Dynamical Psychology:
Complexity, Self-Organization and Mind

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CHAPTER 1
Introduction—What Is This Book About?

Dynamics, Complexity, Self-Organization and Mind

The world is a complicated place. Obviously we haven't figured it all out yet. However, we certainly have come a long way. Modern science and technology have yielded a remarkable understanding and control of the physical universe. A person transported in time from the beginning of even the 19th century to now would be in awe of humankind's current achievements.

But let's not get carried away. There are still many fundamental mysteries that have yet to be solved. One of these is very close and personal. In fact, you are using it right now. It's called the human brain and much about the way it operates is still a mystery. Part of what makes the brain so hard to understand is its dynamic nature. Brains are never the same from one instance to the next. Messages are always being sent back and forth between billions of cells in an intricate dance. This activity is what gives rise to our mental selves. It underlies what we see, think, and feel.

It is difficult to get a handle on this activity in part because of its complexity. There are an estimated 100 billion neurons in the human brain. Each of these can have as many as ten thousand connections to other cells. At any given time, there are multiple patterns of activation that course through this network. These patterns are constantly changing in response to the environment and to each other.

This complexity is compounded by the fact that brain processes are simultaneously happening at many different spatial and temporal scales. At the level of the neuron, neurotransmitter molecules are being packaged, released and recycled, in some cases, many times a second. At the level of a society, brains make decisions that affect how we interact with each other. Is there an appropriate level of organization that we should study? One theme of this book is that we must study complex phenomenon at multiple levels. No level is privileged. What's more, we need to fathom the connectivity between these levels. No complex system can be fully understood by focusing only on one level, it is often the coordination and interaction between levels that yields new and interesting insights.

Another problem with studying complex systems has to do with organization. Many natural processes seem to develop and organize themselves. There is no single external "boss" to tell a brain how to grow or what to do. The brain figures it out on its own. This runs counter to traditional conceptions in psychology and cognitive science, where there is a central executive or processing unit that monitors ongoing functions, issues commands and generally keeps things operating smoothly.

When we look at nature, we can never seem to find this boss. Nature instead builds and operates using the principles of self-organization by which systems come into existence and function under their own command. The interaction of parts with each other and with the environment is enough to give rise to ordered behavior. These processes are an integral part of who we are. They are taking place in the chemical reactions inside our cells, governing how our cells grow and differentiate during development, and probably underlie mental and conscious phenomena. To explain the mind we therefore need to understand self-organization.

So far we have touched on several themes. These are change over time, intricacy, and how ordered behavior emerges and operates. Each of these themes corresponds to a particular scientific-theoretic approach; namely, dynamics, complexity, and self-organization. In this book, we discuss these approaches in great detail and then apply them to the study of mind. Separate chapters are devoted to each, where we first introduce the topic from a theoretical standpoint and then examine how it helps us to understand mind.

Networks and Neurodynamics

The brain is a network made up of units and connections between them. There are many other examples of complex networks, both natural and man-made. The society we live in is a network, made out of individuals that move around and exchange information. The Internet is also a network. In recent years we have seen the development of a new approach to the study of networks. Called network science, researchers in this discipline attempt to understand the abstract principles by which networks operate.

After introducing the ideas of dynamics, complexity, and self-organization, we therefore next turn our attention to the study of networks. We start by examining Boolean networks, whose nodes operate in a very simple way, but whose overall behavior when wired up together is quite complex. We then examine random graphs, whose nodes are connected randomly but which still display ordered and interesting behavior. Following this, we discuss how self-organizational processes can lead to ordered connectivity, even in networks that are mostly random to start.

One problem in networks is how activity gets coordinated, especially if there is no "leader". How for example, does a message spread from one part of a net to another? We look at different ways that this can occur, along the way discussing networks like corporations and the human brain that show hierarchical organization.

A fascinating discovery, first noted by social psychologists some years ago, but only recently studied with more rigor, are small-world networks. In these nets, any two nodes can communicate with one another through a small number of connections, even though the number of nodes can be very large. In popular culture, this phenomenon is referred to as "degrees of separation". We look at the scientific study of small-world networks and what the implications of these findings are for mental processing.

It turns out, perhaps not unsurprisingly, that brains are small-world networks. This makes sense, because animals need to react quickly in order to survive. If information has to flow through too many connections, reaction times are slow and the proverbial tiger will eat you before you can react quickly enough. A number of other interesting properties can be instantiated in small-world networks, including signal synchronization and collective computation.

