Complexity, Reductionism and the Natural World

Albert Shansky

Fairfield University

International Institute for Field-Being

Fairfield, CT 06430-5195

ashansky@fair1.fairfield.edu

Complexity is defined as a new way of thinking about the behavior of interacting units, be they atoms, ants in a colony, neurons firing in a human brain, or people in a society. Complexity reaches far beyond the concept of chaos and represents a profound shift away from the reductive principle that has guided science for centuries.[1]

Murray Gell-Mann, a 1969 Nobel laureate in physics for his work on the classification of elementary particles and their interactions, also studies aspects of simplicity and complexity, a transdisciplinary endeavor he calls *plectics*.[2] The general characteristics of a complex adaptive system (CAS), he asserts, include its ability to identify "regularities," as opposed to random data, in the stream of information it receives about itself and its surroundings. These regularities are then compressed into a schema, or internal model, that can supply descriptions of the real world, make predictions about what will happen there, and thus prescribe behavior for complex adaptive systems. The results obtained by this schema in the real world feed back into the system, to affect the schema's standing in competition with rivals that have arisen from mutations of various sorts. In biology, the genotype is a schema In human society, the schemata can be laws, customs, myths, or institutions. The scientific enterprise also is a complex adaptive system, in which regularities are identified from a vast quantity of data and compressed into a theory, which is the schema. A complex adaptive system has a tendency to spawn other such systems, in the way that, perhaps, biological evolution gave rise to human thinking.[3]

Complexity affords a holistic perspective and with it insights into many difficult concepts, such as life, consciousness, and intelligence, that have consistently eluded science and philosophy. For example, the question of whether viruses are living or nonliving is frequently debated. From the point of view of complexity, this question is meaningless, since life is a property of a large collection of entities undergoing evolution by natural selection, rather than a term that can be applied to any single entity within it. Indeed, there is growing support for basing a description of life on emergence and complexity, with some of that support coming from unexpected quarters.

Equations of quantum mechanics are designed to describe the microscopic world of electrons; its laws thus underpin the entire microelectronics industry. Quantum theory provides a dazzlingly successful description of the subatomic world, not just of electrons in transistors and the movement of photons in fiber-optic cables but of chemical and nuclear reactions, and much else besides. Indeed, quantum theory was invented to overcome the failure of classical physics to describe the world of the atom. According to classical physics, atoms – the very building blocks of matter – should not even exist. An electron orbiting an atomic nucleus should radiate away its energy, slow down, and consequently spiral inward; atoms should collapse. The early pioneers of quantum theory, including Max Planck, Albert Einstein, and Niels Bohr, assumed, with little justification other than that it seemed to work, that quantities such as energy are not infinitely divisible but come in chunks, called quanta. The laws of quantum mechanics as subsequently formulated by Werner Heisenberg and Erwin Schrodinger explained these assumptions in a mathematically consistent way; quantum rules prevent an orbiting electron from radiating energy continuously. In this way we avoid the embarrassing collapse of the atom. Quantum theory is good at explaining the results of scientific observations, but it puts our concept of an independent underlying Platonic reality in serious jeopardy. In our everyday world, we expect effects to have causes. Yet quantum mechanics seems to admit intrinsically unpredictable hops – " quantum leaps" – between electronic, atomic, and molecular states. There seem to be no limits to how accurately we can measure the properties of an object like an apple, such as its weight or dimensions. Not so in quantum theory. The uncertainty principle, enunciated by Werner

Heisenberg in 1927, states that measurements of certain pairs of quantities, such as position and momentum, can be made only to a certain degree of precision and no further. This restriction is so small on the everyday scale that for all practical purposes it appears to be nonexistent, yet it dominates the microscopic world.[4]

