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Since his publication of *On the Origin of the Species* in 1859, Charles Darwin has become a household name. Anyone unfamiliar with his theory of natural selection is likely to at least have encountered the saying, "survival of the fittest" – a phrase, many are surprised to learn, actually coined by Herbert Spencer (Wright, 1994). Since Darwin's time, advances in technology have led to the accumulation of massive amounts of evidence for the evolution of species by natural selection. Developments in the fields of biogeography, cosmology, paleontology, and biochemistry, including inventions of techniques such as fossil dating and genetic engineering, each lend overwhelming support to the view that all living things evolved by natural selection from a single common ancestor over the course of about 3.5 billion years.

Yet many continue to question the theory's credibility. Much of this doubt represents confusion about the meaning of the term "theory". In common language, a theory is little more than a hunch, an unfounded hypothesis regarding the cause of a given phenomenon. In *scientific* language, however, a theory is a body of knowledge with firm empirical basis (Wikipedia, 2005). A scientific theory must be compatible with other well-established theories, be supported by a variety of types and sources of evidence, be the best explanation out of all possible explanations for a given set of data, and have survived numerous tests that could have proven it false (Wikipedia, 2005). In fact, practically all of higher-level science is theory. Einstein's theories of special and general relativity, quantum mechanics, plate tectonics, the existence of atoms and electricity – even the notion that the Earth revolves around the sun – each of these falls under the category of "theory" (Wikipedia, 2005). Certainly, some scientific theories are better supported than others. But many of the central theories in science – the theory of relativity, of electricity, of a heliocentric solar system, and, yes, of evolution – are so well supported that scientists consider

them as fact. Clearly, a body of knowledge's classification as theory has nothing to do with whether it has withstood the test of time, the amount of evidence supporting it, or even the scientific community's general consensus. Rather, the term is used when a given phenomenon is not directly observable. Although heliocentric theory has been validated so many times – and in so many different ways – that it is now essentially undisputed, the fact remains that the Earth's journey around the sun is unobservable to the naked human eye. Although evolution can be witnessed today through the processes of natural and artificial selection, it is impossible to travel back in time 3.5 billion years and watch as species change, diverge, become extinct and begin almost the entire process over again. *This* is what identifies evolution by natural selection as a scientific theory – not a lack of evidence. In the following essay, a wide range of fields are explored to illustrate the compelling evidence for the theory of evolution and the force that drives it.

The Theory of Evolution and of Natural Selection

As early as the eighteenth century, scientist knew that evolution – genetic change in a line of decent over time – was a plausible explanation for the diversity of life forms. However, no existing theory was capable of explaining how such drastic change could come about. Darwin's theory of natural selection was just such a mechanism. Drawing on his observations of bird and tortoise species in the Galapagos archipelago, Darwin proposed the theory of "decent with modification". He argued that even a slight deviation from the normal would be preserved if conducive to the survival of the individual exhibiting it.

Our understanding of evolution has grown dramatically since Darwin's time. For instance, we now know that for natural selection to act on a trait, three essential conditions must

be satisfied (Starr, 2003). First, the trait must vary within the population. Second, the trait must affect fitness, or the number of viable offspring successfully produced. Third, offspring must resemble their parents in the trait.

It is evident that these conditions have been satisfied in nature. First, there is an immense amount of variation within species. In humans, for example, traits like height and weight vary along a continuum. Second, offspring often resemble their parents in a plethora of physical and behavioral characteristics. In humans, this is very clear. What may be less intuitive to us is that, in our evolutionary past, environmental pressures played a huge role in shaping these characteristics. Traits that enabled individuals to not only triumph over natural environmental hazards but to successfully reproduce – these were the traits that appeared in future generations. For example, qualities conducive to the procurement of meat (e.g., muscle mass, long legs, were almost certainly selected for in males because of increased ability to provide for self and family. On the other hand, hips and higher level of body fat likely evolved in women because of the advantages to childbearing. The process goes something like this. Variation arises naturally in nature. Adaptive forms grow in proportion to those that are not. Eventually, maladaptive alternatives are entirely replaced.

Clearly, genetic variation is essential to the process of evolution. One might wonder how all of this variation comes to exist in the first place. The answer is mutation. Mutation results from errors in the copying of genetic information. Although most mutations are harmful (for the same reason that randomly altering a circuit on your computer is unlikely to improve its performance), the sheer number of mutations ensures that some will be beneficial. Each individual inherits about 500-2000 mutations from their parents, plus one or two new mutations resulting from mistakes in the copying of germ line cells. From this perspective, it doesn't seem

at all odd that a beneficial mutation arises now and then. Once this occurs, the adaptive allele is almost certain to increase in frequency.

The powerful effects of evolution are clearly demonstrated in the northern European peppered moth, *Biston betulari.* During the 19th century, the peppered moth underwent extraordinary selective pressure as a result of Great Britain's industrial revolution. Prior to this period, a light, peppered form of the moth was by far the most common. The moths rested on lichen-covered trees, which served as protective camoflauge against predator birds. However, during the industrial revolution, the lichen on these trees was covered and destroyed by soot. The light moths were now easily spotted and devoured by predators. Within a few years, the (previously rare) dark form of the moth greatly increased in. Their advantage in eluding predator birds enabled the melanic form to survive and pass down their genes at higher frequencies than their lighter counterparts. Within one hundred years, the darker form was the more common of the two, and the lighter form relatively rare.

