Without Miracles

1. Puzzles of Fit

We see beautiful adaptations everywhere and in every part of the organic world.

--Charles Darwin[1]

Are you awed by the exquisite fit between organism and environment, and find in this fit a puzzle needing explanation? Do you marvel at the achievements of modern science, at the fit between scientific theories and the aspects of the world they purport to describe? Is this a puzzling achievement? Do you feel the need for an explanation as to how it could have come about?

--Donald T. Campbell[2]

Much about the world we live in captures our attention and elicits our wonder. Majestic snow-crowned mountains demand our gaze as they rise above the surrounding plain. Raging storms hurl rain, wind, and jagged spears of fire. The normally unyielding ground on which we walk shakes violently as the continents continue their slow drift over the earth's molten core. The rising and setting of the sun, the waxing and waning of the moon, and the orderly march of the seasons and tides provide welcome rhythm and predictability to our lives and activities.

Whereas our ancestors invoked gods, goddesses, and a host of spirits to account for such happenings, science has now provided a naturalistic understanding of these and other physical events as the mechanical consequences of principles of physics and chemistry. The sun is no longer driven across the sky in a chariot, and serpents no longer consume the moon. Myths and religious interpretations for such natural phenomena certainly continue to exist, but few expect miraculous explanations to be offered in our schools and universities.

But there is another side to the world we inhabit, the *organic* side that Darwin mentions in the epigraph above. And here is even more to marvel at. This living world includes both microscopic bacteria and giant redwood trees, the wildly colorful birds and insects of the rain forests, the large mammals of the African savannah, the fishes and bizarre denizens of the ocean's depths, as well as the creature who wrote these words and the one now reading them. These and other living organisms evoke our awe because they appear so marvelously designed to fit the particular environment in which they exist. This fit of organism to environment involves not only the structure and behavior of organisms, but often also the inanimate products of these organisms. Whereas biology now recognizes that living organisms must observe the materialistic laws of the physical world, all forms of life appear somehow to have obtained knowledge of their environment that transcends the blind, uncaring forces of physics, and the ignorant, inevitable principles of chemistry.

The common web-spinning spider provides many examples of wonderful instances of fit. Its eight legs, moving in a coordinated fashion, allow it to travel rapidly across the ground, scale vertical surfaces, and even go with ease upside down across our bedroom ceilings. It can drop quickly and safely from high locations by riding down on its internally produced silk dragline, excreted by special organs called spinnerets, and if it should change its mind, it can hoist itself up again by reeling in the line it has just laid. Being a predator, the spider must catch insects to survive. This is accomplished by constructing a well-designed web whose strands ensnare and quickly entangle any edible insect unfortunate enough to touch them. When this occurs, the spider rushes over and injects a deadly venom into the helpless victim. Then it must decide whether to consume the meal now, drawing out the nutritious body fluids and perhaps spraying it with digesting juices to make it even more palatable to the spider's sucking stomach, or save it for later by wrapping the lifeless prey with silk. Spiders also engage in elaborate courtship behaviors, with the customs of some species requiring the male to present the female with a gift-wrapped fly so that he can mate with her without being eaten himself. Some females protect their eggs until the spiderlings emerge and cast their draglines into the wind to go ballooning off to new locations to establish residence.

The spider thus provides us with many instances of fit--a remarkable meshing of its body, behavior, and products with its environment. Its appendages and their movements fit the demands of locomotion. Thanks to a special oil covering its body, it can move with ease over its sticky web. Its web is designed to fit the space in which it is built and to enmesh unsuspecting insects. Its venom is chemically suited to kill its prey. And we have not even mentioned the intricately designed respiratory, circulatory, digestive, nervous, and reproductive systems that function together to give life to the spider and permit its reproduction.

These and other instances of organic fit are quite unlike anything in the inanimate world. They attract our attention and elicit our wonder because they seem to have a purpose. Legs are for walking, mouths are for eating, and webs are for snaring prey. In biology, the word *adaptation* (from the Latin *adaptare*, "to fit") is used to describe such instances of fit between organism and environment (with the environment understood to include other organisms as well, as in the fit between a male's and a female's sexual organs).