According to this unsettling and strongly counterintuitive theory, all physical objects are intrinsically ghostly. They exist in a twilight state – a "superposition" – of all possibilities of position and velocity. Only when a measurement is made on an object do we gain information about specific values of its observable properties. Particles of matter are waves of energy, and waves are particles, appearing as one or the other depending on what sort of measurement is being performed in any experiment. Stranger still, a particle moving between two points in space simultaneously travels along all possible paths between them. Indeed, the behavior of particles that are at opposite ends of the universe cannot be described separately by quantum lore. The main difference between quantum and classical physics is that the latter deals directly with *observable* quantities such as the position of a ball, its velocity, and its acceleration. But if we shrink this ball to the size of an atom, quantum mechanics replaces such continuously variable properties with discrete properties – quanta (chunks) of energy. A deeper level of description is used, based on so-called wave functions, which provide the probabilities of making particular observations of these quantities at particular times and places. The wave function contains information on all possibilities that could befall a system. It is used to calculate, for instance, the probability of an excited atom spitting out a photon of light when a measurement is made. Although the wave function contains information on all such observable properties, it is not itself observable. When an actual measurement is carried out, the system's wave function is usually said to "collapse" to yield a particular value of the quantity we are interested in.[5]

The complexity of life has been fashioned in the process of evolution by natural selection, a powerful concept that has withstood a great deal of abuse since Charles Darwin unveiled it in 1859. As the foundation stone of modern biology, the theory of evolution has emerged unscathed from more than a century of stringent evaluation by scientists and attacks by creationists.[6]

The human brain is in a sense one solution to the optimization problem posed by biological evolution. Because of the brain's immense capabilities, it furnishes another source of inspiration in its own right. One of the ironies of recent attempts to come to grips with intelligence by simulating it is that all the insight and opportunity afforded by our understanding of evolution had been set aside in favor of an approach now called artificial intelligence.

The catch phrase "survival of the fittest" usually springs to mind when people try to summarize Darwin's thinking about evolution. Plants, animals, and insects seem to have evolved in order to refine various features, whether the wings of a bee, the white fur of a polar bear, or the spots on a leopard's coat. Each of these is called an adaptation, a term used to designate any open-ended process by which a structure evolves through interaction with its environment to deliver better performance. These structures may range from proteins, through brains, to interacting ecologies of organisms such as the wildlife of Tasmania. The kind of adaptation these examples of living art undergo can be amazingly specific. The bee orchid, has evolved to look like a female bumblebee so that it can be fertilized when male insects are lured for sex. These plants have not deliberately optimized their appearance; their goal in life is simply reproduction. Among the decaying matter at the bottom of ponds, the thiobacilli bacteria have evolved to cope with high levels of sulfur by means of a complex suite of enzymes enabling them to use sulfur in place of oxygen. In the process of surviving through reproduction, even the lowliest species must be capable of adaptive improvement, for otherwise they would be eliminated in the biological arms race.

Species caught up in this struggle are engaged in an attempt to solve a complex optimization problem. The resulting adaptations, which crucially take into account the creatures environment, are in some sense nearly optimal, leading to such features as the shape of the bee orchid, the hydrodynamic features of a whale's fins, and the eyesight of an owl. Although adaptation produces organizations and interactions that are highly refined, they are invariably still improvable and not truly optimal. Finding effective improvements, not optimization, seems to be the heart of the Darwinian process. Defined in its most general sense, adaptive processes have a critical role in fields as diverse as psychology, economics, control engineering, and computational mathematics. Evolution would, therefore, seem to be a good metaphor to plunder for inspiration. In the past ten years or so, many have done just that, reproducing natural evolutionary structures within computers and using them to model, and find connections between, the recognition of visual information, learning, memory, intelligence, and artificial intelligence. By the standards we have considered so far, biological evolution is an adaptation process of staggering complexity.

Evolution occurs whenever there is reproduction and competition for finite resources. A reproducing system might intend to produce exact copies of itself, but no copying process works perfectly. Usually mistakes will impair the copy's ability to reproduce successfully. The mutant will probably perish, or at least its genes will become less numerous than those of its parent. Sometimes, however, the mutant will be superior, in which case its genes may be more successful than its parent and thus become more common. Because resources are limited, competition usually occurs between different organisms and species. In view of all these contributing factors, it is helpful to think of organisms as having a "reproductive fitness." All sorts of things will contribute to this fitness. For example, in a monkey, such factors as visual acuity, agility, attractiveness to other monkeys, intelligence, and strength play a role in determining how likely a monkey is to survive.

