

How can evolution account for the complexity of life on earth today?



A complex biological structure with many interacting parts might appear, at first glance, as if it were originally created in its present form with all its interlocking components fully formed and intact. It doesn't seem possible that they developed step by step via biological evolution. In *Darwin's Black Box*, Michael Behe introduces a term that he and other proponents of Intelligent Design use for this concept: irreducible complexity. No part of an irreducibly complex system has any apparent function except in its relation to the other parts.

Behe suggests that the parts of irreducibly complex biological structures would be useless unless they appear all together, and evolution has no mechanism to build complex structures like this. Natural selection, after all, works just one step at a time. Furthermore, natural selection has no foresight. Put simply, if a change is going to be preserved, that change will generally need to confer some extra benefit—no matter how small—to the next generation. Behe has oversimplified things a little. Evolutionary theory predicts that in small populations, neutral changes—and even changes that are slightly deleterious—will survive sometimes. Still, in general, he is correct. So let's examine what evolutionary biologists believe about how complex structures are built.

A Seemingly “Irreducibly Complex” System

As Scott Gilbert shows in his textbook *Developmental Biology, Eighth Edition*, the evolution of the interconnecting bones of the middle ear illustrates how supposedly irreducibly complex structures can in fact be generated by the stepwise process of gradual change and natural selection. Fish, for example, have a special system called the lateral line system that extends along the length of their bodies and enables them to detect vibrations in the water. They also have an inner ear, which is useful for balance and supplements the lateral line system in detecting vibrations. With the movement of certain water-dwelling species to land, the lateral line system became obsolete because what was needed was a way of amplifying the vibrations in air, not water. A bone that had previously been used as a support for the skull became the stapes. Along with supporting the skull, the stapes also transmitted sound vibrations—which come in part through the skull and jaw—to the inner ear. How do we know it's the same bone? By examining its embryological origin in fish and reptiles. In reptiles, there is just one bone that transmits air vibrations to the inner ear: the stapes.

We can also trace the origin of the two other middle ear bones, the incus and malleus, by looking at fossils from the time of the origin of mammals about 230 million years ago. Until that point, two bones—the articular and quadrate bones—served as the hinge of the jaw. Investigators, however, believe they carried out a second function. Because they were located adjacent to the stapes, it is likely they also aided in transmitting sound vibrations to the stapes.

Here is where the story gets especially interesting. Right at the time of the origin of mammals it turns out there were several species—perhaps many, paleontologists are sure they don't have all of the transitional species preserved in the fossil record—that had a double hinge at the jaw. Not only did the articular/quadrate bones serve as a hinge, but another pair of bones, the dental/squamosal bones, served that purpose as well. So the articular/quadrate bones, which transmitted sound, no longer had to also serve as a jaw-hinge. This second function became redundant because there was another set of bones doing the same thing.

With that redundancy, the articular/quadrate bones of the jaw were free to become the incus/malleus of the middle ear. We have a record of the transition, and we have a record of the building of a so-called irreducibly complex structure. Parts that were initially used for one function became, for a period of time, useful for two functions. Then, one function was refined while the other function became redundant or unnecessary. In other words, parts that were initially used for one purpose become co-opted for another purpose; and looking back through the fossil record, we can see the intermediates.

The Bacterial Flagellum

In *Darwin's Black Box*, Behe focuses on three things he considers to be irreducibly complex: the bacterial flagellum, the blood clotting cascade and the immune system. The elements of these systems are molecular in nature and therefore the evolutionary intermediates are somewhat harder to document. Interacting molecules are not preserved for historical analysis like fossil bones of the skull and middle ear. In his book, Behe suggests that biochemistry gives no clue as to how complex interacting parts like these might have come about, and he confidently states that investigations have run up against a blank wall.

It has now been 13 years since *Darwin's Black Box* was written. The structures and processes Behe chose to focus on have been studied quite extensively. Although it is impossible to go back and analyze step by step what actually did happen, much evidence for straightforward evolutionary explanations has accumulated over the years. The diversity in a given structure that we see when we compare different species tells us a great deal about how that structure might have come about.