With this foundational knowledge in mind, we turn next to the specifics of how brain networks operate. The focus is on dynamical activity inside neural networks, what we call neurodynamics. Neurons are oscillators because they exhibit repetitive wave activity. We look at neural oscillation and how this can code for information. Then we summarize some of the research on synchrony and coupling, the means by which brains coordinate their activity between different regions. Another interesting feature of brain networks is metastability, a state that allows both for pattern formation and dissolution. Metastability may explain many cognitive processes like memory and free association.

Levels of Organization, Fractals and Noise

Classical methods in science have been useful at getting nature to reveal her secrets. Traditional science adopts an analytical and reductionist approach. It takes a whole such as the brain and breaks it down into its component parts. Once we know what the parts are and how they work, we can then figure out how they combine and interact to produce the behavior of the whole they make up.

Unfortunately, many wholes in nature defy reductionist explanation. The behavior of these wholes, to borrow a phrase from the Gestalt psychologists, is "more than the sum of their parts". There are several reasons for this. The sheer number of parts and the possible ways they can combine is vast in even moderately complex systems. Another obstacle has to do with our conception of what a whole is. Many investigators draw arbitrary lines around what they investigate. They agree to study a certain aspect of a whole, such as a neuron, person, or society, while neglecting that the "piece" they look at is both part and parcel of larger and smaller systems respectively.

The holistic emergent paradigm arose in reaction to these problems. In this approach, one takes care to examine interactions between levels and to consider any phenomenon in light of the other systems of which it is a part. In this book, we favor neither the reductionist or emergent perspectives. Rather, we advocate that both approaches are necessary to understanding complex systems. They must be used in conjunction with one another as part of a proper cognitive science. However, we spend more time examining the emergence perspective because it is newer and has yet to be applied in the same general and systematic way as its reductionist cousin.

A fractal is a pattern that is self-similar at different scales. Fractals exist everywhere in nature. We describe what fractals are and summarize some of the literature on psychology and fractals. This literature includes magnitude estimation, perception of fractal stimuli and aesthetic judgments. The brain has a very definite fractal organization, so we describe this activity and how it relates to mind and human nature.

A persistent problem in statistics and research methods is what to do with noise. Traditionally noise has been treated as error, the proportion of variance in the dependent variable that cannot be accounted for by the manipulation. A dynamical account views noise very differently. In this view, noise should be studied as it reflects some mechanism or aspect of the system under investigation. So we next describe sources of nervous system noise, different types of noise, including white, pink, and brown noise, and how they can account for neural and cognitive processes.

Dynamical Psychology and Cognition

The scientific study of how complex systems like the brain change is called dynamical systems theory, although it is has also been referred to as chaos theory. This relatively new paradigm provides us with a novel theoretical orientation and a set of tools and techniques that we can apply to things like the mind and understand them better. Unfortunately, psychologists do not seem ready for it just yet. In the section on dynamics and psychology we mention a number of reasons for this. We then summarize dynamical theory and practice for several major areas of the discipline, including development, social behavior, and industrial and organizational psychology. The amount of research that has gone into clinically relevant fields requires a separate chapter on personality, pathology and therapy.

Perhaps the greatest application of dynamical ideas in psychology has occurred in the cognitive area. There is much to talk about here. The dynamical approach forces us to rethink our traditional notions of representation, concepts and learning. We contrast classical views in cognitive science with the dynamical approach. Classical cognitive science advocates a mind that is modular, component-dominant, closed and feed-forward. The dynamical account sees mind instead as distributed, interaction-dominant, open, and recurrent. The recurrence theme is a particularly important one, so we describe several theories of cyclical processes in cognition.

This is followed by an in-depth analysis of studies in different areas of cognition. Each area corresponds to a distinct form of cognitive processing. We cover visual perception, including perception of ambiguous figures, Glass patterns and apparent motion. Then we look at attention in a temporal context. Following this we examine dynamical processes in memory, looking at the stability-plasticity issue. Language has been analyzed from the dynamical perspective, so we look at dynamics and the lexicon, syntax, and conversation. This chapter ends with a discussion of human decision-making and problem solving.

