The Cognitive Science of Science: Explanation, Discovery, and Conceptual Change

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13 Conceptual Change in the History of Science: Life, Mind, and Disease

Introduction

Biology is the study of life, psychology is the study of mind, and medicine is the investigation of the causes and treatments of disease. This chapter describes how the central concepts of life, mind, and disease have undergone fundamental changes in the past 150 years or so. There has been a progression from theological, to qualitative, to mechanistic explanations of the nature of life, mind, and disease. This progression has involved both theoretical change, as new theories with greater explanatory power replaced older ones, and emotional change, as the new theories brought reorientation of attitudes toward the nature of life, mind, and disease. After a brief comparison of theological, qualitative, and mechanistic explanations, I will describe how shifts from one kind of explanation to another have carried with them dramatic kinds of conceptual change in the key concepts in the life sciences. Three generalizations follow about the nature of conceptual change in the history of science: there has been a shift from conceptualizations in terms of simple properties to ones in terms of complex relations; conceptual change is theory change; and conceptual change is often emotional as well as cognitive.

The contention that historical development proceeds in three stages originated with the nineteenth-century French philosopher Auguste Comte, who claimed that human intellectual development progresses from a theological to a "metaphysical" stage to a "positive" (scientific) stage (Comte, 1970). The stages I have in mind are different from Comte's, so let me say what they involve. By the *theological* stage I mean systems of thought in which the primary explanatory entities are supernatural ones beyond the reach of science, such as gods, devils, angels, spirits, and souls.

For example, the concept of fire was initially theological, as in the Greek myth of Prometheus receiving fire from the gods. By the *qualitative* stage I mean systems of thought that do not invoke supernatural entities, but which postulate natural entities not far removed from what they are supposed to explain, such as vital force in biology. Early qualitative concepts of fire include Aristotle's view of fire as a substance and Epicurus's account of fire atoms. By the *mechanistic* stage I mean the kinds of developments now rapidly taking place in all of the life sciences in which explanations consist of identifying systems of interacting parts that produce observable changes. The modern concept of fire is mechanistic: combustion is rapid oxidation, the combination of molecules. Much more will be said about the nature of mechanistic, qualitative, and theological explanations in connection with each of the central concepts of life, disease, and mind. I will show how resistance to conceptual change derives both from (1) cognitive difficulties in grasping the superiority of mechanistic explanations to the other two kinds and (2) from emotional difficulties in accepting the personal implications of the mechanistic worldview. First, however, I want to review the general importance of the topic of conceptual change for the history and philosophy of science.

History and Philosophy of Science

Historians and philosophers of science are concerned to explain the development of scientific knowledge. On a naïve view, science develops by simple accumulation, piling fact upon fact. But this view is contradicted by the history of science, which has seen many popular theories eventually rejected as false, including: the crystalline spheres of ancient and medieval astronomy, the humoral theory of medicine, catastrophist geology, the phlogiston theory of chemistry, the caloric theory of heat, the vital force theory of physiology, the aether theories of electromagnetism and optics, and biological theories of spontaneous generation. Rejection of these theories has required abandonment of concepts such as *humor*, *phlogiston*, *caloric*, and *aether*, along with introduction of new theoretical concepts such as *germ*, *oxygen*, *thermodynamics*, and *photon*. Acceptance of a theory therefore often requires the acquisition and adoption of a novel conceptual system.

We can distinguish different degrees of conceptual change occurring in the history of science and medicine (Thagard, 1992, 1999, p. 150):

1. Adding a new instance of a concept, for example, a patient who has tuberculosis.
2. Adding a new weak rule, for example, that tuberculosis is common in prisons.
3. Adding a new strong rule that plays a frequent role in problem solving and explanation, for example, that people with tuberculosis have *Mycobacterium tuberculosis*.
4. Adding a new part-relation, for example, that diseased lungs contain tubercles.
5. Adding a new kind-relation, for example, differentiating between pulmonary and miliary tuberculosis.
6. Adding a new concept, for example, *tuberculosis* (which replaced the previous terms *phthisis* and *consumption*) or AIDS.
7. Collapsing part of a kind-hierarchy and abandoning a previous distinction, for example, realizing that phthisis and scrofula are the same disease, tuberculosis.
8. Reorganizing hierarchies by *branch jumping*, that is, shifting a concept from one branch of a hierarchical tree to another, for example, reclassifying tuberculosis as an infectious disease.
9. *Tree switching*, that is, changing the organizing principle of a hierarchical tree, for example, classifying diseases in terms of causal agents rather than symptoms.