Changes in the prevalence of certain traits in a species, such as the changed coloration of the northern European peppered moth, are the products of natural selection. As example of the peppered moth demonstrates, a sufficiently demanding environmental pressure can cause natural selection to operate at an extraordinary pace. Evidence from a variety of such episodes of evolution make comprehensible the extreme changes natural selection has invoked over the last few billion years. The remainder of this essay draws from a broad spectrum of scientific fields in order to present the evidence for evolution by natural selection.

The Geographical Distribution of Species

Darwin observed that the forms and features of an organism are not completely explainable in terms of their immediate environment. Rather, as one would expect from evolution, organisms' features are often congruent with earlier environments. Thus, a good many features in any organism appear to be suited to an environment that no longer exists (or at least that they no longer inhabit). Furthermore, subpopulations that separate during migration often develop differences in appearance and behavior. The changes that occur allow these organisms to avoid dangers and capitalize on resources in their new environment. In such ways, the geographic distribution of species provides important evidence for evolution by natural selection.

Ring Species

Another way in which geographic distribution provides evidence of evolution is the tendency for species to vary continually along some trait. When the classification of species become arbitrary (that is, when species A can mate with B, and B with C, but not A with C, is B a member of A or of C?), we have found good evidence that the differences we witness within species are simply a close-up of the differences between species produced by evolution. Some of the most compelling pieces of such evidence come from ring species.

A 'ring species' is a geographical ring of closely related populations. At least two of these populations must reside in the same region and be incapable of interbreeding (and are, therefore, technically separate species), while other populations along the ring must be able to interbreed (Ridley, 1996). Famous examples of ring species are the herring and lesser black-backed gulls in northern Europe and the Ensatina salamanders of California.

A ring species can be best imagined in the following way. Consider a species that is geographically distributed in a straight line from east to west across America. It is possible that

the forms in the east and west are so different that they are incapable of interbreeding. Now imagine taking the line and bending it into a circle, such that the end points (formerly in the east and west) come to overlap in space. If it is the case that the two former end points are unable to interbreed, yet other populations along the ring are able, the phenomenon qualifies as a ring species.

Ring species provide important evidence for evolution because they demonstrate the existence of a continuum from intra-specific difference to inter-species variation (Ridley, 2003). Variation between species differs from variation within species only in degree. Skeptics of evolution often argue that although natural pressures might produce intra-species change, the creation of an entirely new species is implausible. In ring species, we see that new species are not synthesized from scratch. Species adapt to their environments little by little, and although undetectable at the level of individual organisms, small intra-species changes are the first step in the process of speciation.

Geographic Isolation

Yet another piece of evidence for the evolution of species comes from natural geographic barriers. Populations are often physically split during migration or when their original habitat becomes divided, as is the case when new land or water barriers form. Geographical isolation often leads to speciation because each population adapts to its own unique environment. Even if these environments are highly similar, the physical separation prevents interbreeding. If a beneficial mutation arises in one population, it will spread throughout that population but not the other.

One example in which geographic isolation illustrates the process of evolution lies in the American finches. When a group of these finches colonized the Hawaiian Islands, the group became geographically isolated from the rest of the species. This one group eventually gave rise to the 23 species of Hawaiian honeycreepers. Another example in which geographic isolation is likely to have led to speciation occurred in the desert of Death Valley, California. The desert has a number of isolated ponds formed by springs; each pond contains a species of fish that lives only in that pond. Scientists suggest that these species arose through geographic isolation. Geological evidence from a study of wave patterns in sedimentary rocks indicates that most of Death Valley was covered by a huge lake during the last ice age. When the ice age ended, the region became dry. Only small, spring-fed ponds remained. Members of a fish species that previously formed a single population in the lake were likely isolated in the different ponds. The environments of the isolated ponds differed enough that natural selection effected the populations differently. Genetic drift may have also played a significant role, since the populations were so small. Eventually the fish in the different ponds diverged so much genetically that they could no longer interbreed even when brought together.

A study conducted on the small island of Daphne Major by biologists Peter and Rosemary Grant (1978) provides further evidence for evolution. They showed that the 13 distinct species of finches observed by Darwin did in fact descended from a common ancestor. However, each species is adapted to a specific environmental niche, as is evident by the fact that each finch eats a different type of food. For example, the cactus finch has a long beak that reaches into the blossoms of cacti, the ground finch has a short beak adapted for eating seeds buried under the soil, and the tree finch has a parrot-shaped beak suited for stripping bark to find insects. Grant and Grant went on to document the effect of a natural drought on the beak and body size of the

next generation of medium ground finches. By measuring and comparing beak sizes in post- and pre- drought generations, the Grants documented natural selection in action. They found that the post-drought generation's beaks were three to four percent larger than their grandparents' – more suitable for consuming the predominantly large-seeded food supply resulting from the drought.