Consider the bacterial flagellum, the example most commonly used to illustrate the principle of irreducible complexity. First, it is important to point out that the bacterial flagellum comes in many different varieties, sometimes with profound differences between one species and another. This alone illustrates that the flagellum is probably not irreducibly complex. It can be altered, and when it is altered, it does not necessarily lose its function.

There are many species of bacteria, for example, that use the basal parts of the flagellum to deliver toxins into their host. A different set of bacterial species uses a portion of the flagellar machinery for another purpose. Species of the genus *Buchnera* live inside the sheltered environment of aphid cells in a symbiotic relationship. These bacteria no longer need flagella. However, each tiny *Buchnera* cell is studded with hundreds of copies of the flagellar base. As a [recent paper](#) in the journal *Trends in Microbiology* shows, the purpose now is to serve as a passageway for the export of proteins and other material into the surrounding environment—the aphid cell in which the bacterium resides. So while we cannot follow the sequence of events step by step to illustrate how the various types of flagella have arisen, we can see how they have changed and, in some cases, even taken on whole new functions. The term for adapting a structure for a different purpose than that for which it originally arose is “exaptation.” This is one important way in which complexity arises.

That is not the whole story, however, because individual parts have to be added into the structure as it becomes more complex or takes on new function. Where do those parts come from? Recently, investigators have [shown](#) that the key protein in the molecular motor that causes the flagellum to rotate has a very similar structure to another protein that is used to transport magnesium into and

out of cells. Both protein molecules have sections that fold in almost exactly the same manner, and when we analyze the order of their building blocks (amino acids), we see profound similarities. This illustrates a second principle in building complexity: It is done by co-option. Parts that are used for one purpose are co-opted to take on a second function as well. Sometimes, the instructions to build a part are encoded by identical duplicate genes. When that happens, co-option is especially straightforward. One set of instructions for making the original part is preserved while the duplicate set of instructions can gradually be modified through mutation and natural selection, allowing the part to become better and better at carrying out its new function. This illustrates a third principle of assembling complexity: adaptation through natural selection.

Even more revealingly, the supposedly irreducibly complex bacterial flagellum turns out not to be irreducible after all. For example, there is a protein at the base of the flagellum, an ATPase, that drives the key structural subunit (flagellin) of the long hollow tube through its inner core, causing the flagellum to grow in length. Yet, it has been shown that flagellin can be transported to the end of a flagellum without this ATPase. The protein that was thought to be one of the flagellum's most important parts can be done away with. This illustrates a fourth principle of building a complex structure: redundancy. Inside of cells, there is often more than one way to accomplish a particular purpose; as evolution "tinkers" with a complex structure, there is likely to be redundancy with certain parts at certain stages. One of these redundant mechanisms may become more specialized, and even perfected, as time goes by.

The Eye

Another system that is often held up as an example of irreducible complexity is the eye. People often ask: What good is a partly assembled eye? Is there any logical series of steps that could result in the creation—through the process of natural selection—of a structure so elegant as the eye of an eagle? What would be the starting point, anyway?

All light-sensing devices in the animal world make use of a single light-sensitive molecule, retinal, which is derived from Vitamin A. Retinal can change its shape when it absorbs a photon of light. This molecule is always complexed with a protein known as an opsin. The two work together to sense light.

By analyzing the arrangement of the building blocks, or amino acids, in opsin, it is possible to show that all opsins are derived from a single ancestral gene. What purpose could the retinal/opsin combination have had in the earliest days of animal history? It likely functioned to detect light in order to set the internal body clock that regulates the 24-hour cycle of biological processes, known as the Circadian rhythm. In recent years, it has become apparent that living processes inside of

cells are tuned to function in a manner that is synchronized with the cycle of sunlight.