An Ecological Approach

People are not the only systems capable of problem solving. The process of biological evolution can viewed as a continuous solution to the problem of adapting organisms to an ever-changing environment. We discuss evolution in terms of optimization on a fitness landscape. This model is not complete however, without the introduction of self-organization. The key ingredients of selection, variation, and reproduction explain how evolutionary change happens. But the tendency for the world to form into ordered and stable forms is necessary to produce the structures upon which such change acts.

Evolutionary optimization on a fitness landscape can also serve as a model of human problem solving. We outline some of the work on human cognitive problem solving such as analogical reasoning, functional fixedness, insight learning, means-end analysis, heuristics and their relation to optimization processes.

The analogy between dynamic processes in ecological and human systems does not stop here. Ecological systems can be viewed as dynamical systems. They have web-like structures, consist of multiple differentiated competing/cooperating units, and play an active role in regulating themselves and their environments. Both ecologies and the mind defend against intruders and reorganize themselves after damage. It seems that similar underlying forces are at work in both, and perhaps in all complex systems with a given nature.

Models and Recommendations

A hallmark of the dynamic approach is the use of models. These are created and run in order understand some aspect of a complex real world system. Models of course cannot capture every aspect of a system, but if done correctly, they can reveal many interesting features and processes. Models are best used in concert with empirical methods. Experimental validation of a model is a crucial technique that all researchers should practice.

There are many sorts of models. Traditional cognitive science models are either statical or fail to capture important dynamical aspects of the process under consideration. We briefly summarize some of the basic types of models, including deterministic and stochastic, oscillatory, differential equation, cellular automata, and agent-based models. Examples are given for how some of these can be used to model brain activity and cognitive processes. We then present the advantages and disadvantages of various models and of modeling in general.

To conclude, we summarize the salient points made in this book and analyze the concept of emergence levels. We then evaluate the reduction-emergence debate and make suggestions for how to deal with some of the issues raised. The book concludes with a discussion of how the dynamical approach can serve to unify psychology and cognitive science.

Classical Science vs. the Dynamical Approach

Before describing the dynamical approach in any depth we need to first compare it to classical notions in science. The dynamical systems approach represents a sharp break with these views (Goerner, 1995). In this section we will summarize the classical scientific perspective and show how it contrasts with the ideas of dynamical systems theory. Table 1.1 shows a summary of these differences. Many of these distinctions are discussed in greater detail in other sections throughout the book. We introduce them here now to provide the reader with an overview.

Assumption	Classical Science View	Dynamical Systems View
System's Output	Linear	Nonlinear
System's Parts	Independent	Interdependent
Methodological Approach	Analytic	Holistic
System	Closed	Open
Causality	Linear	Circular
Prediction	Complete	Limited
Change	Slow and Gradual	Can be Fast and Rapid
How Order Arises	Unspecified or Agents	Spontaneously
Philosophical Perspective	Reduction	Emergence

Table 1.1 *A comparison of the differences between the classical and dynamical views of science.*

Linearity and Independence

Historically, scientists have focused on *linear* explanations, where the output of a system is proportional to its inputs. This type of relationship assumes a simple sort of system whose processes can be measured and understood. Of course, most if not all systems in nature are *nonlinear*. Outputs in this case are not proportional to inputs. A small input to a complex system can produce a small, moderate or even large effect. The processing taking place in these systems is intricate, convoluted and difficult to explain.

The parts of a system are in many cases assumed to be independent in the classical view. *Independence* assumes that a part functions with little regard for what is occurring in other parts of the system. It is compartmentalized, insulated or "boxed off" from the rest of the system to which it belongs. The cognitive science postulation of separate modules in the brain is a good example of independence. These modules are dedicated to processing specific information. When they receive an input, they crank through a computational routine uninfluenced by other modules. The result is that we always know what the result will be regardless of the overall state of the system. We discuss modules in greater detail later.

Modularity makes the brain easier to understand and model, but it throws the baby out with the bath water, since it fails to account for complex interactions between modules. The dynamical systems view can account for this. It sees the parts of a system as *interdependent*. In interdependent systems a processor in one location may be monitored, modulated or regulated by other processors. In this case, a processor's performance is dependent on the state of the entire system. The way it operates in one state is different from the way it might operate when the system is in another state.