Convergent Evolution

Natural selection is also apparent when similar adaptations are found in unrelated species that occupy similar habitats. This phenomenon is called convergent evolution. Marsupials in Australia and placental mammals in North America provide a good example of this phenomenon. These two subclasses of mammals have evolved similar traits ranging from their feeding habits to loco-motor skills. Despite their diversion from a common ancestor over 100 million years ago, marsupials in Australia and placentals in North America retain a striking similarity. Their resemblance in overall shape, loco-motor skills, and feeding and foraging habits are superimposed upon different modes of reproduction, the feature that accurately reflects their distinct evolutionary relationships.

Another example of the power of natural selection lies in the fish of the Arctic and Antarctic. The immense distance separating these species is so great that in effect it serves as a geographical barrier. As scientists discovered in the 1960s, Antarctic fish have adapted to life in extremely cold water by evolving a kind of antifreeze mechanism. This mechanism is composed of molecules called glycoproteins, which circulate in the blood and surround ice crystals to prevent them from growing. This allows the fish to survive in temperatures that would otherwise cause their body fluids to freeze.

Fish at the other end of Earth, in the Arctic, also have antifreeze proteins. But these two populations of fish diverged long before they developed this complex method of survival. As would be expected by two separate evolutions of these species, the genes that produce the antifreeze proteins are quite different in the two populations. This is evidence that similar environments can produce independent sequences of evolution with very similar end results. There are a finite number of effective solutions to certain environmental challenges, and many of them emerge independently again and again. Convergent evolution is everywhere in nature. The wings of the bat, the bird, and the pterodactyl; the eyes of the squid and the chimpanzee; the fur of the catepillar and of the domestic cat – in each of these cases, these very adaptive and specific structures evolved independently. Other examples are the different species of anteaters found in Australia, Africa, and America. Though not closely related, each species evolved the characteristics necessary to subsist on an ant diet: a long, sticky tongue, few teeth, a rugged stomach, and large salivary glands. In each case, evolutionary adaptations allowed them to exploit a food niche of ants and termites, but the developments occurred independently.

Fossil Evidence

Fossils also provide direct evidence for evolution. Fossilization occurs rarely and only when three conditions are met (Johnson & George, 2004). The first is that the organism must not be scavenged or destroyed. Second, it must be buried in sediment. Finally, the calcium or some other tissue of the creature must mineralize and the sediment around the organism must become hard and turn into rock. Fossilization requires the harder parts of a creature, such as bone, to be deposited in a location where the environment is stable and sediment deposit occurs. Even when these three conditions are met, fossils are often inaccessible or destroyed by erosion or other

natural disasters. Although fossilization rarely occurs to the bones of any given animal, over time enough organisms are fossilized to provide valuable evidence for the evolutionary lineages of species.

When fossils are discovered, they can be dated, thus allowing us to infer the chronological order of fossil lineages. This rarity of fossil evidence explains why there are gaps in the fossil records ranging from 25,000 to millions of years. Fossil evidence of the earliest forms of life is the rarest because these early organisms seldom had hard body structures such as shell, bone, or teeth (Fortey, Richard, 1982). These organisms only exist in such forms as microfossils, the fossilization of ancient burrows, and a few soft-bodied organisms.

Fossils allow us to establish an evolutionary chronology. The fossil evidence is vast in time span: it ranges from eukaryotic organisms 2.65 mya (just prior to the beginning of the Proterozoic), to the evolution of fishes, the radiation of land-living organisms, the reign of the dinosaurs, and to the rise of mammals and current life forms (Johnson & George, 2004).

Thousands of fossils have been discovered across the globe. If an organism dies in a relatively stable environment, sediment is gradually deposited on it layer by layer. By studying each layer, geologists can establish the relative time that the evidence was first deposited at the site. There are three basic principles that allow for this type of dating. The first is the *Principle of Original Horizontality,* which states that strata form in horizontal layers because the forces of gravity are directed towards the center of the earth. If the layers of strata that surround the fossil evidence appear horizontally, it can be inferred that the fossil evidence was not damaged. The second principle is the *Principle of Superposition*, which explains that the first (deepest) layer is the oldest, the next is second oldest and so forth until the final, most recent layer is reached. The third principle is the *Principle of Cross-cutting Relationship,* which states that all types of

structures, such as faults, cut across the layers and therefore are younger than the strata they deform (Holtz, 2000).

A global survey of fossils is crucial in deducing major changes in earth history, such as the movement of continents (Fortey, 1982). Fossils are found on every continent in the world, including Antarctica. Evidence from fossils demonstrates that the Earth was not always the way it appears today, but has undergone immense changes in configuration on more than one occasion. Continental drift occurs when massive bodies of land separate and move apart from one another, and fossil evidence has been one of the most compelling pieces of evidence for this phenomenon. For example, South America and Africa continue to move apart; this can be observed through various measurements. But fossil evidence suggests that they were once completely connected. Fossils of the same species on the two different continents pinpoint the exact location where they used to connect. Faunal, floral, geological, and geophysical information leads to the belief that up until the Triassic period, these continents were a single, immense body of land. Scientists have named this ancient continent 'Pangea' (Fortey, 1982).