The most radical kinds of conceptual change involve the last two kinds of major conceptual reorganization, as when Darwin reclassified humans as animals and changed the organizational principle of the tree of life to be evolutionary history rather than similarity of features.

Thus, understanding the historical development of the sciences requires attention to the different kinds of conceptual change that have taken place in the noncumulative growth of knowledge (see also Kuhn, 1962; Horwich, 1993; Laporte, 2004; Nersessian, 1992, 2008). I will now describe the central changes that have taken place in the concepts of life, mind, and disease.

Life

Theology

Theological explanations of life are found in the creation stories of many cultures, including the Judeo-Christian tradition's book of Genesis. According to this account God created grass, herbs, and fruit trees on the second day, swarms of birds and sea animals on the fifth day, and living creatures on land including humans on the sixth day. Other cultures worldwide have different accounts of how one or more deities brought the Earth and the living things on it into existence. These stories predate by centuries attempts to understand the world scientifically, which may only have begun with the thought of the Greek philosopher-scientist Thales around 600 BC. The stories do not attempt to tie theological explanations to details of observations of the nature of life. Thus, the first substage of the theological stage of the understanding of life is a matter of myth, a set of entertaining stories rather than a detailed exposition of the theological origins of life.

During the seventeenth and eighteenth centuries, there was a dramatic expansion of biological knowledge based on observation, ranging from the discovery by van Leeuwenhoek of microorganisms such as bacteria to the taxonomy by Carl Linnaeus of many different kinds of plants and animals. In the nineteenth century, attempts were made to integrate this burgeoning knowledge with theological understanding, including the compellingly written *Natural Theology* of William Paley (1963). Paley argued that, just as we explain the intricacies of a watch by the intelligence and activities of its maker, so we should explain the design of plants and animals by the actions of the creator. The eight volumes of the Bridgewater Treatises connected divine creation not only to the anatomy and physiology of living things, but also to astronomy, physics, geology, and chemistry. Nineteenth-century natural theology was a Christian enterprise, as theologians and believing scientists connected biological and other scientific observations in great detail with ideas drawn from the Bible. Unlike the purely mythical accounts found in many cultures, this natural-theology substage of theological explanations of life was tied to many facts about the biological world.

A third substage of theological understandings of life is the relatively recent doctrine of intelligent design that arose in the United States as a way of contesting Darwin's theory of evolution by natural selection without directly invoking Christian ideas about creation. Because the American constitution requires separation of church and state, public schools have not been allowed to teach Christian ideas about divine creation as a direct challenge to evolution. Hence in the 1990s there arose a kind of natural theology in disguise claiming to have a scientific alternative to evolution, the theory of intelligent design (see, e.g., Dembski, 1999). Its proponents claim that it is not committed to the biblical account of creation, but instead relies on facts about the complexity of life as pointing to its origins in intelligent causation rather than the mechanical operations of natural selection. American courts have, however, ruled that intelligent design is just a disguised attempt to smuggle natural theology into the schools.

Qualitative Explanations of Life

Unlike theological explanations, qualitative accounts do not invoke supernatural entities, but instead attempt to explain the world in terms of natural properties. For example, in the eighteenth century, heat and temperature were explained by the presence in objects of a qualitative element called caloric: the more caloric, the more heat. A mechanical theory of heat as motion of molecules only arose in the nineteenth century. Just as caloric was invoked as a substance to explain heat, qualitative explanations of life can be given by invoking a special kind of substance that inhabits living things. Aristotle, for example, believed that animals and plants have a principle of life (*psuche*) that initiates and guides reproductive, metabolic, growth, and other capacities (Grene & Depew, 2004).

In the nineteenth century, qualitative explanations of life became popular in the form of *vitalism*, according to which living things contain some distinctive force or fluid or spirit that makes them alive (Bechtel & Richardson, 1998). Scientists and philosophers such as Bichat, Magendie, Liebig, and Bergson postulated that there must be some sort of vital force that enables organisms to develop and maintain themselves. Vitalism developed as an opponent to the materialistic view, originating with the Greek atomists and developed by Descartes and his successors, that living things are like machines in that they can be explained purely in terms of the operation of their parts. Unlike natural theology, vitalism does not explicitly employ divine intervention in its explanation of life, but for vitalists such as Bergson there was no doubt that God was the origin of vital force.

