

EMERGENCE



FROM CHAOS

TO ORDER

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CHAPTER 1

Before We Proceed

A WONDROUS vine emerges when Jack plants the seed for his beanstalk, and it unfolds into a world of giants and magic harps. When we were children, Jack's miraculous beanstalk wasn't so far removed from the everyday miracles of fall colors and germinating seeds. Now that we're grown, seeds still fascinate us. Somehow these small capsules enclose specifications that produce structures as complicated and distinctive as a giant redwood, the common day's-eye (daisy), and a beanstalk. They are the very embodiment of emergence—much coming from little. Nowadays we know that genes in the seed specify a step-by-step unfolding of biochemical interactions, but only fragments of this complex process are clearly understood. Indeed, it is evident that we will not truly understand genes and chromosomes until we understand the gene-specified interactions that take a seed, or a fertilized egg, to a mature organism. In short, we will not understand life and living organisms until we understand emergence.

We can contemplate emergence in another guise if we turn to a seemingly unrelated arena, that of board games. Agreement on a few rules gives rise to extraordinarily complex games. Chess is defined by fewer than two dozen rules, but humankind continues to find new possibilities in the game after hundreds of years of intensive study. As with the seeds, much comes from little.

In a still different arena, Newton's laws of gravity, or Maxwell's equations describing electromagnetic phenomena, have much in common with the definition of a game. Their equations describe the "rules" of games in which "moves" can be made with the help of the tools of mathematics. These moves take us to new equations

and mathematical statements that are consequences of the defining equations. As in the case of games, we uncover possibilities quite unsuspected by the authors. Newton could not have guessed that his equations would reveal the gravity-assisted boost that takes space probes to the outer planets, and Maxwell, for all his insight, could not anticipate that his equations would make possible the exquisite control of electrons that is the sine qua non of electronic devices. Like Jack's beanstalk, these equations reveal marvels. Indeed, much of our understanding of the physical world emerges from a small corpus of fundamental equations built on the foundations laid by Newton and Maxwell.

The hallmark of emergence is this sense of much coming from little. This feature also makes emergence a mysterious, almost paradoxical, phenomenon smacking of "get rich quick" schemes. Yet emergence is a ubiquitous feature of the world around us. Mundane activities such as farming depend on rules of thumb for emergence—for example, knowing the conditions that influence the germination of seeds. At the same time, human creative activity, ranging from the construction of metaphors through innovation in business and government to the creation of new scientific theories, seems to involve a controlled invocation of emergence.

We are everywhere confronted with emergence in complex adaptive systems—ant colonies, networks of neurons, the immune system, the Internet, and the global economy, to name a few—where the behavior of the whole is much more complex than the behavior of the parts. There are deep questions about the human condition that depend on understanding the emergent properties of such systems: How do living systems emerge from the laws of physics and chemistry? Can we explain consciousness as an emergent property of certain kinds of physical systems? We will not know the limitations of scientific answers to questions like these until we understand the whys and wherefores of emergent phenomena. The central objective of this book is to provide convincing evidence that scientific investigation will greatly increase our understanding of emergence.

Where Are We Going?

Despite its ubiquity and importance, emergence is an enigmatic, recondite topic, more wondered at than analyzed. What understanding we do have is mostly through a catalog of instances, augmented in some cases by rules of thumb such as "Place the seed in damp soil" or "Get your major pieces in action." Indeed, our present understanding of emergence is often little better than the child's invocation of Jack Frost to explain the wondrous colors of autumn. Such an explanation stirs our imagination but is ultimately unsatisfying. Our instinct is to start looking for a deeper explanation, an explanation that may go as far as the molecular biologist's contemplation of the tangled biomolecular interactions that produce autumn changes. The deeper explanation, once understood, inevitably gives the imagination an exhilarating boost. But just what is it that is being investigated?

It is unlikely that a topic as complicated as emergence will submit meekly to a concise definition, and I have no such definition to offer. I can, however, provide some markers that stake out the territory, along with some requirements for studying the terrain.

First of all, I will restrict study to systems for which we have useful descriptions in terms of rules or laws. Games, systems made up of well-understood components (molecules composed of atoms), and systems defined by scientific theories (Newton's theory of gravity) are prime examples. Emergent phenomena also occur in domains for which we presently have few accepted rules; ethical systems, the evolution of nations, and the spread of ideas come to mind. Most of the ideas developed here have relevance for such systems, but precise application to those systems will require better conjectures about the laws (if any) that govern their development.