An example of evidence for this massive continent is the Carboniferous fossil of the plant *Glossopteris* floras that are extremely similar in India, Southern Africa, Antarctica and South America. The most logical explanation for these findings is that these continents once fit together in the mega-continent of Pangea. When the shapes of the current continents are connected, the discovery sites of fossil *Glossopteris* floras in India, Southern Africa, Antarctica and South America become very geographically close indeed. Thus, fossils can be used not only to establish lineages of species, but also to infer information regarding the history of the Earth.

Carbon dating of fossils and other dating techniques are some of the most reliable ways to place an organism along the continuum of life forms. Many lineages were established with the

help of a dating technique called radioactive fossil dating, which relies on modern chemistry to determine the age of a given fossil. This principle behind this technique is that nuclei decay at random points in time, but that a group of atoms of a radioactive nuclide always decay at a certain rate, called a half-life (Wikipedia users, 2005). A half-life is the unit of time that it takes for half the atoms in a creature or substance (such as bone) to decay.

Fossil evidence for the evolution of the horse lineage is among the most complete. The evolution of the horse can be followed through a series of fossils dating from 55 million years ago to the present. The oldest found fossil ancestor of the horse is about the size of a dog and bears little resemblance to the current horse, but by tracing the lineage through time, gradual changes demonstrate the connection. The next rung in the ladder of horse evolution has been dubbed the "middle horse"; these animals are most recent and roamed the earth approximately 37-32 million years ago. The horse family became more diverse with the Miohippus between 32 and 25 million years ago. All the horses before this date were found in early Miocene locations in both the Great Plains and Florida, dating from 24-17 million years ago. The next milestone in the evolution of horses appears with the Merychippus, mostly found in late Miocene sites across the United States and dating from 17 to 11 million years ago. The closest relative to the modern horse yet discovered is the Dinohippus. The Dinohippus gave rise not only to the modern horse, but also to other animals such as asses and zebras. These fossils can be found in the Upper Miocene of North America and date between 13 and 5 million years ago. Finally, the modern horse is the genus Equus, which was domesticated approximately 3,000 years ago. The current species of wild horses, asses and zebras and can be found on all the continents except for Australia and Antarctica, which is consistent with geographical evidence regarding continental drift (Simpson, George 1954).

The remarkably compete set of fossil records for the horse demonstrates fossils' unique contribution to the deduction of evolutionary relationships. Although relatively rare, thousands of incredibly well preserved fossils have been discovered around the globe. These treasures are incredible evidence of the life that existed before humankind – evidence for the evolution of organisms.

Homologies

Homologous structures represent yet another piece of compelling evidence for evolution. Homologous structures are anatomical structures present in two species that are similar to each other in form and/or function. It is an arresting fact that all species have structures that are, to varying degrees, homologous with other species. The paws of a dog and a wolf, for example, are akin in both form (in the way they are shaped) and function (because both animals use their paws to walk). However, homologous structures are not always so obvious. Many homologies, such as the pentadactyl forearm bone structure, require a deeper understanding of physiology in order to be recognized as such.

Important evidence for evolution lies in the engineering of these homologous structures. Each structure in the body serves a function (or at least used to in the ancestral past) and most likely has a design suited for that purpose. Eyes can be found in many species; they are designed to take in light rays and transform them into an image useful for navigating the world. Despite separate paths of evolution, all eyes have a hole (a pupil) allowing for light to pass to the retina. There are, however, structures within certain species that seem to serve no particular function at all. Examples are the human appendix or the hind legs of certain species of snakes. It is an anomaly that these structures exist at all if they serve no purpose. Furthermore, in almost any

given species there is a body part for which humans could have found a more practical design. By taking a closer look at one of these structures, the anomaly might be made more salient for discussion.

The whale fin has been engineered to provide stability for the animal in the ocean. Its structure is aqua dynamic, strong, and would seem to be perfectly engineered to suit its purpose. The bones, however, tell a different story. Bones in general provide an organism with not only stability but flexibility. The fin of a whale is made up of five sets of bones, attached to a stocky set of increasingly larger bones. Some are so tightly packed that they are basically immovable; this obviously limits the whale's mobility. A more efficient design would be one like the shark's, which consists of a continuous piece of cartilage with a strong joint for mobility located at the base of the limb.

Vestigial characters lead to the obvious question of why animals have been designed in such suboptimal ways. Why does a whale have so many extraneous, unnecessary bones? The answer lies the fact that new species are not created from scratch. They evolve by natural selection, which works with the materials it has.

In the case of the whale, scientists have traced this peculiar fin bone structure to that of ancient tetrapods, vertebrates with four legs. It has been found that the whale's basic pentadactyl (five-digit) forearm bone structure is analogous to that of both the bat and the human (Ridley, 2003). The five phalanges (fingers) in a human look incredibly similar to the bones that make up the bat wing, which also look similar to the structure of the whale fin. Even the wrist structures bear an amazing resemblance to one another. This would be an amazing (indeed, unbelievable) coincidence if such striking resemblances had arisen by chance. Moreover, such similarities in design make little sense from an engineering point of view; the whale's fin would certainly be

more efficient if it was not constrained by the same set of bone structures that make up a hand or a wing. Only one reasonable explanation exists for this set of data – natural selection. Each of these species descended from a common ancestor with a primitive version of the pentadactyl bone structure. This bone structure then evolved (whether into fin, hand or wing) into the most adaptive structure possible given the circumstances.

