription factors which transcribe the next set of genes in the genetic cascade. This genetic cascade is just like the domino effect.

First, egg polarity genes divide the egg along the anterior/posterior axis. This tells the egg where it will form a head and where it will form a tail. Along this axis, segmentation genes divide the developing embryo into specific areas, or segments. And then homeotic genes, called Hox genes for short, give those areas a specific identity.

So, these developmental genes, in general, are very "conserved" in nature, meaning they don't mutate very much at all. Because when there is a mutation in one of these genes, it affects this critical early development, which affects everything after that in the genetic cascade, and almost always results in an unsuccessful organism.

But the question remains, what part of DNA does create successful mutations? If not the very conserved egg polarity, segmentation, or hox genes, then what? Well, this is what is currently being researched on the frontiers of evolutionary developmental science, called "evo-devo." While conducting research at UTSW Medical Center in Dallas, evolutionary biologist Dr. Trey Fondon, discovered one possibility for how, or where, DNA mutates. He studied many breeds of dog skulls and the variation in their morphology. He scanned the skulls with a 3d laser and found mathematical relationships in their shapes. The mutations he found in their DNA were tandem repeats of triplet DNA code upstream from the Hox genes controlling the skull morphology. This would allow for more or less transcription of the developmental protein, which would affect skull morphology. Evolution almost never takes the simplest path, but that's what makes it so fascinating. And there's so much more out there left to discover about how genes mutate and affect Evolution.

Chapter 5: Phylogeny

<u>Phylogeny</u> is the evolutionary history of a species or group of related species. Meet your extended family tree for the last 400 million years. At these nodes are all the living species that

you can go observe today. And at these nodes are representations of our common ancestors with these species. Every year, as we uncover more fossils and gain better technologies science is improving our understanding of what these ancestor species looked like. So these are visual estimates which are becoming more definite over time. Also keep in mind that this is an incredibly simplified version of a phylogenetic tree. If we were to zoom in on just one of these branches we would see many smaller branches of species.

Phylogenetic trees are often just represented like this, to simplify matters. So, where would you find our most recent common ancestor with Amphibians? The node representing Tetrapods is correct. Your genetic link to a frog or salamander was a four-limbed Tetrapod with air breathing lungs. Now can you find the most recent common ancestor of all Chondrichthyes and all Reptiles? A fish with jaws and paired fins was the common ancestor between these two groups. It was a Gnathostome, and this fish was also our ancestor. And because this represents a part of our lineage, it means that humans are also Mammals, Amniotes, Tetrapods, Gnathostomes, Craniates, and Deuterostomes. But we are also so much more. Our DNA is a shared trait that relates us to all life, like trees and even bacteria.

Which leads to the question, what is this so called "phylogenetic tree" based on? In other words, how do we know that the puzzle pieces fit together just like this? Well, a phylogenetic tree like this one is based on something called homologies. A <u>homology</u> is a shared trait between species that is due to common ancestry. Sometimes biologists refer to homologies as "synapomorphies." When a homology is structural we call it a <u>homologous structure</u>.

We can label our tree with some homologous structures like this. These are certainly not all the homologous structures, but just a few to give you an idea of how this works. Now, when we label this with homologous structures, it means that every group after has that structure, or something homologous to that structure. So, looking at the homologous structures on this phylogenetic tree, which group or groups have terrestrial legs? Yes, all tetrapods originally had legs that evolved to walk on land. That includes mammals, reptiles, and amphibians.

So we can say that your arms and legs are "homologous" to the arms and legs of any amphibian, reptile, or mammal. These are homologous structures; our ancestral tetrapod evolved legs that walked on land and amphibians, reptiles and mammals continued to evolve those legs. Do you see how in all these limbs there is a very similar arrangement of bones? But then what about this fish fin? Pretty different arrangement right? We do know, however, that our tetrapod limbs evolved from fish fins. But how do we know this? How do we know this when both the structure and function of fish fins are different than the structure and function of our arms and legs?

This is where current DNA research enters the picture. Remember those hox genes from the previous chapter, the ones that control those critical stages of embryological development? Well it just so happens that these hox genes regulate another gene called Sonic Hedgehog (named after the video game), which controls development of both fish fins and our arms and legs. So we know that even shark fins are genetically homologous to our arms and legs, which makes them homologous structures. So all “Gnathostomes,” which are jawed vertebrates and include everything from sharks to mammals, have homologous limbs.

OK, so what about insect legs or wings? Are they homologous to all of these other homologous structures? Actually, no. We can trace our phylogenetic lineage back to when our aquatic ancestors had no fins... no limbs at all. But our common ancestor with arthropods, including all insects, lived millions of years before this. So, the insects developed their limbs independently from ours in a process known as <u>convergent evolution</u>: that’s when a similar, but not homologous, trait evolves in two or more distinct lineages. And we call that trait an <u>analogous structure</u>. These are structures which have similar functions but evolved separately. Therefore, insect limbs and vertebrate limbs are called analogous structures.

Now, I said all reptiles have limbs which are homologous to our limbs, right? And that includes birds because they are actually reptiles that evolved from dinosaurs. That’s right. Phylogenetically speaking, the dinosaurs are still roaming... and er, flying over... the planet. And their wings are analogous to insect wings but homologous to our arms. But how about snakes, they’re reptiles right? Where are the homologous limbs? They don’t appear to have ANY limbs... or do they? In truth, some snakes, like boas and pythons, do still develop little hind limbs when they’re embryos, and the limbs remain as vestigial structures in the adult.

Now, a <u>vestigial structure</u> is a homologous structure which has lost all or most of its original function through Evolution. So do humans have any vestigial structures? Yeah, lots of them. First of all you’re probably sitting on one right now. That little nubbin of a bone called a “tailbone” you got back there is homologous to the tails of all our vertebrate cousins, even the ones swimming in the ocean. But it’s not much use to us any more, kind of like those limbs on snakes, so we call it a vestigial structure. You even have vestigial blood vessels. Here’s one in your heart, called the ductus arteriosus. It was useful for delivering blood in our fish ancestors, but for human adults... not so much. It closes up during our development and becomes, well, a vestigial structure.

There’s one more very fascinating human homology which you should know about: the pharyngeal arches. The pharyngeal arches look kind of like little gills, right? Here’s a fish embryo during the same stage of development. In adult fish the pharyngeal arches develop into jaws and gills. But since our development has evolved in another direction, gills not being so adaptive to breathing air on land, our pharyngeal arches develop into jaws and various structures in your neck. So, these bones and cartilages in your neck and the bones and cartilages in fish gills are homologous structures. Our lower jaw, which forms from the 1st pharyngeal arch, is homologous also.