The Emergence of Everything: How the World Became Complex

Harold J. Morowitz

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Preface

This book began as an attempt to reify the concept of emergence by finding observed examples and looking for defining features and similarities. The emphasis was on emergences in nature as distinguished from the examples that can be generated almost without limit in computer modeling of complex systems. Rather than selecting cases at random, I chose a set that constituted a temporal array from the beginnings of the known universe to the most human of activities. These were somewhat arbitrarily divided into 28 cases. The intent was a more detailed view of the character of each emergence.

While pondering the cases I had chosen, I continued to peruse the journals *Science* and *Nature.* Almost every week I found at least one paper of significance in exploring one or more emergences. It became clear that the original goal was too ambitious. The detailed analysis of each emergence, while desirable, was far too unrealistic. I decided to settle for a broader view and try to get the "big picture" of emergences. Therefore, I apologize to the experts for such a fleeting view of each example. I am reminded of Herman Melville's description of his system of cetology: "The whole book is but a draft—nay, but the draft of a draft."

We are clearly at the beginning of viewing science from the new perspective of emergence. I believe that it will provide insights into the evolutionary unfolding of our universe, our solar system, our biota, and our humanity. This essay is to introduce some of the concepts that are coming into focus. The outlook is largely scientific, but certain more philosophical and theological elements keep appearing. I offer no apology. I have a deep belief in monism, a world ultimately comprehended by a unified path of understanding. It is the same world on Monday through Thursday as it is on Friday, Saturday, and Sunday.

This book owes a debt to everyone who has shared a dialog with me on the subject matter, to those who have read portions and commented, and to those who have shared the quest. I list the following, with some trepidation that other names have been momentarily overlooked: Ann Butler, James Trefil, Ann Palkovich, James Olds, Robert Hazen, Rob Shumaker, Barbara Given, Lev Vekker, Neil Manson, Karl Stephan, James Barham, Rob Waltzer, James Salmon, and Philip Clayton. My very special thanks go to Iris Knell: amanuensis, guardian of the Robinson professoriate, and she who would never split an infinitive.

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The Emergence of Emergence

The writer of Ecclesiastes who proclaimed that "The thing that hath been is that which shall be; and that which is done shall be done: and there is no new thing under the sun" was taking an extremely short-term point of view. He certainly failed to reckon that the sun itself was less than 5 billion years old in a universe probably dating back sometime over 12 billion years. He did not note that the kingdom in which he lived had only been around for a few hundred years, and changes in culture and government were constantly occurring.

This book on emergence deals with ways of thinking that are new under the sun: fresh perspectives for looking at the world that are accompanying the computer revolution, a new willingness of scientists to deal with complexity, and the very construct of emergence that provides a clue as to how novelty can come to be in a very old universe. In short, we are picking arguments both with the author of Ecclesiastes and with those who think about "the end of science." Something new and exciting is taking place in analytical thought, and it promises different ways of looking at philosophy, religion, and world-view.

When I was an undergraduate, I read the philosopher José Ortega y Gasset, who explained that science is that discipline that replaces the hard questions that we are unable to answer by simpler questions to which we are competent to seek solutions. Ortega y Gasset (1883–1955) was writing about the science and mind-set of his time, when the search for simplification and mathematical certainly took precedence over approaches to complexification, thus severely limiting the domain of the sciences. The invention and elaboration of high-speed computers over the last half-century has radically changed the questions we are able to ask and has altered how we choose to pose them. Let us look at how all of this came to be.

In order to appreciate the concept of emergence and the complexity framework within which it arose, we might first take a brief tour of the history of post-Renaissance science to sense how the precomputer mindset developed and how views constantly changed. We then turn to the causes of the substantial alterations of understanding that have come with the latest findings during the past few years.