If we assume independence, then a system can be understood *analytically*. One can examine the behavior of the different pieces of a system and then put these separate descriptions together to explain the behavior of the whole. This is the reductionist approach. However, this approach often fails. Many systems in nature, including the human brain, resist reductionist explanations. This suggests that they function in a holistic manner. A system is *holistic* if it cannot be broken down piecemeal. Each piece relies on the parts around it to function properly. In the words of the gestalt psychologists, "the whole is greater than the sum of its parts". Emergence is a property of these kinds of systems.

Systems in the traditional view are considered closed. That is, the system as a whole is assumed to be shut-off from the larger world around it. So when considering the brain as a *closed system* we treat it as distinct from the body in which it is embedded. The dynamical systems view instead sees the brain as an *open system* that cannot be considered independent of its surroundings. The brain is part of a body that is in turn part of the world. Treating the brain as an open system means taking into account "external" factors such as hormones from the body or visual stimuli from the outside world. It also postulates a two-way street between brain and its context, where the brain influences the environment and the environment also influences the brain. We discuss open and closed systems later in the section on the continuity of mind.

Causality and Rules

The independence approach has a linear view of causality, where variables affect others in a sequential manner. The best way to conceive of this is as a chain of arrows where variable A affects B, which then affects variable C, etc. (Figure 1.1). The dynamical systems view is that variables can have all sorts of causal relations that act concurrently. Much of this occurs as the result of feedback, where a variable's output at one point in time can alter the future activity of both itself and many other variables. We can diagram this type of *circular causality* by showing loops and networks as shown in Figure 1.1.

The difference between linear and circular causality is to some extent reflected in the serial vs. parallel processing approaches in cognitive science. In the serial approach, information processing happens one step at a time. Information processing must finish in one module before it can be passed on, as is the case in most contemporary computer architectures. In the connectionist or parallel-distributed processing perspective, streams of information are processed simultaneously. There is no need to wait for one unit to finish before proceeding.

Dynamical systems takes a long-term view of system action, since feedback can alter not just what happens in the immediate moment following a cause, but over the entire future course of the system's behavior. Feedback mechanisms can promote the maintenance of homeostasis, but they more often produce increases, decreases, oscillations, fluctuations, and other sorts of dynamic processes that change with time. So while the traditional view sees short-term immediate effects, the dynamical systems view sees long-term dynamical effects.

The classical view in science was that the world operated according to deterministic rules. These rules can be summarized in general as the laws of physics and more specifically as the laws that govern each of the different branches of

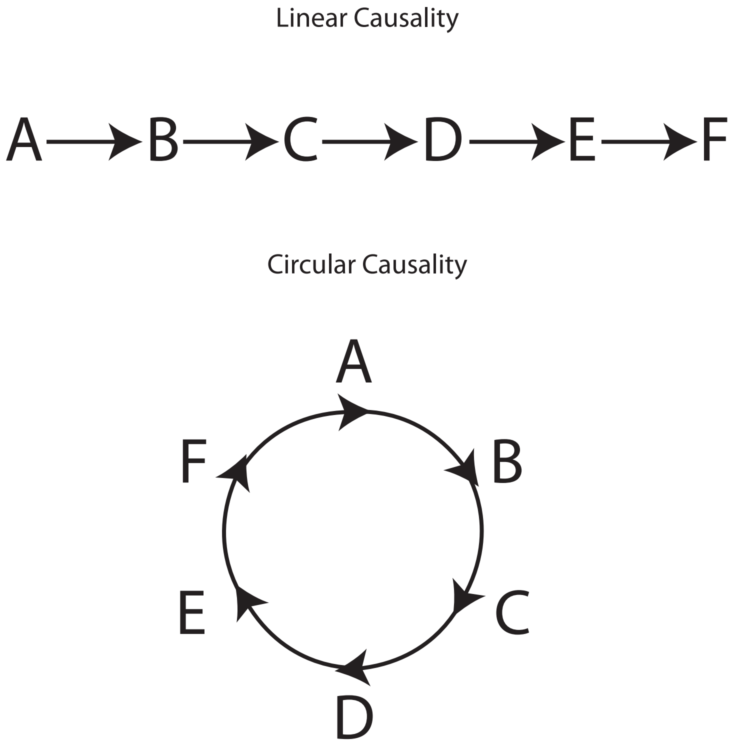

Figure 1.1 *The classical view in science is that causality is linear. The dynamical perspective allows for circular causality.*

science like chemistry and biology. If we can know these laws and have sufficient information as to the state of a system, then we can predict with accuracy what the system will do far into the future. We have *complete predictability*. Knowledge of physical law and conditions not only enables prediction, it implies also that complete understanding and control of a system are possible.