Contrast the theological and vitalist explanation patterns.

Theological explanation pattern

Why does an organism have a given property that makes it alive?

Because God designed the organism to have that property.

Vitalist explanation pattern

Why does an organism have a given property that makes it alive?

Because the organism contains a vital force that gives it that property.

We can now examine a very different way of explaining life: in terms of mechanisms.

Mechanistic Explanations of Life

The mechanistic account of living things originated with Greek philosophers such as Epicurus, who wanted to explain all motion in terms of the interactions of atoms. Greek mechanism was limited, however, by the comparative simplicity of the machines available to them: levers, pulleys, screws, and so on. By the seventeenth century, however, more complicated machines were available, such as clocks, artificial fountains, and mills. In his 1664 *Treatise on Man*, Descartes used these as models for maintaining that animals and the bodies (but not the souls) of humans are nothing but machines explainable through the operations of their parts, analogous to the pipes and springs of fountains and clocks (Descartes, 1985). Descartes undoubtedly believed that living machines had been designed by God, but the explanation of their operations was in terms of their structure rather than their design or special vital properties. The pattern is something like this:

Mechanistic explanation pattern

Why does an organism have a given property that makes it alive?

Because the organism has parts that interact in ways that give it that property.

Normally, we understand how machines work because people have built them from identifiable parts connected to each other in observable ways.

In Descartes's day, mechanistic explanations were highly limited by lack of knowledge of the smaller and smaller parts that make up the body: cells were not understood until the nineteenth century. They were also limited by the simplicity of available machines to provide analogies to the complexities of biological organisms. By the nineteenth century, however, the cell doctrine and other biological advances made mechanistic explanations of life much more conceivable. But it was still utterly mysterious how different species of living things came to be, unless they were the direct result of divine creation. Various thinkers conjectured that species have evolved, but no one had a reasonable account of how they had evolved.

The intellectual situation changed dramatically in 1859, when Charles Darwin published *On the Origin of Species*. His great insight was not the concept of evolution, which had been proposed by others, but the concept of natural selection, which provided a mechanism that explained how evolution occurred. At first glance, natural selection does not sound much like a machine, but it qualifies as a mechanism because it consists of interacting parts producing regular changes. (For philosophical discussions of the nature of mechanisms, see Salmon, 1984; Bechtel & Richardson, 1993; Machamer, Darden & Craver, 2000; Bechtel & Abrahamsen, 2005.) The parts are individual organisms that interact with each other and with their environments. Darwin noticed that variations are introduced when organisms reproduce, and that the struggle for existence that results from scarcity of resources would tend to preserve those variations that gave organisms advantages in survival and reproduction. Hence variation plus the struggle for existence led to natural selection, which leads to the evolution of species. Over the past 150 years, the evidence for evolution by natural selection has accumulated to such an extent that it ought to be admitted that evolution is a fact as well as a theory.

Why then is there continuing opposition to Darwin's ideas? The answer is that the battle between evolution and creation is not just a competition between alternative theories of how different species came to be, but between different worldviews with very different emotional attachments. Theological views have limited explanatory power compared to science, but they have very strong emotional coherence because of their fit with people's personal goals, including comfort, immortality, morality, and social cohesion (Thagard, 2006a, ch. 14). People attach strong positive emotional valences to the key ingredients of creationist theories, including supernatural entities such as God and heaven. In contrast, evolution by natural selection strikes fundamentalist believers as atheistic and immoral.

Although Darwin conceived of a mechanism for evolution, he lacked a mechanistic understanding of key parts of it. In particular, he did not have a good account of how variations occurred and were passed on to offspring. Explanation of variation and inheritance required genetic theory, which (aside from Mendel's early ignored ideas) was not developed until the first part of the twentieth century. In turn, understanding of genetics developed in the second part of that century through discovery of how DNA provides a mechanism for inheritance. Today, biology is thoroughly mechanistic, as biochemistry explains how DNA and other molecules work, which explains how genes work, which explains how variation and inheritance work. The genomes of important organisms including humans have been mapped, and the burgeoning enterprise of proteomics is filling in the details of how genes produce proteins whose interactions explain all the operations required for the survival and reproduction of living things.