We start with what many regard as the formal beginning of modern science, the mechanics of Galileo Galilei, that focused on space and time as the appropriate variables for the study of physics. The Italian savant derived the law of falling bodies and developed the concept of inertia. These were major conceptual alterations of existing views in a time of great intellectual change. Galilei also endorsed the heliocentric theory of Copernicus. His contemporary, Johannes Kepler, was able to deduce from the observational data of Tycho Brahe that the planetary orbits were shaped like ellipses having the sun at one of the foci. Kepler also found that a line (radius vector) joining any planet to the center of the sun sweeps out equal areas in equal lengths of time. His third law of planetary motion relates the squares of the orbital periods of planets (planetary years) to the cube of the mean distance from the sun.

These observed laws of planetary motion with the sun at one focus stood as empirical generalizations until Isaac Newton formulated the laws of motion, developed differential calculus, and postulated the universal law of gravitation between any two bodies. Using these generalized laws of mechanics and gravity, it was possible from first principles to derive Kepler's laws of planetary motion. This is simple enough physics that it is usually done in contemporary undergraduate courses. I recall the thrill of deriving the laws in my own undergraduate course in physical mechanics. The cherished textbook is still on my bookshelf. These results about planetary dynamics, available since the late 1600s, were enormously powerful, because they enabled one to make predictions of planetary trajectories on the basis of mathematical law. Observations then verified the predictions. This approach established the methodological framework of physical science for the next 300 years. Note that realizing the full power of Newtonian physics required the invention of calculus by Newton and independently by Leibnitz. This mathematical advance was required in order to generate numerical solutions. The relation of mathematics to science is a matter of special interest. There are those, myself included, who believe that high-speed computation is to biology and the social sciences what calculus was to physics. Computer science is the mathematically based or formal tool that seems to map best onto the structure of the questions asked by many modern natural sciences, and moves into the domain of the social sciences.

The success of Newtonian physics had a great impact in eighteenth-century thinking in any number of fields. Alexander Pope summed up many of these ideas when he wrote:

> Nature and Nature's law lay hid in night
> God said let Newton be! and all was light.

In astronomy, mechanics, and celestial mechanics, the Newtonian approach was carried forward by the French mechanists Laplace, Lagrange, D'Alembert, and others. In optics and electricity and magnetism, the 1800s saw the work of Gauss, Faraday, Maxwell, and Hertz establish the classical branches of those parts of physics. By the end of the nineteenth century, science was firmly in place with a certain completeness in a number of areas designated as classical physics. In those domains, the mathematical postulates and boundary conditions led to firm numerical predictions that could be checked against observation. The range of soluble problems was limited only by certain severe restrictions in the mathematics.

In biology, the nineteenth century saw two grand theories, one thoroughly reductionist and one of a different character. The first was the cell theory—all living matter is made of cells, and all cells come from previously existing cells. The science of histology was developed to visualize and analyze tissues in terms of cells, and physiological chemistry began to explain cells in terms of molecules. The second theory—evolution—was enigmatic because it analyzed the appearance of all species in terms of evolution from previous taxa but had no formalism other than an unclear and somewhat tautological theory of fitness to explain which species survived. A third theory, genetics, the analysis of the hereditary transmission of traits, would have illuminated the other two, except it took 40 years to be rediscovered in the early 1900s. The original work of Gregor Mendel had never found its way into the scientific mainstream, and it took a long time before others independently discovered the same laws of inheritance.

In the late 1800s, chemistry was unified by formulating the periodic table of elements as an empirical generalization. The picture was confused by debates about whether atoms were real or simply explanatory devices. This intense battle has, I believe, disappeared—for all theories consist of explanatory devices to predict phenomena, and "real" atoms are equivalent to the unknowable *"ding an sich"* (thing in itself) discussed by Immanuel Kant that underlies the phenomena. It is a symbolic argument between the positivists and the realists. The question doesn't have to be answered in order to proceed, but the argument persists.