Dynamical systems theory also acknowledges that there are deterministic rules that govern a system's behavior. However, these rules and knowledge of starting conditions are not sufficient to allow complete prediction. The more accurate our knowledge of a system's starting state, the longer we can predict its future course. Eventually over time though, the behavior will diverge from our prediction no matter how accurate our starting observations. This is because the system is sensitive to initial conditions. Whereas the classical science view postulates long-term predictability, the dynamical systems view acknowledges only *limited predictability*. It allows for only partial understanding and control.

Change and Bifurcation

Change in the traditional view occurs gradually and slowly. In natural selection, for example, it was believed that species evolved continuously over long time periods and many generations. Evidence is now available though, that supports faster evolutionary change. This theory, called punctuated equilibrium, states that species evolution can happen fairly quickly, in a short time period with a smaller number of generations.

The dynamical systems perspective allows for such sudden and rapid change. Oftentimes, it is driven by the system's arrival at a *critical point*. These are conditions where a system undergoes a complete and dramatic alteration. For example, water molecules undergo a phase transition when they reach 100° C / 212° F. At this point they transform from water to steam and exhibit many new properties.

Chaotic systems can reach what is called a *bifurcation*, where they can switch to one of two alternate states. A state in this sense is large-scale or macroscopic. The bifurcation is a sizeable qualitative change in behavior. In perception of ambiguous figures such as the Necker cube, the perceptual organization can alternate back and forth between each possibility. The transition from one to the other can be considered as a bifurcation. We should also mention that there is an entire field devoted to the study of rapid change, called catastrophe theory. This discipline tells us that a particular combination of conditions, such as temperature and the degree to which steel is flexed, can give rise to dramatic alterations such as the collapse of a bridge.

Order and Energy

Perhaps one of the most important differences between the classical and chaotic perspectives is their view of order. The traditional science view has difficulty explaining how order in the universe comes to exist. It is accounted for by various factors such as accident, anomaly, or certain "agents of order" such as selfish genes, the human brain, or life itself (Goerner, 1995). According to the supernatural and unscientific view of vitalism, there is a mysterious force, vital spark or energy that creates phenomenon such as life and consciousness.

To a classical scientist, the world is passive and directionless. As we mention elsewhere, it acts much like a giant machine or clock that inexorably ticks away following known physical laws. How then, does order and organization emerge from this machine? According to the principle of self-organization, certain systems spontaneously organize themselves. Numerous examples of this are evident in nature. For instance, in chemistry, there are autocatalytic reactions that sustain themselves based on the amount of available precursor molecules. In biology, we see emergent behaviors when birds flock and fish school. Consciousness and cognition may also be examples of self-organization. This provides a very different conception of the universe, one that is active and directed toward the creation of ordered, complex structures and processes. The idea that natural ordered processes can arise from disorder is not entirely new and was proposed early in the 20th century (Schrödinger, 1944).

Another important distinction between the classical and dynamical systems views has to do with equilibrium. Systems that are in equilibrium have a homogenous distribution of energy and are incapable of driving processes. A process in this sense means any activity that requires energy. In biological organisms energy-requiring processes include locomotion and cognition that rely on metabolism. Self-organizing systems in contrast are *far-from-equilibrium*. They have a large energy concentration that has built up. This energy concentration creates a pressure to flow and drive operations.

According to thermodynamics, energy in any system always "seeks" to flow as fast as possible (Odum, 1988). It turns out that structured energy flow moves more quickly than that which is less structured. For example, energy flow is faster in a chimpanzee than it is in an amoeba because the chimpanzee is more structured and ordered. We can therefore see the creation of order and organization in the universe as driven by energy flow. This property of dissipative efficiency then could cause systems to become more ordered with time. If we plot energy flow over the time course of the evolution of life we see a dramatic increase. Energy flow, measured as metabolic rate, gets faster as organisms evolved over several billion years on earth (Swenson, 1989).

Energy flow can also explain why reorganization occurs within a given system (Goerner, 1995). If the pressure to flow builds up, energy cycles faster and faster within the system. The energy eventually reaches a limit on how fast it can flow. If this limit is reached and the resistance to flow is still less than the pressure driving the flow, a reorganization takes place. A bifurcation occurs and the pattern restructures itself into a more efficient configuration that can dissipate energy better.