At the time of common ancestry all the pentadactyl individuals looked basically the same. However, the habitat of the pentadactyls did not have the means to support every organism within its bounds. This environmental pressure created an elevated differentiation of reproductive success among the organisms inhabiting it. The individuals best suited for the environment survived to reproduction, and reproduced the most. Other individuals evolved methods of exploiting new, untapped niches. The exploitation of new habitats is one of the fundamental reasons for the divergence of the tetrapods.

At common ancestry, certain individuals developed incredibly primitive versions of wings and fins out of their forearms. This change can be explained through mutation, whereby the first proto-bat may have had something as simple as a bit of webbing between its fingers. Modern humans are sometimes born with webbed hands or feet today, although this does not confer any selective advantage. However, to the archaic tetrapod that had this webbing, this characteristic may have been the difference between life and death. An individual who could achieve even a slight amount of lift could exploit resources or avoid predation when others could not. The individual whose forearm began to resemble a paddle would have been better able to exploit the aqueous environment. In the case of primate ancestry, the evolution of hands occurred because of benefits to climbing and moving efficiently in the trees.

In order to better understand this concept, it might be helpful to walk through, roughly, how the whale fin evolved. The tetrapods that eventually became the whale probably had slightly elongated second and third digits, which would have created a rudimentary paddle at the end of the hand. As the species continued to evolve for an underwater habitat, the forearm would have shortened, thus creating a more aqua dynamic design. None of the bones would have necessarily disappeared because evolution can only work with what it has. In addition, individuals with these changes must have had a reproductive advantage. A tetrapod at common ancestry whose four limbs were all paddles would most likely not incur the fitness advantage expected. This individual would likely have been very awkward on land, thus becoming easy prey for a predator. Furthermore, the individual would be out of luck during mating season because all of its potential mates were land-bound.

Vestigial characteristics are thus explainable in this manner. Parts of organisms that served a function in the ancestral past lost their purpose when these organisms began to exploit different niches. As is with the tetrapods, the slow metamorphosis of the whale fin was the result of a great many small structural changes, each of which were better suited to the new niche than the last iteration.

Homologous structures allow scientists to deduce the evolutionary relationships among species past and present. DNA evidence corroborates these findings. DNA is the blueprint on which all living things are built, and it is the frontier of knowledge about organisms on earth. Specific proteins are coded for by DNA nucleotides; the order of these nucleotides makes up the "genetic code." By looking at the genetic sequence of different species, scientists have been able to map organisms onto a "tree of genes" that bears a very close resemblance to the "tree of life." Humans and chimpanzees share approximately 99 percent of their genetic code. The chimpanzee

is also closely related to us on the "tree of life," which was estimated long before DNA was even discovered. One can go further and see that human DNA and lion DNA is more similar than that of the human and bullfrog, but more dissimilar than that of human and lemur. Because DNA is the blueprint of life, it is safe to say that the DNA itself is what has changed over the course of time, and that the changes in the genotype that incur higher reproductive success (like the development of a fin) will be seen in future generations. As these genetic changes add up, so do the phenotypic changes that are expressed by the genes. The DNA blueprints of the tetrapods can show us the similarity between the human, bat and whale, and also explain the similarity found in their bones. This proves that homologies are neither coincidence nor mistake. Rather, they are explicable in terms of evolution from a single common ancestor.

Artificial Selection

Artificial selection demonstrates the evolutionary process first-hand. In a process similar to that of natural selection, artificial selection allows desirable traits to be passed to future generations. The primary distinction between these two processes is the *agent* of selection. While environmental pressures are the force behind natural selection, artificial selection is driven by human preference. The end products can be seen today in our pets, our crops and our medical treatments.

An example of a species that has undergone radical changes through artificial selection is the domesticated dog (*canis familiaris).* This particular species has experienced extreme genetic changes and has a wide variety of phenotypes. Dogs have coevolved with humans over a long period of time; some speculate our relationship began with the introduction of agriculture. In the starting phases of this process, gray wolves – the common ancestor of all domesticated dogs –

were used for various tasks such as hunting or warding off predators. Because wild wolves are not necessarily the most docile and helpful of pets, humans bred the wolves in a way that boosted the frequencies of these traits in the next generation. The friendly disposition of domesticated dogs compared to their ancestors is a prime example of the vast genetic changes that occurred. As time progressed, technology gradually improved and the uses for dogs became more refined and specific. Humans selected and bred animals with traits suited to the tasks they wanted these animals to perform – from retrieving game, to herding sheep, to winning first place for their master in a dog show. This selection accounts for the over four hundred breeds of domesticated dogs in existence today, each with phenotype suited to its unique "purpose".

Through the process of artificial selection, dogs have evolved less aggressive tendencies, smaller size and more benign teeth. However, despite their drastically different phenotypes, domesticated dogs share the original genetic structure of the gray wolf. Like natural selection, artificial selection can only work with existing variability. In this light, the pittbull is really just the extreme of some continuum (or, more likely, multiple continua) on which the gray wolf varies. At the core, a breed as seemingly different as the Chihuahua shares many common traits with its wild wolf relative. For example, if given the opportunity, most domesticated dogs have retained the tendency to live in pack societies – a habit that humans didn't care to select, either for or against. One look at an organism that has not undergone artificial selection (e.g., the gray wolf), compared to one that has reveals the vast changes that can occur in a species. A closer look at the specific properties that have undergone change shows that it is the most desirable traits (defined either by humans or by pressures in the environment) that are passed to the next generation in the highest proportions.