Many of these issues regarding atomism came together in the life and suicide of the great Austrian physicist Ludwig Boltzmann in 1906. His biographer E. Broda wrote:

> A factor contributing to his death may have been his feeling that the atomic theory, for which he had fought throughout his life, was being pushed into the background. This opinion was expressed, for example, by his Leipzig student, Georg Jaffe. The influential Alois Höfler, a personal friend but philosophical opponent, wrote after Boltzmann's death in 1906: "The enemies of traditional atomism who were led by Ernst Mach liked to call him [Boltzmann] the 'last pillar' of that bold mental structure. Some even ascribed his symptoms of melancholia, which went back for years, to the fact that he saw the tottering of that structure and could not prevent it with all his mathematical skill.
>
> . . . It was tragic that opposition to the atomic theory contributed to Boltzmann's depressions, for it was precisely at the time of his death that the atomic theory achieved its greatest victories. Des Coudres wrote: "Here Boltzmann deceived himself to his own detriment. . . . And also the banner under which our young experimenters make their surprising discoveries—be it the ultramicroscope, the Doppler effect in canal rays, or the wonders of the radioactive substances—is the banner of atomism; it is the banner of Ludwig Boltzmann." By 1906 atomism had already weathered the period of lowest repute, thanks in large measure to the new experimental results.

These new experimental results were gathered together in 1913 in an extraordinary work, *Les Atomes,* by Jean Perrin. In perhaps the greatest triumph of connecting different approaches in classical science, Perrin focused on determining Avogadro's number, the presumably universal number of molecules in a gram molecular weight of a substance. Perrin reviewed 16 very diverse methods of determining the number, many of which he carried out experimentally in his own laboratory (See Table 1, below).

The methods chosen by Perrin are a mirror of the physics and chemistry

TABLE 1: VALUES OF AVOGADRO'S NUMBER

Phenomena Observed	$N/10^{22}$ (Avogadro's number)
Viscosity of gases (kinetic theory)	62
Vertical distribution in dilute emulsions	68
Vertical distribution in concentrated emulsions	60
Brownian displacement	64
Brownian movement: Rotations	65
Diffusion	69
Density fluctuation in concentrated emulsions	60
Critical opalescence	65
Blueness of the sky	65
Diffusion of light in argon	69
Black body spectrum	61
Charge as microscopic particles	61
Radioactivity: Projected charges	62
Helium produced	66
Radium lost	64
Energy radiated	60

of his time. The viscosity of gases can be calculated from the kinetic theory of gases and depends on the number of molecules per unit volume. Since this quantity is the number of moles per unit volume times Avogadro's number, the experimental value of viscosity yields the desired quantity.

The distribution of emulsions in a gravitational field is calculated by statistical mechanics and depends on the potential energy of the particles **mgh** (mass times gravitational acceleration times height) divided by the kinetic energy **kT** (Boltzmann's constant times the absolute temperature). Since Boltzmann's constant is the gas constant available from Boyle's law divided by Avogadro's number, its value determines the desired quantity.

The next three methods depend on measuring Brownian motion, the random migration of microscopic particles in a gas or liquid. (Robert Brown first observed this for pollen grains in water.) In 1905 Einstein developed a theory to explain this phenomenon that was based on molecular kinetic theory of liquids. By observing the trajectory of Brownian particles, Perrin was able to calculate the Boltzmann constant and hence Avogadro's number.

The next four methods are based on light scattering that is due to local fluctation of the number of molecules per unit volume. This leads to local fluctuation in the index of refraction and light scattering. (Among other things, this is responsible for the blue of the sky.) The fluctuation depends on the number of molecules per unit volume in the gas that is the number of moles per unit volume times Avogadro's number.

For a novel determination, Perrin went to Planck's famous 1901 formula for the spectral distribution of black-body radiation. It can be fit by two constants, **h,** the Planck constant, and **k,** Boltzmann's constant. The latter is, as noted, the gas constant divided by Avogadro's number, leading to an independent determination.