A good example of this are Rayleigh-Bénard cells. If a thin layer of silicon oil is heated in a pan, the oil particles at first move randomly. As the temperature is increased, this pattern no longer dissipates heat well. There is a sudden reorganization into hexagonal-shaped cells where particles rise in the center of each cell and fall near its edges. This new arrangement is better at dissipating heat. If the temperature is increased further even more complex arrangements, such as rotating spiral patterns develop.

Reduction and Emergence

We have already mentioned reduction and emergence. Whereas reduction is analytic and seeks to break wholes into parts, emergence is holistic and seeks to build wholes out of parts and part interactions. Reduction is part of the classical approach while emergence is more recent. In what follows, we introduce these perspectives in greater detail and discuss the problems that are inherent in each.

Reductionism

In a general sense, *reductionism* is the belief that everything about a whole can be explained entirely by understanding its parts. If we can understand all there is to know about the parts that make up a system, then this enables us to completely understand the whole that they make up. In reduction we attempt to say that a given phenomenon X is "nothing more than" or "nothing above and beyond" phenomenon Y. X thus becomes reduced to Y.

Silberstein (2002) describes two types of reduction. *Ontological reduction* is concerned with the nature of reality and posits that everything in the universe consists of the fundamental constituents of reality, some basic particles or entities, or is determined by them. *Epistemological reduction* is concerned with descriptions of reality and posits that scientific theories or common sense conceptions can be reduced to other scientific theories or conceptions about the fundamental features of the world.

In ontological reduction, the things that need to be related are real-world items such as entities, events, and properties. For instance, we might want to relate the property "heat" from thermodynamics to a more basic global description derived from the properties of individual molecular elements, as is done in statistical mechanics. In epistemological reduction, the things that are being related or reduced are representational items like theories, concepts, models, frameworks, and schemas. A theory in biology for example, might be reduced to another theory in chemistry.

Inherent in the notion of reductionism is the idea of *levels of analysis*. In this view, natural phenomena can be analyzed at different levels of spatial and temporal scale. Usually these two are correlated, with things happening faster at smaller sizes. We can take a given phenomena, such as the mind, and examine it from the large scale of psychology, which examines abstract concepts such as thoughts and emotions, all the way down to the quantum scale of subatomic particles. Because each level contains different phenomena and is organized and operates differently, there are distinct disciplines that have developed to study each. From large to small, we could study the mind from the disciplines of psychology, biology, chemistry, and physics, with multiple sub-disciplines in-between each of these.

Problems with Reductionism

Reductionism was one of the major goals of the traditional scientific endeavor. At one point, it was thought that even the largest scale phenomena could all be reduced to physics. Each level of explanation would eventually reduce to the one below it like the floors of a collapsing building until we would be left with nothing but the "basement". Sociology could be explained by psychology, which could be explained by biology, which could be explained by chemistry, and so on. Findings from modern scientific investigation however suggest that this goal is untenable.

One of the central problems with reductionism is that there are very few actual cases of successful inter-theoretic reduction, where the explanatory constructs of one discipline are explained by those beneath it. Examples of failed or incomplete cases concern the reduction of thermodynamics to statistical mechanics, of thermodynamics to quantum mechanics, and of chemistry to quantum mechanics. In the last instance, the concept of a molecule cannot be accounted for using quantum formulations.

These are troubling because they come from the physical sciences. Reduction is even more problematic in the social sciences. It is not at all clear for example how to link the "hard" problems of consciousness, i.e., those that explain the subjective character of mind, with the "easy" problem of neural states. There are no clear linkages between mental or psychological terms like "perceptions", "thoughts" and "feelings" to particular physical brain states and processes.