Hence what makes things alive is not a divine spark or vital force, but their construction out of organs, tissues, and individual cells that are alive. Cells are alive because their proteins and processes enable them to perform functions such as energy acquisition, division, motion, adhesion, signaling, and self-destruction. The molecular basis of each of these functions is increasingly well understood (Lodish et al., 2000). In turn, the behavior of molecules can be described in terms of quantum chemistry, which explains how the quantum-mechanical properties of atoms cause them to combine in biochemically useful ways. Thus, the development of biology over the past 150 years dramatically illustrates the shift from a theological to a qualitative to a mechanist concept of life. This shift has taken place because of an impressive sequence of mechanistic theories that provide deeper and deeper explanations of how living things work, from natural selection to genetics to molecular biology to quantum mechanics. This shift does not imply that there is only one fundamental level at which all explanation should take place: it would be pointless to try to give a quantum-mechanical explanation of why humans have large brains, as the quantum details are far removed from the historical environmental and biological conditions that produced the evolution of humans. It is enough, from the mechanistic point of view, that the lower-level mechanical operations are available in the background.

In sum, theoretical progress in biology has resulted from elaboration of progressively deeper mechanisms, while resistance to such progress results from emotional preferences for theological over mechanistic explanation. Similar resistance arises to understanding disease and mind mechanistically.

Disease

Theology

Medicine has both the theoretical goal of finding explanations of disease and the practical goal of finding treatments for them. As with conceptions of life, early conceptions of disease were heavily theological. Gods were thought to be sometimes the cause of disease, and they could be supplicated to provide relief from them. For example, in the biblical book of Exodus, God delivers a series of punishments, including boils, on the Egyptians for holding the Israelites captive. Hippocrates wrote around 400 BC challenging the view that epilepsy is a "sacred disease" resulting from divine action. Medieval Christians believed that the black plague was a punishment from God. In modern theology, diseases are rarely attributed directly to God, but there are still people who maintain that HIV/AIDS is a punishment for homosexuality. But even if most people now accept medical explanations of the causes of disease, there are many who pray for divine intervention to help cure the maladies of people they care about. Hence in religious circles the concept of disease remains at least in part theological.

Qualitative Explanations of Disease

The ancient Greeks developed a naturalistic account of diseases that dominated Western medicine until the nineteenth century (Hippocrates, 1988). According to the Hippocratics, the body contains four humors: blood, phlegm, yellow bile, and black bile. Health depends on having these humors in correct proportion to each other. Too much bile can produce various fevers, and too much phlegm can cause heart or brain problems. Accordingly, diseases can be treated by changing the balance of humors, for example, by opening the veins to let blood out.

Traditional Chinese medicine, which is at least as ancient as the Hippocratic approach, is also a balance theory, but with *yin* and *yang* instead of the four humors. On the Chinese view, yin and yang are the two opposite but complementary forces that constitute the entire universe (see chapter 15). Diseases arise when there is an imbalance of *yin* and *yang* inside the body. Treatments such as herbs can restore the balance of *yin* and *yang*. Whereas the Hippocratic tradition used extreme physical methods such as blood-letting, emetics, and purgatives to restore the balance of the four humors, traditional Chinese medicine uses relatively benign herbal treatments to restore the balance of *yin* and *yang*. Unlike Hippocratic medicine, which has been totally supplanted by Western scientific approaches, traditional Chinese medicine is still practiced in China and is often favored by Westerners looking for alternative medical treatments.

Similarly, traditional Indian Ayurvedic medicine has attracted a modern following through the writings of gurus such as Deepak Chopra. On this view, all bodily processes are governed by three main *doshas*: *vata* (composed of air and space), *pitta* (composed of fire and water), and *kapha* (composed of earth and water). Too much or too little of these elements can lead to diseases, which can be treated by diet and exercise. There is no empirical evidence for the existence of the *doshas* or for their role in disease, but people eagerly latch onto Chopra's theories for their promise that good health and long life can be attained merely by making the right choices. Just as creationism survives because it fits with peoples personal motivations, so traditional Chinese and Ayurvedic theories survive because they offer appealing solutions to scary medical problems.

The three balance theories described in this section are clearly not theological, because they do not invoke divine intervention. But they are also not mechanical, because they do not explain the causes of diseases in terms of the regular interaction of constitutive parts. They leave utterly mysterious how the interactions of humors, *doshas*, or *yin* and *yang* can make people sick. In contrast, modern Western medicine based on contemporary biology provides mechanistic explanations of a very wide range of diseases.