The next method is based on electrochemistry, where the charge per gram molecular weight of univalent ions has been determined and called the Faraday. With the first determination of the unit electron charge, it was clear that the Faraday divided by the charge on the electron was Avogadro's number.

For the last four values, Perrin turned to the newly discovered phenomenon of radioactivity from which he found four methods of determining the universal constant of Avogadro. One of these illustrates the phenomenon. In α particle decay, an ionized helium nucleus is ejected. The number of decays can be counted with a scintillation counter, the helium can be collected as helium gas, and the amount determined volumetrically. Thus,

decays/Avogadro's number = moles of helium.

By counting decays and determining moles of helium, Avogadro's number can be directly determined experimentally.

Perrin concluded:

> Our wonder is aroused at the very remarkable agreement found between values derived from the consideration of such widely different phenomena. Seeing that not only is the same magnitude obtained by each method when the conditions under which it is applied are varied as much as possible, but that the numbers thus established also agree among themselves, without discrepancy, for all the methods employed, the real existence of the molecule is given a probability bordering on certainty.
>
> The atomic theory has triumphed. Its opponents, which until recently were numerous, have been convinced and have abandoned one after the other the skeptical position that was for a long time legitimate and no doubt useful. Equilibrium between the instincts towards caution and towards boldness is necessary to the slow progress of human science; the conflict between them will henceforth be waged in other realms of thought.

Note that in all 16 cases, theory permitted one to carry experiments that gave rise to the numbers. The numerical agreement was the verification that validated the theories. This is a key feature to acceptance of a theory in classical physics.

The atomic theory is central to physics, chemistry, and biology. Just at the time Perrin was doing the experiments leading to *Les Atomes,* Einstein and Planck were doing the work that gave us relativity and quantum mechanics and a whole new view of the physical world. Bohr was simultaneously formulating the theory of the energy levels of atoms. Before going on to this new world, let's review where science stood at the beginning of the twentieth century.

Mechanics, electricity and magnetism, optics, hydrodynamics, thermodynamics, kinetic theory, and celestial mechanics were solidly established as the firm foundation of physics. Biology was beginning the great age of genetics, and physiology was searching for its chemical roots. Organic chemistry was finding explanation in the tetrahedral geometry of carbon bonds, and organic synthesis was being extended to a wide variety of new products. Discoveries of the structure of sugars, amino acids, and nitrogen heterocycles were providing a firm basis for biochemistry. A general but not universal agreement was beginning to arise that biology could be reduced to chemistry, which could be reduced to physics.

The often unstated philosophy of science was based in its various forms on starting with observation, developing theoretical explanations of the observations, and using these to predict other observations. The success or failure of the predictions provided the epistemological roots of any science. The paradigm example of this kind of science was the study of the solar system, where future trajectories of planets could be predicted with great accuracy. The social and cognitive disciplines were viewed in a totally different domain than the physical and chemical sciences. Biology stood between them, looking in one direction toward chemistry and in the other toward ethology and anthropology.

There were some attempts to bridge the gaps. Economists in the late 1800s had discovered thermodynamics and were attempting to use the mathematics of that science as a framework to develop theory; however, the approach lacked the predictive power of physics.

The general approach to the philosophy of science followed through for the twentieth century. Two books outline the general approach: *The Logic of Scientific Discovery* (Karl Popper, 1934) and *The Nature of Physical Reality* (Henry Margenau, 1950). Popper provided a prescriptive approach for the logical requirements for a subject to be an empirical science. Margenau provided a descriptive approach of the intuitive metaphysical assumptions that physicists make in formulating and accepting a physical theory.

