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The Other Half of Evolution

For over 150 years, since Darwin coined 'Natural Selection' and laid out the evolutionary process, scientists and non-scientists alike have debated, studied, and learned about evolution by natural selection. Today it is in many high school biology textbooks – that random mutation generates a new trait acted upon by the environment, that this random trait is either selected for or against, and is either passed on or not. It is implied that any beneficial trait could occur.

But what if there were more to the evolutionary story? What if there were an entire part of the evolutionary process we have been forgetting? What if the trait possibilities were not as endless as we have been made to believe? What if there were constraints to how for evolution could go? These questions are what Dr. Emily Buchholtz, a professor of biology at Wellesley College in Massachusetts, has been asking in her research for years.

During an hour long interview with Prof. Buchholtz, we were able to speak about her research, and about how much you can learn about evolution by focusing on particular traits while not forgetting about the bigger picture. Prof. Buchholtz's research is on the evolution of the mammalian vertebral column. While there are obvious differences between the vertebral column of different mammals, such as giraffes having long necks while corgis don't, and spider monkeys having long tails while apes don't, the similarities are just as obvious to an anatomist. For example, though a giraffe's neck can be up to six feet long, and a corgi's head seems to be practically sitting on its shoulders, both of these animals, as well as essentially all mammals, have *exactly* seven cervical (neck) vertebrae. Though evolution was able to give giraffes a long neck and corgis a short one, the number of cervical vertebrae did not change.

If the number of cervical vertebrae is so highly conserved, we must ask why. In order to answer that question, Prof. Buchholtz had to seek out the mammals that, as she says, "break the rules on how to be a mammal," that "diverse animals that are not built like a normal animal have stories to tell us if we spend the time." One such animal is the three-toed tree sloth. Unlike virtually all other mammals which have seven cervical vertebrae, these sloths truly have a long neck with anywhere from eight to ten cervical vertebrae. We see with the three-toed tree sloth that through evolution a mammal can have other than seven cervical vertebrae, but we also see the price the sloths pay to have the trait.

The extra cervical vertebrae of the sloths lead to irregularities all the way down the vertebral column. Prof. Buchholtz and her co-researcher on this study, Courtney Stepien, found that some of the vertebrae possessed "miniature riblets," tiny ribs poking out from vertebrae, which have no apparent use. Also, the pelvis of these sloths has unusual and irregular fusions. The price the sloths had to pay for the extra cervical vertebrae was irregularities all the way down the vertebral column, a price an animal like a sloth perhaps is better able to pay relative to other mammals because of its unusual slow and arboreal life.

Just looking at sloth bones however is squarely in the territory of the organismal subfield of biology, looking at what an organism looks like. There is more to the evolution story however if you also look at the molecular side, to see what genes, what proteins, what tiny molecules are responsible for the huge deviation from the mammalian norm observed in the sloth's vertebral column. Unfortunately for much of biology, Prof. Buchholtz told me, "you can drive a truck between the organismal people and the molecular people," as she moved her hands straight across her desk, dividing it in half for me to imagine molecular biologists on one side, organismal biologists on the other. “I actually see myself as uniquely…positioned between geology, biology, developmental biology, and that I can make these into a whole – that very few people actually have all these parts that they can fit in,” she said. Though Prof. Buchholtz’s specialty lies more in the realm of anatomy, she has been making the connections, what she called the *interplay* of anatomy and molecular biology.

The molecular processes which underlie the development of the vertebral column and limbs are quite complex, Prof. Buchholtz explained, but has been well worked out in the usual model organism for mammalian development: the mouse. Unlike sloths, mice don’t break any of the “rules on how to be a mammal,” so by studying the development of their vertebral column, you can see how things are supposed to play out molecularly. Bones as well as muscles come from a tissue type present very early in development after fertilization called *mesoderm*, basically the tissue in the middle between the ectoderm which forms the exterior of the animal, like skin, and the endoderm which forms the ‘inside,’ the digestive system.

The bone and muscle forming mesoderm early in development comes in different flavors – lateral plate mesoderm and somites, which form different internal structures, for the most part. There are important structures however which are formed by both, and thus there has to be communication between the two mesoderm types to make sure everything is formed correctly. It has been found that a series of genes called *Hox* genes are what organize the mesoderm types to properly form the different structures. For example, if a mix of say three different *Hox* genes is expressed, a cervical vertebra will be formed, while adding a fourth would cause that vertebra to form a rib, or a lumbar vertebra of the low back.

It is within the complex communication between mesoderm types and different genes that Prof. Buchholtz has been identifying the constraints to evolution. At the very bottom of the evolutionary process is the random gene mutation. The thing is, many genes, such as the *Hox* genes that regulate what type of vertebrae goes where, play different roles depending on what other genes are on and off as well. These same genes responsible for the vertebrae also are responsible for other structures like the diaphragm. A mutation of the gene which could allow for changes (evolution if they were beneficial and passed on and on) in the vertebral column, could also affect the normal development of another structure, like the diaphragm. An animal with an abnormal diaphragm would likely have difficulty breathing, and never survive to pass on what might have otherwise been a beneficial trait.

“Natural selection, we’ve been talking about half of it for the last 150 years, and the other half is what variants get generated, and it is not random,” Prof. Buchholtz said, explaining the consequences of these developmental constraints on evolution. While most have been focusing on the potential evolution can offer a species, Prof. Buchholtz says, “what doesn’t get asked is what is the suite of traits that gets generated, and that’s a huge part of natural selection because not all traits can be generated…Some traits cannot be generated.”

What Prof. Buchholtz has found, is that by virtue of the complexity inherent in molecular development, most traits could never be formed in a viable animal for natural selection to ever work on them, for evolution to ever take place. It is only in the exceptional animals, like the three-toed tree sloth that unusual traits have managed to evolve, despite what we might call the other half of evolution, the development of a new trait that doesn’t kill the organism within the first minutes, hours, or days of life.

As Prof. Buchholtz’s published paper on three-toed tree sloths ends with a call for more research to explain why the sloth was able to survive the evolution of a larger cervical vertebrae count, she is continuing her investigations, saying that she never runs out of ideas for her research topics. “Time,” she said, without any hesitation, is the biggest challenge to her research when I asked. Her research since that on sloths has all been related to the developmental constraints on evolution as she seeks out other animals that break the mold, to try and figure out how and why they did it. Her next subject is the giant ground sloths, extinct now, but whose bones might hold the clues to how they, and other mammals, evolved, not just in terms of natural selection, but the other half too.

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About the Author: Adele Clifford is a biology major at Wellesley College who has had a long interest in bones and the way these structures allow us to move and live.

This article is about an interview with Prof. Emily Buchholtz, focusing on her work with three-toed tree sloths to discuss how the molecular mechanisms of developmental biology constrain evolution.