It is very difficult to start with the characteristics and properties of parts and use them to explain the features of the whole, even in simple systems that

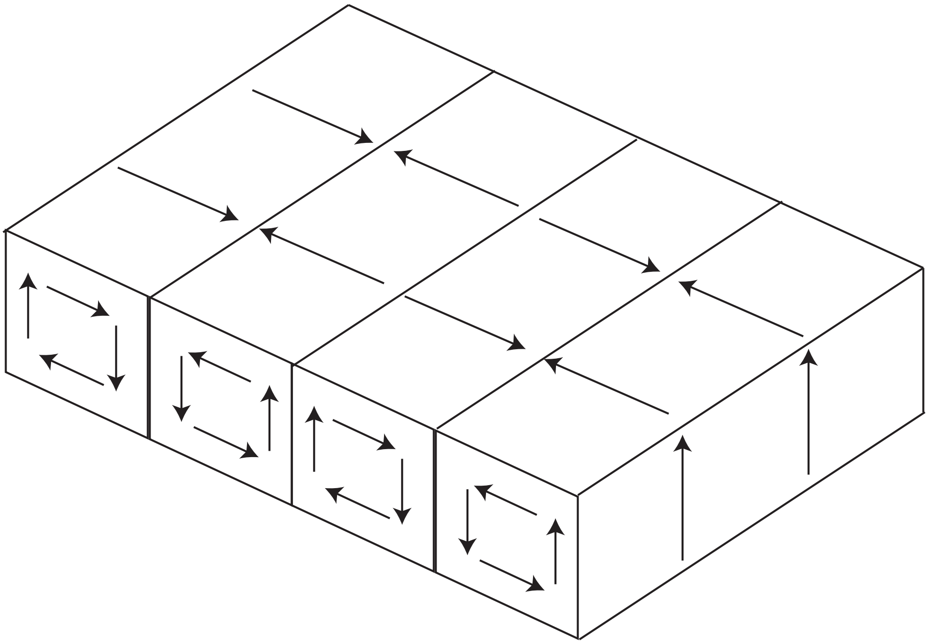

Figure 1.2 *Order from disorder: liquid molecules spontaneously transition into Bénard cells from random motion when heated.*

are just aggregates of a single kind of part. Take water for example. It is made up of the molecule H_2O. But knowledge of this molecule alone does not easily explain the interesting changes that take place when we heat large numbers of them. In this situation, the system undergoes dramatic qualitative changes, turning from ice to water to gas.

Many natural systems are like this. Their behavior doesn't change slowly, gradually, or predictably with a change in conditions, but instead undergoes dramatic alterations. These critical shifts produce a whole new organization, one that is best explained by resorting to different concepts and principles. It may seem disconcerting, but many phenomena in nature act this way. It is as if somebody flipped a switch that changed all the rules, forcing us to constantly come up with a new explanatory language. The failure of reductionism has cast doubt on whether the sciences can be united and has in part contributed to the current popularity of the emergence movement.

Bénard Cells

To show how difficult reductionism is, we will describe one phenomenon in detail. A Bénard cell is a convection cell, a region where gas or liquid matter rolls about upon itself. These cells appear spontaneously in a liquid layer that is progressively heated from below (Figure 1.2). Why should these ordered patterns appear, as it were, out of "nowhere"? It seems that a simpler outcome would be simply to have the liquid molecules move faster and faster, continuing to bump into each other in random fashion as more heat is applied.

The answer has to do with how temperature spreads in a medium. At lower temperatures, heated molecules can get rid of their heat through dissipation. They simply transfer the heat to neighboring molecules, rising from the bottom layers where it is hottest to the top layers where it is cooler. But at a critical value of temperature, this movement cannot get rid of enough heat. A new movement pattern develops consisting of the Bénard cells. These are more efficient at reducing heat because hot particles near the bottom move quickly to the top, lose their heat near the surface, and then plunge back down to heat up once more. The Bénard cells in this capacity can be thought of as a heat "conveyer belt".

From a global perspective, the liquid has spontaneously organized itself into a new and more ordered spatial configuration. Instead of random motion, we see cyclical motion. When viewed from above the cells form into a variety of shapes depending on the geometry of the container and can be in long cylinder-like forms or more spherical shapes. A three-dimensional perspective shows that the direction of flow within a cell alternates clockwise and counterclockwise directions every other cell. This preserves the same flow direction at cell borders, again maximizing the efficiency with which the heat passes out of the liquid.

The Bénard cells seem to emerge spontaneously from the liquid system. They are considered an example of self-organization, where order can arise naturally from disorder. Much of the order we see throughout the natural world is of this sort. It can be seen in weather patterns, chemical reactions, biological development and even human societal organizations.