Mechanistic Explanations of Disease

Modern medicine began in the 1860s, when Pasteur and others developed the germ theory of disease. Bacteria had been observed microscopically in the 1670s, but their role in causing diseases was not suspected until Pasteur realized that bacteria are responsible for silkworm diseases. Bacteria were quickly found to be responsible for many human diseases, including cholera, tuberculosis, and gonorrhea. Viruses were not observed until the invention of the electron microscope in 1939, but are now known to be the cause of many human diseases such as influenza and measles (Thagard, 1999).

The germ theory of disease provides mechanistic explanations in which bacteria and viruses are entities that interact with bodily parts such as organs and cells that are infected. Unlike vague notions like *yin*, *yang*, and *doshas*, these entities can be observed using microscopes, as can their presence in bodily tissues. Thus an infected organism is like a machine that has multiple interacting parts. The germ theory of disease is not only theoretically useful in explaining how many diseases arise, it is also practically useful in that antimicrobial drugs such as penicillin can cure some diseases by killing the agents that cause them.

As we saw for biological explanations, it is a powerful feature of mechanistic explanations that they decompose into further layers of mechanistic explanations. Pasteur had no idea how bacteria manage to infect organs, but molecular biology has in recent decades provided detailed accounts of how microbes function. For example, when the new disease SARS was identified in 2003, it took only a few months to identify the coronavirus that causes it and to sequence the virus's genes that enable it to attach themselves to cells, infect them, and reproduce. In turn, biochemistry explains how genes produce the proteins that carry out these functions. Thus the explanations provided by the germ theory have progressively deepened over the almost one and half centuries since it was first proposed. Chapter 6 argues that this kind of ongoing deepening is a reliable sign of the truth of a scientific theory.

Not all diseases are caused by germs, but other major kinds have been amenable to mechanistic explanation. Nutritional diseases such as scurvy are caused by deprivation of vitamins, and the mechanisms by which vitamins work are now understood. For example, vitamin C is crucial for collagen synthesis and the metabolism and synthesis of various chemical structures, which explains why its deficiency produces the symptoms of scurvy. Some diseases are caused by the immune system becoming overactive and attacking parts of the body, as when white blood cells remove myelin from axons between neurons, producing the symptoms of multiple sclerosis. Other diseases such as cystic fibrosis are directly caused by genetic factors, and the connection between mutated genes and defective metabolism is increasingly well understood. The final major category of human disease is cancer, and the genetic mutations that convert a normal cell into an invasive carcinoma, as well as the biochemical pathways that are thereby affected, are becoming well mapped out (Thagard, 2003, 2006b).

Despite the progressively deepening mechanistic explanation of infectious, nutritional, autoimmune, and genetic diseases, there is still much popular support for alternative theories and treatments such as traditional Chinese and Ayurvedic medicine. The reasons for the resistance to changes in the concept of disease from qualitative to mechanistic are both cognitive and emotional. On the cognitive side, most people simply do not know enough biology to understand how germs work, how vitamins work, how the immune system works, and so on. Hence much simpler accounts of imbalances among a few bodily elements are appealing. On the emotional side, there is the regrettable fact that modern medicine still lacks treatment for many human diseases, even ones like cancer whose biological mechanisms are quite well understood. Alternative disease theories and therapies offer hope of inexpensive and noninvasive treatments. For example, naturopaths attribute diseases to environmental toxins that can be cleared by diet and other simple therapies, providing people with reassuring explanations and expectations about their medical situation. Hence resistance to conceptual change about disease, like resistance concerning life, is often as much emotional as cognitive. The same is true for the concept of mind.

Mind

Theology

For the billions of people who espouse Christianity, Islam, Hinduism, and Buddhism, a person is much more than a biological mechanism. According to the book of Genesis, God formed man from the dust of the ground and breathed into his nostrils, making him a living soul. Unlike human bodies, which rarely last more than 100 years, souls have the great advantage of being indestructible, which makes possible immortality and (according to some religions) reincarnation. Because most people living today believe that their souls will survive the demise of their bodies, they have a concept of a person that is inherently dualistic, according to which people consist of both a material body and a spiritual soul.