Biologists spent much of the nineteenth century looking for the spark of life in the tissues of living things. They never found it. Chemists put forward the notion that some molecules, “organic “ ones based on strings of carbon atoms, were unique to plants and animals[7]. However, they quickly learned how to make these supposedly natural components of life from “inorganic” substances in test tubes[8]. Physicists, blindly conditioned by the second law of thermodynamics and its gloomy suggestion that everything tends toward randomness and disorder, argued (wrongly) that it was odd that life existed at all.[9]

Today we have built up an astonishingly detailed picture of the complexity of life by pooling the enormous collective knowledge of biologists, chemists, and physicists. The fusion of these disciplines has produced molecular biology, a field concerned with the molecular basis of life. There are countless examples of the awesome power of this reductionist science. Consider Marfan’s syndrome, a potentially fatal disorder linked to a wide range of symptoms: abnormal height, a deformed chest, eye problems, and a dangerous dilation of the blood vessels leading to the heart.[10] In 1991 it was discovered that sufferers were making an unusual form of a single protein called fibrillin, one found in the connective tissue that holds together flesh, muscle, and organs.[11] Depending on the precise molecular defect in the fibrillin gene, a wide range of complaints results, from those of the eye to those of the heart.The molecular structure of the foot and mouth virus, the bane of livestock breeders, has recently been discovered.[12] The structure of these tiny agents was found by studying how crystals of the virus scatter radiation in the technique of X-ray crystallography. Using a modern ultrahigh resolution scanning force microscope capable of imaging atoms themselves, we are able to witness the birth of a virus as it escapes from a living cell.[13] Nobel laureate Gerd Binnig and colleagues glimpsed its exit by using the tip of the microscope’s probe to scan a cell. The picture provided by molecular biology is extraordinarily compelling, offering a detailed understanding of many aspects of life. Through our knowledge of so many of its molecular processes, we are today in an unrivaled position to treat disease, avoid illness, and genetically engineer crops. We have detailed descriptions of many of the molecules of life, whether they are individual protein molecules floating within a cell, the structure of itinerant viruses, or excerpts of the genetic blueprint, DNA. And we know that by manipulating these molecules, we can alter the course of life. It is largely because of the remarkable success of molecular biology that the reductionist doctrine has intoxicated the minds of so many scientists. Thus, the popular view has evolved that sees us as being totally controlled by our genetic complement, itself comprised of self-replicating molecules of DNA, in the way advocated by Richard Dawkins.[14]But while molecular biology is powerful, it is far from omnipotent. To find out more about the inherent complexity of life, we need to explore how it thrives on both self-organization and evolution. We need to explore how the myriad components of living processes mesh together, beginning with the search for the self-replicating chemistry that seeded life itself. At that critical moment when the watershed between inanimate and biochemical reactions was crossed, there is little doubt that self-organization played a crucial role. Life was no accident Like many other terms, such as order, disorder, emergence, consciousness, and intelligence, it is hard to define what we mean by life. One dictionary definition describes life as “the property shared by living things that differentiates them from non-living ones,” another calls it the “state of being alive.” Tautologies such as these are often used in desperation. However, biologists can list a whole set of features possessed by nearly all living things. As well as the ability to reproduce, these include the existence of genetic information, complexity, organization, and so on. But exceptions can always be found. For example, the ability to reproduce is not possessed by every object we might expect to call “living”: sterile men, postmenopausal women, mules, and viruses are all incapable of self-reproduction. Nonliving things also show some “vital” signs. Crystals, for instance, are capable of self-reproduction during growth. To define life, we should shift the emphasis away from surviving individuals and selfish genes toward evolving systems. Evolution is a property that belongs not to a single individual or gene but to a whole system, and does us the great service of pointing away from isolated units toward interactions between individuals and with their environment