Dogs are just one of many species affected by artificial selection. Numerous species in agriculture are the result of rigorous artificial selection as well. Since humans subsist on livestock and crops it seems natural that ways to enhance their growth would be sought. Artificial selection has proven to be a useful method of accomplishing this goal. Many farm animals, for example, are bred in a manner that maximizes their meat output. Chickens are bred to reach a specific size in a relatively short amount of time. Pigs, originally domesticated from boars, have changed dramatically over the years. Compared to their wild relatives, pigs tend to be leaner, bigger and less aggressive. With cows it is common to select for altered rates of maturation, such that they begin mating earlier or produce milk for longer periods of time. As these examples show, artificial selection has caused much phenotypic change in domesticated animals. Their genetic structure has been altered in order to suit humankind's needs and desires – or at least maximize the profit of farmers.

The extent of the changes brought by artificial selection transcends physical appearance alone. The majority of agricultural products are now completely dependent upon humans. Corn, for example, comes from a wild grass found in Mexico called *teosinte*. Through the selection practices of Native Americans and various colonizers, *teosinte* evolved into the plant we know today. Yet, unlike its ancestors, modern corn cannot survive in the wild. The genetic makeup of these crops has been altered so that traits for higher food output have eventually replaced those for survival.

Man-made selective pressures also exist in the biomedical field. Advancements in technology have allowed for more refined methods of selection, many of which work on a microscopic level. One such technique is directed molecular evolution. In this method, molecules pass through a series of filters, and only those that produce the desired reaction are allowed to

replicate. These replicated molecules then have the potential to aid in the development of various drugs. Just like in the domestication of dogs, traits that are found useful to humans are cultivated. Thus, changes in the genetic structure of molecules occur – in this case, for the benefit of humans.

However, artificial selection does not always result in desirable outcomes. For example, humans have unwittingly caused an increase in the world's population of bacteria and viruses. Advances in medicine have allowed humans to fight against various microorganisms, but through the selection process they have fought back. Pathogens have extraordinarily high rates of mutation, which gives artificial selection a wide variety of traits to choose from. Chances are good that eventually, one of these mutations will enable the pathogen to break through the defenses humans have devised. The process of artificial selection is incessant. Advancements in medical science have been successful at combating microorganisms – but at the same time they have created more powerful illnesses. Each mutation brings a change in the genetic structure of the bacteria and viruses. Those that overcome human defenses are able to replicate and pass on their immunity, until humans find some means of neutralizing them again. Once this happens, selection becomes fierce again and even more virulent strands are selected for. Because the end results are undesirable, processes such as this are referred to as negative. Nevertheless, the pathogen-host relationship is perfect illustration of the evolutionary process. The example demonstrates that even when change is ultimately the result of human behavior, evolution is indifferent to human intent. Traits that successfully produce the most copies of themselves are the ones that will be found in future generations. Selection (both natural and artificial) adheres to no rule other than this.

As the previous examples show, artificial selection has a profound effect on a variety of species. This process serves as an appropriate model for understanding natural selection, since the underlying concept is the same – traits that (for whatever reason) have an advantage in reproducing copies of themselves are the ones that will appear in future generations.

Laboratory Evidence

A common (albeit naïve) counter-argument to the theory of evolution by natural selection is that we do not see it happen. The laboratory serves as a unique source of evidence for evolution because it allows precisely this. Many people are unaware of the immense amount of research on the evolution and adaptation of organisms that has been generated in the lab. This is unsurprising because the organisms used for these experiments are not generally found in popular science venues. In general, the types of species used in laboratory studies of evolution are those that have short generation lengths – algae, bacteria, fruit flies, and so forth. The reason for this is that species with long life spans reproduce too slowly for scientists to witness change. Millions of bacteria can fit on one petri dish and have generation lengths in the order of minutes. This allows researchers to see how small changes in a population can accumulate over time while avoiding waiting years for an animal such as a shark to reproduce (not to mention the cost of feeding and housing a million sharks!).

Experiments present compelling evidence for evolution because they can manipulate populations and produce genetic change over an observable time span. We have already seen evidence of artificial, human-directed selection, where breeders choose the traits they desire in an organism and breed for those traits. However, artificial selection usually involves animals with long generational lengths. Thus, evolutionary change in these cases cannot be directly

observed. Here we shall provide examples of evolution produced in the laboratory. Furthermore, these experiments are parallel to evolution by *natural* selection. Instead of selectively breeding for a certain characteristic, experimenters place a population of organisms in a specifically designed environment and observe genetic change over time. This design closely simulates evolution as it occurs in the natural environment.