We saw that Descartes argued that bodies are machines, but he maintained that minds are not mechanically explainable. His main argument for this position was a thought experiment: he found it easy to imagine himself without a body, but impossible to imagine himself not thinking

(Descartes, 1985). Hence he concluded that he was essentially a thinking being rather than a bodily machine, thereby providing a conceptual argument for the theological view of persons as consisting of two distinct substances, with the soul being much more important than the body. Descartes thought that the body and soul were able to influence each other through interaction in the brain's pineal gland.

The psychological theories of ordinary people are thoroughly dualist, assuming that consciousness and other mental operations belong fundamentally to the soul rather than the brain. Legal and other institutions assume that people inherently have the capacity for free will, which applies to actions of the soul rather than to processes occurring in the brain through interaction with other parts of the body and the external environment. Such freedom is viewed as integral to morality, making it legitimate to praise or blame people for their actions.

Notice how tightly the theological view of the mind as soul fits with the biological theory of creation. Life has theological rather than natural origins, and God is also responsible for a special kind of life: humans with souls as well as bodies. Gods and souls are equally supernatural entities.

Qualitative Explanations of Mind

Postulating souls with free will does not enable us to say much about mental operations, and many thinkers have used introspection (self-observation) to describe the qualitative properties of thinking. The British empiricist philosophers Locke and Hume claimed that minds function by the associations of ideas that are ultimately derived from sense experience. When Wilhelm Wundt originated experimental psychology in the 1870s, his observational method was still primarily introspective, but was much more systematic and tied to experimental interventions than ordinary self-observation.

Many philosophers have resisted the attempt to make the study of mind scientific, hoping that a purely conceptual approach could help us to understand thinking. Husserl founded phenomenology, an a priori attempt to identify essential features of thought and action. Linguistic philosophers such as J. L. Austin thought that attention to the ordinary uses of words could tell us something about the nature of mind. Analytic philosophers have examined everyday mental concepts such as belief and desire, under the assumption that people's actions are adequately explained as the result of people's beliefs and desires. Thought experiments survive as a popular philosophical tool for determining the essential features of thinking, for example, when Chalmers (1996) uses them to argue for a nontheological version of dualism in which consciousness is a fundamental part of the universe like space and time.

Thought experiments can be helpful for generating hypotheses that suggest experiments, but by themselves they provide no reason to believe those hypotheses. For every thought experiment there is an equal and opposite thought experiment, so the philosophical game of imagining what might be the case tells us little about the nature of minds and thinking. Introspective, conceptual approaches to psychology are appealing because they are much less constrained than experimental approaches and do not require large amounts of personnel and apparatus. They generate no annoying data to get in the way of one's favorite prejudices about the nature of mind. However, they are very limited in how much they can explain about the capacities and performance of the mind. Fortunately, mechanistic explanations based on experiments provide a powerful alternative methodology.

Mechanistic Explanations of Mind

Descartes thought that springs and other simple mechanisms suffice to explain the operation of bodies, but he drew back from considering thinking mechanistically. Until the second half of the twentieth century, these mechanical models of thinking such as hydraulic fluids and telephone switchboards seemed much too crude to explain the richness and complexity of human mental operations. The advent of the digital computer provided a dramatic innovation in ways of thinking about the mind. Computers are obviously mechanisms, but they have unprecedented capacities to represent and process information. In 1956, Newell, Shaw, and Simon (1958) developed the first computational model of human problem solving. For decades, the computer has provided a source of analogies to help understand many aspects of human thinking, including perception, learning, memory, and inference (Thagard, 2005a). On the computational view of mind, thinking occurs when algorithmic processes are applied to mental representations that are akin to the data structures found in the software that determines the actions of computer hardware.

However, as von Neumann (1958) noted early on, digital computers are very different from human brains. They nevertheless have proved useful for developing models of how brains work, ever since the 1950s. But in the 1980s there was an upsurge of development of models of brain-style computing, using parallel processing among simple processing elements roughly analogous to neurons (Rumelhart & McClelland, 1986). Churchland and Sejnowski (1992) and others have argued that neural mechanisms are computational, although of a rather different sort than those found in digital computers. More biologically realistic, computational models of neural processes are currently being developed (e.g., Eliasmith & Anderson, 2003). Efforts are increasingly made to relate high-level mental operations such as rule-based inference to neural structures and processes (e.g., Anderson et al., 2004; J. R. Anderson, 2007; Eliasmith, forthcoming). Thus neuroscience, along with computational ideas inspired by neural processes, provides powerful mechanistic accounts of human thinking.