The story of the universe is one of unfolding complexity. By emulating the processes that created the patterns and rhythms of the cosmos, science can tackle supposedly intractable problems, simulate the organization and activity of the brain, even create artificial worlds. Many people have accepted the reductionist message of contemporary science. Although sometimes powerful, reductionism can be destructively simplistic. Simpleminded reductionism maintains that the whole is nothing more than the sum of its parts, each of which can be studied in isolation. But this form of reductionism is seriously limited. Take the recent successful effort of deciphering the entire human genetic code, the human genome program. There will be many laudable benefits for medicine as the genetic errors that lead to hereditary disease are uncovered and predispositions to major killers such as heart disease, cancer, and dementia are associated with genetic markers. Yet profound dangers are also possible and none more so than in the field of behavioral genetics.[15] Life is an emergent property, one that arises when physicochemical systems are organized and interact in certain ways. Similarly, a human being is an emergent property of huge numbers of cells. And no one should doubt that our innermost thoughts, our emotions of love and hate, are more than a rush of individual hormones, or the firing of individual neurons in the brain.[16] The study of complexity, through its emphasis on emergent properties, goes some way to restoring a balance between the spiritual and materialistic sides of our nature.[17] An understanding of complexity can go a long way toward helping us to make sense of the world, by providing a more global view of our role in it.

Notes

[1] Irreversibility is an essential element of macroscopic complexity as demanded by the second law of thermodynamics. This law conflicts with other laws of microscopic physics, which describe only reversible phenomena.

[2] M. Gell-Mann, *The Quark and the Jaguar* (Little, Brown, Boston and London, 1994) 352

[3] This work is continuing at the Santa Fe Institute in New Mexico under the direction of Stuart Kaufmann.

[4] See P. Coveney and R. Highfield, *The Arrow of Time* (HarperCollins, London, 1991) chapters 4 and 8, for more details of the controversies surrounding the interpretation of quantum mechanics and the associated measurement problem.

[5] R. Penrose, *The Emperors New Mind* (Oxford University Press, 1989)

[6] C. Darwin, The Origin of Species by Means of Natural Selection (Penguin, Hammondsworth, 1968)

[7] J. Hudson, *The History of Chemistry*,(Macmillan, London, 1992) 104

[8] One of the enduring myths in chemistry is that vitalism was disproved in 1828 when Fridrich Wohler made urea synthetically. Vitalism did receive a setback in 1844 when Hermann Kolbe synthesized acetic acid from inorganic materials.

[9] The second law of thermodynamics says that any change in an isolated system will make it more disordered. Living organisms are not isolated systems. They take in energy and matter from their environment and use it to maintain order within their boundaries; the disorder

inexorably created in the process is then eliminated. Animals use oxygen and food as their inputs; plants harness carbon dioxide, oxygen, water and sunlight. The importance of this open system aspect of life was emphasized to physicists by Erwin Schrodinger in his book *What is Life?* (Cambridge University Press, 1944)

[10] H. Dietz, et al., *Nature* **352** 337 (1991)

[11] V. McKusick, *Nature* **352** 279 (1991)

[12] R. Achalya, E. Fry, D. Stuart, G. Fox, D. Rowlands, and F. Brown, *Nature* **337** 709 (1989)

[13] G. Binnig, W. Haeberle, F. Ohnesorge, D. Smith, H. Horber, and C. Czerny, *Scanning Tunneling Microscopy* "STM '91", Interlaken, Switzerland, August 1991, and W. Haeberle, J. Horber, F. Ohnesorge, D. Smith, and G. Binnig, *Ultramicroscopy* 42-44, 1161 (1992)

[14] R. Dawkins, *The Selfish Gene*, 2nd Ed. (Oxford University Press, 1989)

[15] S. Rose, *Nature* **373** 380 (1995)

[16] D. Dennett, Darwin's Dangerous Idea: Evolution and the Meaning of Life (Simon & Schuster, New York, 1995)

[17] I. Prigogine, and M. Sanglier (eds.), *The Laws of Nature and Human Conduct* (Brussels Task Force of Research Information and Study on Science, Brussels, 1985)