One experiment involving this technique involves unicellular green algae. The algae *Chlamydomonas reinhardtii* is capable of growing in two different environments. When light shines on algae, it can convert that energy into food, but when algae is in a dark environment it depends on other food sources. Bell and Rebound (1997) bred a population of genetically identical algae and then exposed it to one of three environments for a year. One population lived in a constantly light environment, one in a constantly dark environment, and one switched from light to dark at each growth cycle. By the end of the year, each population had gone through hundreds of generations. Both of the light and dark lineages increased their ability to convert either sunlight or food into energy, at the cost of their ability to grow in the opposite environment. That is, algae grown in the light environment became better at processing light and worse at processing food, and vice versa. The population grown in the alternating environment retained the ability to grow well in both situations. The type of environment in which the algae was placed determined the adaptiveness of certain traits, which caused these traits to change.

Similar experiments have been performed on the common fruit fly, *Drosophila melanogaster*. A common design is as follows: genetically identical populations of fruit flies are placed in different environments in order to observe changes resulting from the selective pressures of those environments. Prasad and Joshi (2003) and Houle and Rowe (2003) have written comprehensive review articles on the vast amount of selection research on *Drosophila*,

but for purposes of brevity we will discuss only one example. Kennington and et. al (2003) looked at the effects of humidity on body size in fruit flies. In place of lungs, insects have a tiny pipe system that circulates air from the environment through holes in their exoskeleton. This system is prone to water loss, much like our skin in dry environments. One strategy to prevent excessive water loss is to increase body size because then surface area is decreased relative to volume.

Kennington (2003) created a four-condition experiment in which both humidity (high or low) and temperature (high or low) were varied. After 20 weeks of isolation, researchers found that the flies in low humidity environments were significantly larger than the flies in high humidity environments. Temperature had no effect on body size. As predicted, larger body size was selected for in environments causing greater water loss. Bigger flies had a consistently better chance of surviving and reproducing bigger offspring.

The evolution of fruit flies and green algae each show that organisms change according to the type of environment in which they are placed. But can these little changes amount to the evolution of new species? It is often argued that these examples of "micro-evolution" differ fundamentally from "macro-evolution"— that these small changes produced by natural selection cannot result in the creation of new species.

Two populations of organisms are considered different species if they are reproductively isolated, or incapable of interbreeding. If interbreeding is possible, these two organisms are still considered separate species unless their offspring are reproductively viable – that is, able to produce offspring themselves. 'Ligers' exist (a cross between a lion and a tiger), but they are unable to produce offspring; thus, lions and tigers are separate species. Plants, on the other hand,

have a unique characteristic that allows some hybrids to interbreed: they can double their

chromosomes. Primroses (*Primula kewensis*) were the first species to be created in this way.

Researchers crossed pollen from two plants containing 18 chromosomes, *Primula*

verticillata and P. floribunda, and thus generated the first primrose, which has 36 chromosomes.

Primroses are reproductively isolated from both parent species. Although this method more

closely resembles artificial selection, the doubling of chromosomes is a naturalistic form of

speciation for plants. About 70-80% of all flowering plant species in the wild arose through

doubling their chromosomes from parent species (Ridely, 2003). Clearly, laboratory evidence

illustrates natural selection's ability to induce inter-specific, as well as intra-specific, change.

Cosmological and Geographical Evidence

Skeptics might point out that human beings are much slower at reproducing than algae,

fruit flies, or flowers. How does natural selection produce changes in species more similar to our

own? The answer is: "time". Even moderate genetic changes can take thousands of generations

to occur. In humans, this translates to tens of thousands of years. In order for the theory of

evolution to hold up, it must be shown that the earth is old enough for a single-celled organism to

have evolved into the great variety of complex life forms present today.

Archbishop James Uusher estimated the earth's age by literally interpreting the bible and

declared the origin of the earth to be around 4000 B.C. (Lewis & Knell 2001**,** Wikipedia).

Needless to say, this estimate did not allow sufficient time for evolutionary theory. As early as

the 1800's, people began looking for more scientific methods of determining the earth's age.

Indeed, when Darwin's theory of evolution made its breakthrough and the biological evidence

supporting it became more apparent, scientists were pressed to find an age for the earth that was

compatible with this theory. The last two centuries have seen many brilliant minds develop new methods of calculating the earth's age, which is now generally accepted to be at least 4.54 billion years old (Darymple, 1991). The majority of evidence for this figure comes from the dating of radioactive elements found in rocks gathered from the earth, moon, and various meteorites.

Radiometric dating was developed in the early 1900's, shortly after the discovery of radioactive isotopes (Darymple, 1991). These isotopes are atoms that have different masses but belong to the same element due to same number of protons in the nucleus. The differences in mass come from the variable number neutrons that are also in the nucleus. Most isotopes are unstable because their ratio of protons to neutrons produce too high of an energy state. They adjust for this by ejecting or capturing a particle which releases some of that energy in the form of an emitted radioactive ray. But in the process of removing the nucleic particles, the isotope changes its mass and becomes another isotope. Often times the new isotope is a different element because protons are commonly ejected along with the neutrons, and an element is distinguished by the number of protons in its nucleus. The process then repeats; an isotope can go through a series of transmutations before reaching a stable energy state.