When one looks at the fit and function of these adaptations, it does not seem unreasonable to consider them as forms of knowledge. In an important sense, the spider's legs and feet know something about the terrain that the spider considers home. Its venom has a kind of knowledge of the physiology of its prey. And the male spider knows what it must do to find a female and entice it to mate. Of course, in the case of spiders, we are referring to a type of built-in biological knowledge, not the conscious, reflective knowledge that we associate with human thought. But insofar as biological adaptations are functional and aid in an organism's survival and reproduction in what is usually an uncaring and competitive world, these instances of fit clearly reflect knowledge of the world that the organism inhabits.

But the fit of body parts, behavior, and instinctive products (such as the spider's web) are not the only adaptations in the organic world. More is to be found by looking deeper using the instruments of modern science. The cells themselves and the precisely designed organelles they contain reveal remarkable fit in form and function to their surroundings within the organism. Mitochondria produce energy, ribosomes create new proteins, and DNA of the nucleus is an archive of all the genetic information the organism requires to function and reproduce.

Also at the level of cells is the exquisite fit achieved by the mammalian immune system. Ever since it was discovered late in the nineteenth century that animals are able to produce antibodies that provide protection from disease, the mechanism of this process has been the subject of extensive research, leading to discoveries that have earned 12 Nobel prizes since 1901.

An intriguing puzzle motivated this research. Since many different types of antibodies were found, each effective against a particular antigen (virus, bacterium, chemical toxin), it was thought that information for the construction of each antibody was carried in the individual's genes. However, Austrian-born Karl Landsteiner discovered early in the twentieth century that the immune system is capable of producing antibodies that are effective against *artificially synthesized antigens*, that is, foreign substances with which the animal had no contact either during its own lifetime or during its evolutionary past. The creative ability of the immune system to produce antibodies to novel antigens is even more amazing when it is realized just how well an antibody fits its target antigen, a degree of fit comparable to that a key must have to open a lock.

One also must consider more abstract types of fit, particularly when one reflects on the knowledge that humans require to survive in the world's many different environments. Indeed, the human species lives in a wider range of habitats than any other vertebrate on earth, from the steaming jungles of the tropics to the numbing Arctic tundra, from low-lying coastal areas to the Andean *altiplano* 4000 meters above sea level, from sparsely settled wilderness to teeming cities. We have so far made only short visits away from the surface of our home planet, but it may not be too long before we establish permanent settlements in outer space and on the ocean floor.

The desert nomads of the Sahara wear long, loose-fitting garments to protect them from the sun, dry wind, and blowing sand. The Eskimos of the frozen Arctic wear warm garments made from the skins of the animals they hunt. People living in remote tropical rain forests often wear little or no clothing at all. Astronauts working in space wear pressurized, air-conditioned spacesuits with visors coated with a thin transparent film of gold to reflect the intense, damaging rays of an unattenuated sun. Other aspects of how these remarkably diverse people live--what they eat and how they obtain and prepare it, how many spouses and children they have, how their living quarters are made and maintained--provide clear evidence of fit to features of their particular environment, without which human life would not be possible in its wide range of habitats.

But if human knowledge fits aspects of the world, it must also be the case that our brains, the seat of our knowledge, are adapted to aspects of the world. Arguably the most complex object yet discovered in the universe, the human brain is a rather soggy, irregular sphere, about the size of a large grapefruit. Within its modest volume, however, it has enough "hardware" to make even the most sophisticated supercomputer appear crude by comparison, including about 20 billion electrochemical switching units, with each unit having between 1000 and 10,000 connections to other similar units. The pattern of connections and activation of these neural circuits underlie just about everything we do, from walking, eating, and making love to talking, cooking, and making scientific discoveries. The plasticity of our brain allows us to acquire new skills and knowledge as required by our environment, such as learning to speak another language or learning to ride a bicycle, drive a car, or fly a space ship.

Other instances of fit can be found in the material products of human scientific and technological knowledge. A good example is the modern passenger aircraft, which has helped to make today's world a much smaller place. Able to accommodate hundreds of travelers in relative (if often somewhat cramped) comfort, today's passenger jet is jammed full of sophisticated technology. Its sleek aluminum skin resists corrosion and combines strength with low weight. The configuration of its wing and tail surfaces provides the lift necessary for flight. Its engines deliver amazing thrust for their size and weight. Sophisticated navigational and radar systems permit the jet to avoid both bad weather and other aircraft and keep a steady course for its final destination. Flying 10,000 meters above the ground at 1000 kilometers per hour, passengers are provided with in-flight movies, meals, lavatory facilities, and even telephones to keep in touch with their earthbound families, friends, and business associates.