There may be other valid scientific uses for the term "emergence," but this rule-governed domain is rich enough to keep us fully occupied. This book will demonstrate again and again that a small number of rules or laws can generate systems of surprising complexity. Moreover, this complexity is not just the complexity of random patterns. Recognizable features exist, as in a pointillist

painting. In addition, the systems are animated—*dynamic*; they change over time. Though the laws are invariant, the things they govern change. The varying patterns of the pieces in a board game, or the trajectories of baseballs, planets, and galaxies under Newton's laws, show the way. The rules or laws *generate* the complexity, and the ever-changing flux of patterns that follows leads to *perpetual novelty* and emergence. Indeed, in most cases we will not understand these complex systems until we understand the emergent phenomena that attend them.

Recognizable features and patterns are pivotal in this study of emergence. I'll not call a phenomenon *emergent* unless it is recognizable and recurring; when this is the case, I'll say the phenomenon is *regular*. That a phenomenon is regular does *not* mean that it is easy to recognize or explain. The task can be difficult even when the laws underpinning the dynamics are known. In chess it took centuries of study to recognize certain patterns of play, such as the control of pawn formations. Once recognized, these patterns greatly enhance the possibility of winning the game. Similarly, it took centuries of study to extract some of the dynamic patterns inherent in Newton's laws, such as the gravitational boosts used in planetary exploration. And still we learn.

Understanding the origin of these regularities, and relating them to one another, offers our best hope of comprehending emergent phenomena in complex systems. The crucial step is to extract the regularities from incidental and irrelevant details. For example, we may use an idealized form of billiards to gain insights into the way colliding molecules in a gas give rise to measurable regularities such as temperature and pressure (more about this in Chapter 9). Or we may use a mathematical description of poker to discern the complexities of political negotiations. This process is called *modeling*.

Although model building is not usually considered critical in the construction of scientific theory, I would claim that it is. Every time a scientist constructs a set of equations to describe the world, such as Newton's or Maxwell's equations, he or she is constructing a model. Each model concentrates on describing a selected aspect

of the world, setting aside other aspects as incidental. If the model is well conceived, it makes possible prediction and planning and it reveals new possibilities. Because modeling is so important to this study, the next section provides a prologue about modeling. Then, in Chapter 2, we look more closely at scientific modeling by examining games and maps as historical antecedents. Chapter 3 adds dynamics by looking more carefully at games and the complex models made possible by computers. As the book unfolds, modeling will be a recurrent topic.

The possibilities for emergence are compounded when the elements of the system include some capacity, however elementary, for adaptation or learning. In Chapter 4 we look at a *learning* checkersplaying program, which still eclipses most later work when questions of emergence are foremost. This program *learned* to beat its designer—clearly a case of more coming out than was put in. It did this by making small, experience-based changes in its elements, and it finally extended its abilities to the point of playing at tournament level. The program is fully reducible to the rules (instructions) that define it, so nothing remains hidden; yet the behaviors generated are not easily anticipated from an inspection of those rules.

It is tempting to take the inability to anticipate—surprise—as a critical aspect of emergence. It is true that surprise, occasioned by the antics of a rule-based system, is often a useful psychological guide, directing attention to emergent phenomena. However, I do not look upon surprise as an essential element in staking out the territory. In short, I do not think emergence is an “eye-of-the-beholder” phenomenon that goes away once it is understood.

We can get a better idea of what exists beyond the eye of the beholder if we think of the generators of emergent behavior as *agents*. The classic description of agent-based emergence is Douglas Hofstadter's 1979 metaphor of the ant colony. Despite the limited repertoire of the individual agents—the ants—the colony exhibits a remarkable flexibility in probing and exploiting its surroundings. Somehow the simple laws of the agents generate an emergent behavior far beyond their individual capacities. It is

noteworthy that this emergent behavior occurs without direction by a central executive. The simulated neural networks of Chapter 5 supply another example. These networks, constructed by modeling the interconnection of large numbers of simulated neurons, provide an interesting contrast to the checkersplaying program, while still exhibiting clear-cut emergent phenomena.

The combined lessons learned from the checkersplayer and the neural networks lead us to a setting that mimics an idea dating back to classical Greece. The Greeks set forth the idea that all machines can be constructed by combining (copies of) six elementary mechanisms (the lever, the screw, the inclined plane, the wedge, the wheel, and the pulley). Herbert Simon, three decades ago in 1969, refined this notion in a way that has a direct bearing on our objectives: his watchmaker tale illustrates the advantage of constructing a watch by first constructing subassemblies of elementary mechanisms, which are later combined into larger assemblies, which in turn are assembled to yield the watch. We can understand, and manipulate, complex systems more readily within such a setting.