Circadian rhythms function throughout the living world, including single-cell organisms. It seems likely, then, that the simplest light-detecting device arose through exaptation of a molecular device that was used to detect light—not so that an organism might move toward or away from the light, but so it could reset its molecular clock. Even the origin of opsin illustrates a basic principle of building complexity, co-option. Opsin is one of many G-protein receptors, which have come to take on many different functions through the history of life. When coupled with the light-sensitive molecule retinal, a G-protein receptor allows the cell to be sensitized to the presence and absence of light. Although we have no fossilized transitions that allow us to trace the various eye intermediates that have occurred in animal history, as we do with the middle ear, we do have a myriad of light-sensing devices in the animal kingdom that allow us to piece together how sophisticated eyes could have been created through a gradual process driven by natural selection. (You can read more about the prospective intermediates that exist in the animal world in a [wonderful paper](#) by Ryan Gregory.)

If you choose to explore eye development in detail, be watching for examples of exaptation, co-option, step-by-step adaptation and redundancy. For example, you will note that the evolution of the lens illustrates co-option and redundancy. There are two ways to focus the image on the light-receiving cells at the back of an eye. One way is through an independent lens. The other way is through the transparent cornea in front of the lens. The lens is simply transparent crystallized protein molecules that are assembled in such a manner that they bring the image into sharp focus. There are a variety of proteins that can be crystallized to serve as an effective lens. It turns out that, depending on the evolutionary lineage, various proteins—including enzymes such as alcohol dehydrogenase (an enzyme for breaking down ethanol), glutathione S transferase and protein chaperones—are used for this purpose. This is a simple example of co-option and redundancy functioning together as part of the tinkering mechanism used for building a complex structure like the eye.

Two-thirds of animal phyla have some sort of light-sensing device. Although all of these light-sensing devices make use of retinal and opsins, there are differences in structure that we can trace to differences in evolutionary origin. In his 2003 book, *Life's Solution*, Simon Conway-Morris documents at least seven independent origins of the eye resulting in very similar outcomes. For example, the eye of a squid and the eye of a mammal work in a remarkably similar manner. However, the ways the two eyes are constructed during development are quite different. Differences in structure are constrained by how particular bodies are constructed as the embryo develops. Eyes also bear telltale signs of the fact that there has been a certain amount of jury-rigging in their construction. They are not perfect. They have blind spots, are subject to retinal detachment, glaucoma and macular degeneration, all of which are a function of the history of how

the eye has been assembled through time.

Although we don't have the eye intermediates preserved in stone the way we can see the simpler assembly of the parts of the mammalian middle ear, we do have a vast array of eye structures in the animal kingdom, any one of which might appear to be irreducibly complex but which, in fact, has been put together through a set of processes that has included exaptation, co-option, step-by-step adaptation and some redundancy at various stages along the way. Indeed, these eye structures themselves are likely intermediates. Everything changes as it passes through the eons of time. This is the legacy of creation through the process of natural selection.

Consulted Experts:

The BioLogos Foundation is grateful for the assistance of [Darrel Falk](#) and [Francis Collins](#) in drafting this response.¹

Notes

1. All of Dr. Francis Collins' work on this response was completed before [being sworn in](#) as Director of the National Institutes of Health.

Further Reading

Blogs

- ["On Reducing Irreducible Complexity, Part I"](#) by Darrel Falk, from *Science and the Sacred*

Articles

- ["Bacterial Flagellar Diversity and Evolution: Seek Simplicity and Distrust It?"](#) by Lori Snyder, Nicholas J. Loman, Klaus Futterer, and Mark J. Pallen, *Trends in Microbiology* 17:1-5, 2009
- ["From The Origin of Species to the origin of bacterial flagella"](#) by Mark J. Pallen and Nicholas J. Matzke, *Nature Reviews, Microbiology* 4:784-790, 2007.
- ["The Evolution of Complex Organs."](#) by T. Ryan Gregory, *Evolution: Education and Outreach*.

Books

- [*Endless Forms Most Beautiful: The New Science of Evo Devo*](#) by Sean Carroll, W.W. Norton and Company, 2005
 - [*Only a Theory: Evolution and the Battle for America's Soul*](#) by Kenneth Miller, Viking Adult, 2008
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