Radioactive decay occurs at different rates in different elements. This decay is meaused in half-lives – the number of years for half the atoms in a sample of an isotope to decay. The rate of decay is highly variable, ranging from a few thousand to even a few billion years. Scientists are able to use slow-decaying elements to date rocks, fossils, and artifacts. Depending on the time scale for each of these artifacts, some elements are more appropriate for dating than others. Archaeologists, for instance, have long been dating human artifacts with the carbon 14 isotope, which has a half-life of 5,370 years (Eicher, 1968). For measuring the oldest rocks, uranium 238 is most suitable because of its 4.47 billion year half-life (Darymple, 1991). Scientists have now

calculated the half-lives of every known element within accuracy of around 2% -- in the case of

uranium, accuracy is within 1 % (Darymple 1991). As new technology has become available

over the years, radiometric dating has greatly improved. It is now considered the most accurate

method of estimating the earth's age.

In order to determine the earth's age, scientists have gathered the oldest rocks available

and measured the chemical composition inside. In particular, they measured the ratio of uranium

238 isotopes to lead atoms, the stabilized product of uranium. Using the half-life of uranium,

they then traced the progress of the uranium decay by comparing its present composition to that

of its formation from magma (in which no natural lead should have been present).

How can scientists be sure the rates of decay have remained constant since the beginning

of the earth? To check this, they subjected the compositions to extreme conditions of

temperature, chemical composition, and electromagnetic fields. None of these methods affected

the decay rate in any way. This makes sense when one considers that the energy required to keep

quantum particles in the nucleus together is much higher than the energy to bind its larger

components, such as electrons to their atom (Darymple, 1991). There is then little evidence to

suggest that the earth has been subject to any such force sufficient enough to change the decay

rates of elements in the past, much less in the last 6,000 years. Surely such an event would have

left some sign of its occurrence. It is therefore more than reasonable to assume that the physics

on which radiometric dating relies upon has remained reliably constant.

Uranium occurs naturally in some of the oldest rocks we know of, such as the zircon

crystals in Australia. The initial expected composition is simply derived from the total number of

daughter and parent atoms present. This assumption works if the rock being dated is known to

reject lead atoms during its formation. This resets the geological clock as future lead atoms will

remain trapped in the rock after crystallization. However, because of the possibility of lead

contamination with certain types of rocks, isochron dating is often used as well. This method

relies on the presence of a lead isotope that cannot be formed from radioactive decay. By

measuring the ratio of uranium to that isotope and the ratio of the lead product to that isotope,

one compares the uranium-lead concentration to another source so the initial amount of lead does

not need to be calculated. However, the exact age of the earth cannot be directly determined,

since the crust of the earth has continually recycled itself. Therefore we do not know if we truly

have the oldest rocks, as it is quite possible the older ones have been destroyed and remade at a

later time. The oldest rocks set the minimum age of the earth at 4.2 billion years (United States

Geological Survey).

Evidence of an ancient earth is found from other sources besides the earth's crust.

Astronauts over the last half-century have brought back a number of different rocks specimens

from the moon. The moon is a planetary body that does not share the degree of continual tectonic

activity that the earth has and thus can be considered somewhat reliable. The chances of finding

the oldest rocks on the moon are better than the chances of finding them on earth because the

moon's crust does not continually recycle itself as the earth's does. The oldest of these moon

rocks have been measured estimated to be between 4.4 billion and 4.5 billion years old,

depending on the method used. If the earth and moon were formed at the same time, it would

then be reasonable to conclude that the earth is older than the available rock evidence indicates.

Meteorites found around the world provide another source of consistent radiometric data.

We can compare the ages of meteorites with that of the earth when considering the hypothesis

that the planets in the solar system structured themselves relatively soon after the originating

nebula collapsed on itself. Using five independent radiometric dating methods, these meteorites

have measure to be around 4.4-4.6 billion years, and thus concide with estimated of the earth's

age (USGS, Darymple 1991). The data remains consistent even in the dating of rocks found

beyond our atmosphere (Darymple 1991).

Conclusion

Evidence for the scientific theory of evolution is overwhelming. The study of

biogeography shows that groups separated by geographical barriers are consistently more

dissimilar than those that are not, and the differences groups develop are predictable by

environmental pressures. Paleontology provides evidence of strange prehistoric species, and the

constancy of radioactive decay allows for accurate dating of fossils. The study of morphology

and the existence of homologous structures allow the deduction of evolutionary relationships

among species both past and present, and recent developments in genetics corroborate these

theories of species interrelatedness. Finally, artificial selection allows us to witness the birth of

new species in the lab. Estimates of the earth's age no longer constrain evolutionary theory; to

the contrary, current estimates provide support for the theory. Any one of these pieces of

evidence would provide ample support for the theory of evolution. Combine them, and the

conclusion is almost undeniable.

All species living today evolved from a common ancestor by natural selection over the

course of about 3.5 billion years; this is of general consensus in the scientific community. Some

fear that this view leaves no room for religious belief. However, numerous highly religious

individuals, including Pope John Paul II, see no conflict between evolution and their faith. Open-

minded believers see that modern Darwinism negates only a very small part of a literal

interpretation of the Bible. Those with not only a devotion to God but an allegiance to the truth

should not be discouraged by such a detail. So far, all of the evidence points to evolution, and

none of it conflicts with a belief in a higher meaning to life.

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