Both approaches start with the observable world and move to the formulation of a theory, usually mathematical, to explain relations among observables. The theory then makes predictions about other observables and is tested by comparing predictions with observations. The theory stands or falls on the agreement or disagreement, usually numerical, between prediction and observation. It is difficult to put the theory of evolution in this context, so that biological science did not fit this epistemic scheme nearly so well as physics, a failing constantly stressed by the ideological enemies of "evolution." When we discuss the emergent nature of evolution, it will be clearer why biological science did not fit the simplified scheme.

Both Popper and Margenau dealt with the subject of the epistemology of science: "How do we know?" This kind of inquiry had been established by Immanuel Kant in his critiques. It has not been a popular subject in science, and less so in religion where knowledge by faith is the ultimate test. I consider epistemology crucial to our understanding.

In science we start with the immediately given, the sense data that are of course the contents of minds. From these sense data that are shapes, colors, sounds, feels, and meter readings, we develop theoretical constructs such as solid objects, atoms, electrons, and probability waves. The constructs, as Kant points out, are not the incompletely knowable "thing in itself," but deal with the contents of our minds. Science starts with the mind, both the perceiver of sensations and the postulator of constructs. Science also assumes a community of minds who can agree on the sense data and the verifiability of consequences of the constructs. Regardless of one's philosophical position, science begins with the mind and is a public activity. Constructs have a hierarchy from quarks to atoms to molecules to organisms. The contemporary position of most neurobiologists is to try to go up the hierarchy from atoms to minds to understand the emergence of mind in terms of the underlying members of the hierarchy.

This of course presents an epistemic circle. One starts with mind as the primitive and goes around the circle of constructs in an effort to explain mind. I have no trouble with this circularity, but it comes as a surprise to many scientists. It is an epistemology that somehow accords with the emergence view of the evolving universe, or at least our part of it.

In terms of this view, one can understand materialists or naïve realists as individuals who believe that the constructs of particles are more real than the minds that constructed them. Idealists in the philosophical sense are individuals who believe that the minds are more real than the hierarchy of things that constitute the world out there, the things in themselves. I find both views much less enlightening than accepting the circle as the ontological sequel of this type of epistemology. It recognizes the existence of the world out there without requiring people, but also recognizes that the kind of knowledge we have of that world is not independent of us, and we will never have God's knowledge of the thing in itself.

In my series of hierarchical emergences, I operate without commitment to an ontology, which may be unknown, but I do adopt the epistemology that has made physics work. However, in understanding the new views of emergence, we will find this epistemology will require some developments that have not yet been discussed.

A sharp distinction is often drawn between the immediately given sensory inputs and the rational constructs. These distinctions are quite fuzzy, and the mind operates with both, often without a sharp distinction so that observations already have a theoretical component, and constructs are often not far from the immediately given. This need not cause philosophical problems; the world is what the world is. The clear distinction between mind and nature simply does not exist.

Two developments in physics at the turn of the century were harbingers of ideas whose full philosophical significance would not be generally appreciated for almost 100 years. The central concepts of emergence trace back to the statistical mechanics of Ludwig Boltzmann, James Clark Maxwell, and Josiah Willard Gibbs. The main idea of deterministic chaos was formalized in the work of Henri Poincaré on the stability of the solar system.

The founders of the statistical mechanics assumed the atomic molecular view of matters and further posited that the atoms and molecules obeyed the laws of mechanics. They were then interested in showing how the macroscopic laws of thermodynamics and kinetic theory could be obtained from the mechanics of the reductionist agents, the atoms and molecules. By dealing with ensembles of particles or ensembles of states and showing that the macroscopic observables were averages over microscopic states, they were able to deal with variables like pressure and temperature as emergent properties. Thus while Perrin and others were pursuing the development of the reductionist view of atoms and molecules as the operative agents, the statistical mechanicians were showing that the microscopic particle view led to the macroscopic laws of thermodynamics in terms of emergent properties. This is a model that we should keep in mind in going back and forth between reductionism and emergence in the study of hierarchical levels.