Here I use these insights to gain a setting that lets us look at complexity and emergence in terms of mechanisms and procedures for *combining* them (Chapter 7). To do so, we have to extend the idea of mechanism beyond the overtly mechanical. We thereby come closer to the physicist's notion of elementary particles as mechanisms for mediating interactions, as when a photon causes an electron to jump from its orbit around an atom. Mechanisms so defined provide a precise way of describing the elements (agents), rules, and interactions that define complex systems. The setting that results gives us a common way of describing the diverse rule-governed systems that exhibit emergence.

The first benefit of this setting is that we can compare quite different systems and models that exhibit emergence. Therein lies our hope of finding similarities and common rules or laws. With diligence and good fortune, we should be able to extract some of the "laws of emergence." Chapter 8 initiates this process by describing the checkersplayer, central nervous system (CNS) models, and Copycat (an insightful computer-based model of the analogy-

making process) within this general setting. The setting makes it obvious that these systems have mechanisms in common, though they are quite different in detail. In particular, we see that mechanisms for recombination of elementary "building blocks" (recall Simon's subassemblies) play a critical role in all three systems. Furthermore, we find that (a) the component mechanisms interact without central control, and (b) the possibilities for emergence increase rapidly as the flexibility of the interactions increases.

These insights focus attention on agent-based models, where mobile "mechanisms" (agents) interact with and adapt to each other. Chapter 9 modifies the setting of Chapter 7 to allow the mechanisms themselves to modify the pattern of interactions, through adaptation to each other. This extended setting encompasses a new set of examples of emergence, from the miniature universes called cellular automata to the billiard-ball models mentioned earlier. By analyzing these examples in the extended setting, we gain a deeper understanding of the critical role of subassemblies in fostering emergence.

The new examples also demonstrate that emergence usually involves patterns of interaction that persist despite a continual turnover in the constituents of the patterns. A simple example is the standing wave in front of a rock in a white-water river. The water molecules making up the wave change instant by instant, but the wave persists as long as the rock is there and the water flows. Ant colonies, cities, and the human body (which turns over *all* of its constituent atoms in less than two years) offer more complex examples. These emergent macropatterns that depend on shifting micropatterns make emergence fascinating, and difficult to study.

Persistent patterns at one level of observation can become building blocks for persistent patterns at still more complex levels. The subassemblies of the watch in Simon's example illustrate the point in a static framework: the elementary mechanisms known to the Greeks—a lever, a wheel, and so on—are the building blocks for the mainspring subassembly. That subassembly is combined with other similarly formed subassemblies, such as the gearing of the watch hands, to form the complex system known as a watch.

At each level of observation the persistent combinations of the

previous level constrain what emerges at the next level. This kind of interlocking hierarchy is one of the central features of the scientific endeavor (see Table 1.1). It will lead us into, and out of, the thorny thicket known as *reduction*—roughly, the idea that we can reduce explanations to the interactions of simple parts. Because we are dealing with emergence in rule-governed systems, reduction has much to do with our exploration. Reduction has been repeatedly examined in philosophy, and sometimes in the other humanities, but its connection to rule-governed emergence has not usually been a facet of these examinations (with some important exceptions—see for example Daniel Dennett’s *Darwin’s Dangerous Idea*). Chapter 10 examines the creative aspect of reduction as it applies to emergence. Here we see that emergence in rule-governed systems comes close to being the obverse of reduction.

Another point is closely related to the creative side of reduc-

Table 1.1

A typical hierarchy of interlocking scientific descriptions. Mechanisms at each level are based on mechanisms at the previous level.

SYSTEM (SCIENCE)	TYPICAL MECHANISMS
Nucleus (physics)	Quarks, gluons
Atom (physics)	Protons, neutrons, electrons
Gases and fluids (physics)	
confined (e.g., a boiler)	PVT (pressure/temperature/volume), flows
free (e.g., weather)	Circulation (fronts), turbulence
Molecule (chemistry)	Bonds, active sites, mass action
Organelle (microbiology)	Enzymes, membranes, transport
Cell (biology)	Mitosis, meiosis, genetic operators
Organism (biology)	Morphogenesis
Ecosystem (ecology)	Symbiosis, predation, mimicry

Mechanisms from lower levels provide constraints and suggest what to look for at higher levels. Proposed additions at any level must be consistent with observations at all levels.

tion. The building blocks of a watch have been familiar since the time of the Greeks, but the watch is an innovation that has been with us for less than two centuries. Why was the watch so slow to emerge when the building blocks are so familiar? Here we come upon a central point about model building, innovation, and the study of emergence: building a model, or developing a theoretical construct in science, is *not* a matter of deduction. The standard deductive presentation of theoretical constructs in science hides the earlier, metaphor-driven models that lead to the constructs.