For our purposes, Bénard cells provide us with a simple but useful guide for understanding how mind and consciousness might arise from the brain. It could be that mental properties are the result of self-organizing principles at work in the brain. Just as the dissipation of heat, the liquid structure and the geometry of the container create a context that gives rise to rolling convection, energy laws, neural structure, function and other properties naturally give rise to mind. The challenge for cognitive science is to describe how this happens.

Emergence

The concept of *emergence* is that the features of a whole or complex are not completely independent of the parts that make them up. They are said to go beyond the features of those parts or emerge from them. Many phenomenon in the natural world seem to be emergent. In fact, emergence has been used to explain almost everything from the big bang to mind. Table 1.2 outlines a fairly comprehensive list (Morowitz, 2002). Just as was the case with reduction, there is both ontological and epistemological emergence. The first is concerned with real world items such as parts/wholes, properties, events/processes, laws and entities. The latter deals with concepts, theories, models, frameworks, and states of a system (Silberstein, 2002).

Holland (1998) describes several features of emergence. Emergent systems are made up of interacting parts. The function of these systems is rule governed. These rules are invariant even though the parts or components of which they are made do change over time. In fact, the states or processes of these systems are in constant flux; we say they are dynamic. Their dynamic and constant-

Step	Process	Description
1.	The Primordium	Origin of the universe
2.	Large-Scale Structure	Structured matter like galaxies
3.	Stars	Formation of stars like our sun
4.	The Elements	Creation of chemical elements
5.	Solar Systems	Matter organized around suns
6.	Planets	Condensation of planetary bodies
7.	The Geospheres	Geological structures like rocks, water, and gas
8.	The Biosphere	Chemical combinations, replication, autocatalysis
9.	The Prokaryotes	Primitive biological cells
10.	The Eukaryotes	Cells with organelles
11.	Multicellularity	Multicellular organisms like plants, animals and fungi
12.	Neurons	Cells allowing the transmission of information
13.	Protostomia and Deuterostomia	Evolution of animals with single and dual gut openings
14.	Vertebrates	Animals with brains
15.	Fish	Various forms of fish in aquatic environment
16.	Amphibians	Transition to land-based life
17.	Reptiles	Animals with shelled eggs
18.	Mammals	Emergence of these major terrestrial vertebrates
19.	Arboreal Animals	Forest-Dwelling Animals fill this ecological niche
20.	Primates	Enlarged cerebral cortex, extended maternal care and training of young
21.	The Great Apes	Adaptation to savannah ecology
22.	Hominids	Full bipedal locomotion, cooperative food acquisition, and increased cognitive skill
23.	Toolmakers	Creation of effective instruments for altering the environment
24.	Language	Cultural transmission of information
25.	Agriculture	Domestication of animals and plant cultivation
26.	Technology and Urbanization	Applied mathematics and city-dwelling
27.	Philosophy	Efforts at self-understanding
28.	The Spiritual	Attempts to ascribe meaning to other emergences

Table 1.2 *Natural processes attributed to emergence in the temporal order in which they occurred (from Morowitz, 2002).*

ly changing nature gives rise to novelty; a non-stop parade of new patterns or behaviors that are difficult if not impossible to predict.

There is another sense in which things change but stay the same in emergent systems. Holland (1998) calls this persistence. This is where patterns of interaction persist despite a continual turnover of their constituent parts. He cites as an example the standing wave in front of a rock in a white-water river. The water molecules making up the wave are constantly changing, but the global wave pattern remains. So we can say that although the rules and particular patterns of emergence are invariant, their parts are always on the move.

Emergent systems, even though they are complex, demonstrate regularity. Under certain conditions, the system will show patterned behavior. Although the system may not repeat itself exactly, it can be shown to act similarly in a given situation. A random process would not be like this. Random processes cannot be predicted and cannot be guaranteed of acting in similar ways in a given context. Emergent systems are therefore not random or stochastic.

Problems with Emergence

Like reduction, emergence is not without its own set of difficulties. To start, a philosophical account of emergence doesn't count as an explanation. It merely says that if one thing cannot be reduced to another then it must be something more than what it is made of. In most cases there is no attempt to say exactly what happens. What is needed is some sort of explanation or theoretical account of how this something extra comes into being. Given this explanatory vacuum, some may come to equate emergence with magical, mystical, or theological workings. If relationships between parts are considered important in emergent phenomena, then a theory is needed that explains how relational processing gives rise to emergent properties.

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