Central to modern cognitive science is the concept of *representation*, which has undergone major historical changes. From a theological perspective, representations such as concepts and propositions are properties of spiritual beings, and thus are themselves nonmaterial objects. Modern cognitive psychology reclassifies representations as material things, akin to the data structures found in computer programs. Most radically, cognitive neuroscience reclassifies representations as *processes*, namely, patterns of activity in neural networks in the brain. Thus the history of cognitive science has required *branch jumping*, which I earlier listed as one of the most radical kinds of conceptual change. It is too soon to say whether cognitive neuroscience will also require *tree switching*, a fundamental change in the organizing principles by which mental representations are classified.

We saw in discussing life and disease how mechanistic explanations are decomposable into underlying mechanisms. At the cognitive level, we can view thinking in terms of computational processes applied to mental representations, but it has become possible to deepen this view by considering neurocomputational processes applied to neural representations. In turn, neural processes—the behavior of neurons interacting with each other—can be explained in terms of biochemical processes. The study of mind, like the study of life and disease, is increasingly becoming molecular

(Thagard, 2003, 2006a, ch. 7). That does not mean that the only useful explanations of human thinking will be found at the molecular level, because various phenomena are more likely to be captured by mechanisms operating at different levels. For example, rule-based problem solving may be best explained at the cognitive level in terms of mental representations and computational procedures, even if these representations and procedures ultimately derive from neural and molecular processes.

Indeed, a full understanding of human thinking needs to consider higher as well as lower levels. Many kinds of human thinking occur in social contexts, involving social mechanisms such as communication and other kinds of interaction. Far from it being the case that the social reduces to the cognitive which reduces to the neural which reduces to the molecular, sometimes what happens at the molecular level needs to be explained by what happens socially. For example, a social interaction between two people may produce very different kinds of neurotransmitter activity in their brains depending on whether they like or fear each other.

Of course, there is a great deal about human thinking that current psychology and neuroscience cannot yet explain. Although perception, memory, learning, and inference are increasingly subject to neurocomputational explanation, puzzles such as consciousness remain, where there are only sketches of mechanisms that might possibly be relevant. Such sketchiness gives hope to those who are opposed for various religious or ideological reasons to the provision of mechanistic explanations of the full range of human thought. From a theological perspective that assumes the existence of souls, full mechanistic explanation of thinking is impossible as well as undesirable. The undesirability stems from the many attractive features of supernatural souls, particularly their immortality and autonomy. Adopting a mechanistic view of mind requires abandoning or at lease modifying traditional ideas about free will, moral responsibility, and eternal rewards and punishment. This threat explains why the last fifty years of demonstrable progress in mechanistic, neurocomputational explanations of many aspects of thought are ignored by critics who want to maintain traditional attitudes. Change in the concept of mind, as with life and disease, is affected not only by cognitive processes such as theory evaluation, but also by emotional processes such as motivated inference. In the next section I will draw some more general lessons about conceptual change in relation to science education.

Conceptual Change

Of course, many other important concepts occur in the history of science besides life, mind, and disease, and there is much more to be said about other kinds of conceptual change (see, e.g., Thagard, 1992). But, because the concepts of life, mind, and disease are central, respectively, to biology, psychology, and medicine, they provide a good basis for making some generalizations about conceptual change in the history of science that can be tested against additional historical episodes. The commonalities in ways in which these three concepts have developed are well worth noting.

In all cases, there has been a shift from conceptualizations in terms of simple properties to ones in terms of complex relations. Prescientifically, life could be viewed as a special property that distinguished living from nonliving things. This property could be explained in terms of divine creation or some vital force. In contrast, the mechanistic view of biology considers life as a whole complex of dynamic relations, such as the metabolism and reproduction of cells. Life is no one thing, but rather the result of many different mechanical processes. Similarly, disease is not a simple problem that can be explained by divine affliction or humoral imbalance, but rather is the result of many different kinds of biological and environmental processes. Diseases have many different kinds of causes—microbial, genetic, nutritional, and autoimmune, each of which depends on many underlying biological mechanisms. Even more strikingly, mind is not a simple thing, a noncorporeal soul, but rather the result of many interacting neural structures and processes. Thus, the conceptual developments of biology, psychology, and medicine have all required shifts from thinking of things in terms of simple properties to thinking of them in terms of complexes of relations. Students who encounter scientific versions of their familiar everyday concepts of life, mind, and disease need to undergo the same kind of shift. Chi (2005) describes the difficulties that arise for students in understanding emergent mechanisms, ones in which regularities arise from complex interactions of many entities. Life, mind, and disease are all emergent processes in this sense and therefore subject to the difficult learning challenges that Chi reports in other domains.