Thus, while statistical mechanics has some features similar to modern emergence theory, in one very important way it is totally different. In the Gibbsean approach, one assumes that the time average of a behavior of a simple system is equal to the average of a whole ensemble of possible entities chosen to represent the system of interest; thus, the pruning rules force the behavior to converge about the mean, rather than the divergence that sometimes occurs in the nonequilibrium systems we study in contemporary examples of emergence. The solution to the seeming paradox is that the classical case deals with the unique state of equilibrium, which is a global extremum and sits at the bottom of an energy well. Complex systems are generally far from equilibrium and are represented mathematically by rugged landscapes in a phase space. There is a radical difference between equilibrium and nonequilibrium systems. The latter cannot be treated by global extrema, a mistake often made by those who haven't focused on how different the two cases are and assume they can derive biological behavior as extrema.

Henri Poincaré was a French mathematician in the tradition, going back to Isaac Newton, of the mathematical study of the workings of the solar system, the orbits of planets, and more detailed considerations. When we celebrated the triumph of the law of Newtonian mechanics and gravity predicting Kepler's laws of planetary motion, we ignored a problem in the approach that Poincaré subsequently considered.

The Keplerian laws and the Newtonian explanation came from dealing with only two bodies, the Earth and the sun. When later theoreticians tried to include the moon and the other planets in the calculation, they discovered a severe problem. For systems of three or more bodies, exact analytical solutions to problems in mechanics were not possible. The difficulty was deep within the mathematics employed. Following Newton, generations of mathematicians tried unsuccessfully to solve the three-body problem analytically, and they all failed.

A parallel difficulty was seen in the study of the stability of the solar system. Were the orbits of the planets fixed for all time, or would they change in some unknown way? In the late 1800s Poincaré undertook the problem and discovered certain uncertainties in celestial dynamics that we would now designate as deterministic chaos. It was not possible to predict the orbits for all time. One hundred years later, Poincaré's finding became central to chaos and complexity theory.

The physics of the nineteenth century viewed the scientist as an observer removed from the operation of the system under study. This changed in three ways in the first half of the twentieth century. First, the special theory of relativity referred all measurement to the frame of reference of the inertial system of the *observer,* thus more closely relating the scientist to the system of study. Second, one view of quantum mechanics reduced a probability distribution function to an event when an observation was made by a classical observer. This made the scientist as observer a necessary part of the system under study. Lastly, information theory identified entropy with a measure of the observer's ignorance of which microstate a given system was in when the macroscopic state was known. The probabilistic nature of quantum mechanics fuzzed out the firm nature of physical reality that characterized classical physics. All of this was nevertheless consistent with the epistemic loop from observation to theory to observation that characterized most of reductionist science, but established a special role for the observer.

Biology, which began the twentieth century as an observational science to classify organisms and place them on an evolutionary tree, became over the next century the most reductionist, atomistic, and structural discipline of all the sciences. Molecular biologists reduced all process to the operation of known chemical structures. Molecular biology, symbolized by the double helical structure of DNA, achieved enormous success, the ultimate in what one could achieve with this approach to science. Only when one got to neural or cognitive science was it necessary to return to the problem of the observer in biology.

An example of what one can and cannot do in the context of reductionist molecular biology is helpful. If we have a purified protein, we can cause it to form into crystals, and by X-ray diffraction we can determine the precise three-dimensional structure, atom by atom. Now suppose we have the amino acid sequence of a protein derived from knowing the DNA sequence of the gene that codes for it. We wish to calculate structure from sequence. Assume we have all the interaction energies as a function of distance between various amino acids, and we wish to calculate the configuration of minimum energy. There are so many possible configurations that a computer the size and age of the universe cannot enumerate all the possibilities. Such calculations we designate as transcomputable.

We need ways of doing or short-circuiting such a calculation by selecting or pruning or radically eliminating most of the states. The emergent solution gives some idea of the route to the folded state. Selection algorithms are required to reduce the dimensionality of the problem to something that can be comprehended.