Earlier, I mentioned the billiard table as a model—a metaphor—for the colliding molecules in a gas. Chapter 11 begins with James Clerk Maxwell’s use of a mechanical metaphor to increase his understanding of electromagnetic fields. The whole question of model building and the use of metaphor in the study of emergence is shadowed by a larger question: how do scientists discover the laws and mechanisms that are so effective in uncovering the hidden order in our universe? Scientists rarely discuss this aspect of their work, though Maxwell is a glorious exception. Chapter 11 brings out the close relation between the construction of metaphors and the construction of models. Together, Chapters 10 and 11 place the book’s earlier discussion of model building and emergence in the larger arena of creation and innovation.

This quick tour of the chapters to come should make it obvious that the terrain of emergent phenomena is convoluted. Nevertheless, certain terms can serve as landmarks. Watch for:

- *mechanisms* (building blocks, generators, agents) and *perpetual novelty* (very large numbers of generated configurations)
- *dynamics* and *regularities* (persistent, recurring structures or patterns in generated configurations)
- *hierarchical organization* (configurations of generators become generators at a higher level of organization)

And *model building*, the subject of the next section, underpins the whole venture.

In the final chapter we look again at the ground we’ve covered and work out a map of the landmarks and core concepts. We see

how the general setting developed in the middle of the book resolves some of the mysteries associated with emergent phenomena in complex systems. We also look at the mysteries that remain, and at the approaches the general setting suggests for resolving those mysteries.

Models

From earliest times, human endeavor has been directed toward discovering ways to channel a chaotic world. In the beginning
 → we rule-bound sacrifices to the gods—we modeled the world in terms of personalities and ways of propitiating those personalities. Later, we discovered mechanisms (gates, pumps, and wheels) and ways of using them to control parts of the world, and we began to model the world with mechanisms instead of personalities.
 → Eventually, we arrived at complex computer-controlled devices and models, and scientific models that employ abstract mechanisms. Despite this pervasive use of models, the art of model building is not a familiar topic, even to many practicing scientists. We return to the topic again and again, treating it with increasing sophistication as the book progresses.

Among living forms on earth, the construction of objects and scripts that serve as models is a uniquely human activity. The models may be small—the early Egyptians produced exquisite miniatures of animals and boats—or they may be large—that huge immobile arrangement of monoliths, Stonehenge, can model the passage of seasons. It is less apparent that models are a pervasive part of day-to-day activity. Driving to or from work is model directed; we have a kind of internal map of the principal landmarks and turning points along the way. We are typically unaware of this map until we have to search for an alternate route because of construction or traffic. In that search we carry out a virtual experiment, rather than actually testing the alternative routes. Herein lies a major value of models: we can anticipate consequences without becoming involved in time-consuming, possibly dangerous, overt actions. Even scale models (model ships, model planes,

model railroads, and so on) enable us to make measurements that would be awkward otherwise. We can use the scale of a model ship to determine the distance on the real ship between the top of the mast and the tip of the bowsprit. Model planes grow into the models used in wind tunnels to determine flight characteristics. Indeed, as we'll see later, models are indispensable to careful experiment.

The word “model” is used with connotations that go beyond maps and scale models, and the word has been so used for some time:

When we meane to build, We first survey the Plot, then draw the Modell.

(Shakespeare)

A [model is] a tentative ideational structure used as a testing device.

(American Heritage Dictionary)

It is this broader usage that plays a key role in the study of emergence. A model need bear no obvious resemblance to the thing being modeled. Newton's equations, as symbols confined to a sheet of paper, look not at all like the orbits of planets around the sun. Yet they model this physical reality in ways that no scale model of the solar system could achieve. Today we go further, programming computers to model real or imagined situations. The examples range from video games to highly detailed flight simulators. We'll soon see how this is done, but for now simply note that models, above all, make anticipation and prediction possible.

For most of us model building starts at an early age. As children we use building blocks to generate concrete realizations of our imagination—castles and space stations. This facility for recombining standard objects to make new items carries over into later occupations. A watchmaker uses familiar mechanisms—gear wheels, springs, pinions, and so on—to generate marvels of timekeeping, and a scientist does the same thing at a more abstract level, generating complex objects, such as molecules, from simpler objects, at-