The sophisticated technology represented by the jet is even more impressive when one takes into account the planning and coordination that is required to construct it. Considering the complexity of these remarkable flying machines, it is hard to imagine how any single person could ever have all the expertise necessary to design one, let alone the time, skill, and strength to build one. But despite these difficulties, air travel in the industrialized countries has become almost as routine as taking the family car on a trip, with accidents much lower on a passenger-distance basis than for any other form of transportation. Clearly, the modern jet airplane is an amazingly fit vehicle for the purpose of transporting passengers safely, quickly, and comfortably over distances that not very long ago would have taken months to cover. And its success in doing so reflects well on the scientific knowledge that is applied to its design, construction, and operation.

As these examples indicate, the world of living organisms and their products provides countless remarkable instances of fit. The spider's body, behavior, and web make it well equipped for the demands of its predatory lifestyle. The mammalian immune system is able to produce antibodies that precisely match the structure of disease-producing antigens. The variety of human cultural knowledge is remarkable for its adaptation to the very different environmental and social conditions throughout the world. The human brain's exceedingly intricate "wiring" permits us to experience and do a remarkable variety of things. Our stubborn insistence on finding ever faster, easier, and more enjoyable ways to satisfy our needs for food, shelter, sex, health, companionship, and entertainment has spurred the growth of science and technology and has led to technological achievements like the jet airplane, gene therapy, and the personal computer.

It could be argued that such fit is a universal characteristic of life and its products. Indeed, if the earth should ever lose the delicate balance that makes life here possible, future extraterrestrial visitors to our then-dead planet would certainly look for artifacts of fit to determine if life had ever existed and the degree to which it might have been accompanied by intelligence.

Fit, as used here, may be difficult to define formally, but as a judge once said in a pornography case, we seem to know it when we see it. What criteria do we use to determine that fit is present? It must appear that it was designed for some purpose and is able to achieve this purpose by functioning in a way that takes into account important, relevant aspects of its environment. A structure or behavior is fit only insofar as it is adapted to its environment and contributes in some useful way to the organism or system that created it or of which it is a part. We recognize such fit when we observe "any system composed of many interacting parts where the details of the parts' structure and arrangement suggest design to fill some function."[3]

Such instances of fit also demonstrate a degree of *complexity* that is highly unlikely to be due to chance. This is certainly the case when we observe any living organism, even one as simple as a common bacterium such as *Escherichia coli*. The probability that billions of different organic molecules would by pure chance just happen to assemble themselves to form the complex arrangement required to produce a cell that is able to take in and metabolize nutrients, eliminate wastes, move about, and reproduce seems (and is) too tiny to consider seriously. It is the astronomical improbability of such functional arrangements of many components that makes them puzzling in the first place. Such achievements of design are instances of what will be called "adapted complexity" throughout this book. When considering examples of adapted complexity in the biological world, such as the spider's prey-catching behavior, it appears as if knowledge had somehow been obtained by an organism about some aspect of its environment.

But there is something even more puzzling about the many instances of adapted complexity among living organisms and their products. In cases such as the mammalian brain and immune system, a continuing process of "fit making" results in the emergence of further achievements of adapted complexity. The ability to fashion novel and more impressive instances of fit is itself an instance of adapted complexity. It is at the same time a very special kind of adapted complexity that can perhaps be best described using the related but distinct term adapt*ive* complexity, with the descriptor *adaptive* intended to indicate a continuing process of fit making in contrast to *adapted,* which describes already achieved fit.

The goal of this book is to explore explanations for both adapted complexity (already achieved fit) and adaptive complexity (ability to achieve new fit) in our world--existing puzzles of fit and the emergence of new ones that are just about everywhere we look, and that we have yet to find anywhere else in the universe. A quite simple and compelling explanation for the puzzles of fit demonstrated by the structure and behavior of living organisms was proposed over 130 years ago and is still regarded as the central unifying principle of biology. No comparable explanation, however, is generally accepted for all other puzzles of fit of the type mentioned above. The purpose of this book is to present a case for just such an explanation--and one that works without recourse to miracles.

[1] Darwin (1859).

[2] Campbell (1974b, p. 139).

[3] Pinker & Bloom (1990, p. 709).