The shift in understanding life, mind, and disease as complex mechanical relations rather than as simple substances or properties is an example of what I earlier called branch jumping, reclassification by shifting a concept from one branch of a hierarchical tree to another. The tree here is ontological, a classification of the fundamental things thought to be part of existence. Life, for example, is no longer a kind of special property, but rather a kind of mechanical process. Mind is another kind of mechanical process, not a special substance created by God. Many more mundane cases of branch jumping have occurred as the life sciences develop, for example, the reclassification in the 1980s of peptic ulcers as infectious diseases (Thagard, 1999).

Most radically, the shift from theological to qualitative to mechanistic conceptions of life, mind, and disease also involved tree switching, changing the organizing principle of a hierarchical tree. From a mechanistic perspective, we classify things in terms of their underlying parts and interactions. Darwin's mechanism of evolution by natural selection yielded a whole new way of classifying species, by historical descent rather than similarity. Later, the development of molecular genetics provided another new way of classifying species in terms of genetic similarity. Similarly, diseases are now classified in terms of their causal mechanisms rather than surface similarity of symptoms, for example, as infectious or autoimmune diseases. More slowly, mental phenomena such as memory are becoming classified in terms of underlying causal mechanisms such as different kinds of neural learning (Smith & Kosslyn, 2007). Thus, conceptual change in the life sciences has involved both branch jumping and tree switching.

Another important general lesson we can draw from the development of concepts of life, mind, and disease is that conceptual change in the history of science is theory change. Scientific concepts are embedded in theories, and it is only by the development of explanatory theories with broad empirical support that it becomes reasonable and in fact intellectually mandatory to adopt new complexes of concepts. The current scientific view of life depends on evolutionary, genetic, and molecular theories, just as the current medical view of disease depends on molecular, microbial, nutritional, and other well-supported theories. Similarly, our concept of mind should be under constant revision as knowledge accumulates about the neurocomputational mechanisms of perception, memory, learning, and inference. In all these cases, it would have been folly to attempt to begin investigation with a precise definition of key concepts, because what matters is the development of explanatory theories rather than conceptual neatness. After some theoretical order has been achieved, it may be possible to tidy up a scientific field with some approximate definitions. But if theoretical advances have involved showing that phenomena are much more complicated than anyone suspected, and that what were thought to be simple properties are in fact complexes of mechanical relations, then definitions are as pointless at later stages of investigation as they are distracting at early stages.

My final lesson about conceptual change in the history of science is that, especially in the sciences most deeply relevant to human lives, conceptual change is emotional as well as cognitive. The continuing resistance to mechanistic explanations of life, mind, and disease is inexplicable on purely cognitive grounds, given the enormous amount of evidence that has accumulated for theories such as evolution by natural selection, the germ theory of disease, and neurocomputational accounts of thinking. Although the scientific communities have largely made the emotional shifts necessary to allow concepts and theories to fit with empirical results, members of the general population, including many science students, have strong affective preferences for obsolete theories such as divine creation, alternative medicine, and soul-based psychology. Popular concepts of life, mind, and disease are tightly intertwined: God created both life and mind and can be called on to alleviate disease. Hence conceptual change can require not just rejection of a single theory in biology, psychology, and medicine, but rather replacement of a theological worldview by a scientific, mechanist one. For many people, such replacement is horrific, because of the powerful emotional appeal of the God-soul-prayer conceptual framework. Hence the kind of theory replacement required to bring about conceptual change in biology, psychology, and medicine is not just a matter of explanatory coherence, but requires changes in emotional coherence as well (for a theory of emotional coherence, see Thagard, 2000, 2006a).

From this perspective, science education inevitably involves cultural remediation and even psychotherapy, in addition to more cognitive kinds of instruction. The transition from theological to qualitative to mechanistic explanations of phenomena is cognitively and emotional difficult, but crucial for scientific progress, as we have seen for the central concepts of life, mind, and disease.