

Why Intelligent Design Fails

*A Scientific Critique of
the New Creationism*

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*It is interesting to contemplate an entangled bank, clothed
with many plants of many kinds, with birds singing on the
bushes, with various insects flitting about, and with worms
crawling through the damp earth, and to reflect that these
elaborately constructed forms, so different from each other,
and dependent on each other in so complex a manner, have
all been produced by laws acting around us.*

Charles Darwin,
On the Origin of Species, 1859

Chapter 7

Self-Organization and the Origin of Complexity

NIAL SHANKS AND ISTVAN KARSAI

EVEN A CASUAL examination of nature reveals the existence of complex, organized states of matter. Organization is found on all scales—for example, in the elaborate spiral shapes of galaxies in space and hurricanes on earth, in organisms, in snowflakes, and in the molecules that participate in many important chemical reactions. Ordered, organized, complex states of matter abound in the world around us. How are we to explain this complexity? Our current best account of these types of phenomena is given by dynamical systems theory, a branch of natural science that explains the existence of complex, organized systems in terms of self-organization.

But natural science has critics who want to explain the existence of organized complex systems as the result of intelligent design by a supernatural being. One such critic is William Dembski (2002b), who modestly claims to have discovered a fourth law of thermodynamics, which he calls the law of conservation of information (169). As Dembski observes, “intelligent design is just the Logos theology of John’s Gospel restated in the idiom of information theory” (192). To understand the proposed law, we must see what Dembski means when he refers to what he calls complex specified information (CSI; see also chapter 9 in this book).

Specified events are those forming part of a pattern that can be specified independently of the events. Suppose you want to impress your friends with your skill at archery. You shoot from a distance of 50 meters. Having hit the wall of the barn with all your arrows, you then go and paint bull’s-eyes around them and call your friends over to have a look. What can your friends conclude when they arrive at the barn? Dembski (2002b) tells us:

Absolutely nothing about the archer's ability as an archer. Yes, a pattern is being matched, but it is a pattern fixed only after the arrow has been shot. The pattern is thus purely ad hoc.

But suppose instead the archer paints a fixed target on the wall and then shoots at it. Suppose the archer shoots a hundred arrows, and each time hits a perfect bull's-eye. What can be concluded from this second scenario? Confronted with this second scenario we are obligated to infer that here is a world class archer, one whose shots cannot legitimately be referred to luck, but must rather be referred to the archer's skill and mastery. Skill and mastery are of course instances of design. (180)

An archer who draws bull's-eyes around his arrows might generate a pattern, but it won't be a specified pattern. An archer who shoots once and hits the bull's-eye might have been lucky; it could have happened by chance. By contrast, an archer who shoots numerous arrows from a distance and scores many bull's-eyes will have generated a complex, specified pattern of events. Complexity here simply means that the events have a very low probability of occurring just by chance. Dembski claims that when a pattern exhibits complexity and specification and moreover is contingent (that is, is not simply the result of an automatic pattern-generating mechanism), it reveals the presence of intelligent design.

According to Dembski (1999), the law of conservation of information is captured by the claim that natural causes cannot generate CSI. He lays out its implications:

Among its immediate corollaries are the following: (1) The CSI in a closed system of natural causes remains constant or decreases. (2) CSI cannot be generated spontaneously, originate endogenously or organize itself (as these terms are used in origins of life research). (3) The CSI in a closed system of natural causes either has been in the system eternally or was at some point added exogenously (implying that the system, though now closed, was not always closed). (4) In particular any closed system of natural causes that is also of finite duration received whatever CSI it contains before it became a closed system. (170)

Bringing out a connection with thermodynamics, he observes:

Moreover, it tells us that when CSI is given over to natural causes it either remains unchanged (in which case the information is conserved) or disintegrates (in which case information diminishes). For instance, the best that can happen to a book on a library shelf is that it remains as it was when originally published and thus preserves the

CSI inherent in the text. Over time, however, what usually happens is that a book gets old, pages fall apart, and the information on the pages disintegrates. The law of conservation of information is therefore more like a thermodynamic law governing entropy, with the focus on degradation rather than conservation. (2002b, 161–62)

What is the connection between Dembski's law and the second law? Dembski's proposed law is related to the second law of thermodynamics through the relationship of information to entropy. He, in fact, asks

whether information appropriately conceived can be regarded as inverse to entropy and whether a law governing information might correspondingly parallel the second law of thermodynamics, which governs entropy. Given the previous exposition it will come as no shock that my answer to both questions is yes, with the appropriate form of information being complex specified information and the parallel law being the law of conservation of information. (166–67)

So he is arguing that as the entropy of a system decreases, information increases, and as entropy increases, information decreases. Any increases in information in a universe such as our own arise from the input of an intelligent designer.

Thermodynamics, Entropy, and Disorder

One of the great achievements of physics in the late nineteenth century was the forging of connections between the basic ideas of thermodynamics and basic ideas of atomic theory, according to which the familiar objects of everyday experience are actually vast conglomerations of tiny particles in jostling motion. Thinking along these lines, let us examine some basic thermodynamical ideas.

Imagine a system that has no exchanges with its surrounding environment (perhaps a large impenetrable box containing cold air and a smallish lump of very hot iron). Such a system is an example of what physicists call a closed system. The first law of thermodynamics, also known as the law of conservation of energy, tells us that the energy of such a system remains constant over time. But even though energy cannot be created or destroyed, it can be redistributed. The second law tells us that the entropy of the closed system will approach a maximum. In practice, the lump of iron will get colder and the air will get warmer until they reach the same temperature. How does this process happen?

Part of the answer is that macroscopic systems like lumps of iron are made

of particles. Particles carry energy, and energy is dispersed when particles change their locations by moving about in space, or when energy is transferred from particle to particle as they jostle and bump into each other. The hotter macroscopic systems are, the more energy their constituent particles have and hence the more vigorously these particles move and jostle. The iron in the box cools and the air warms because particles of iron jostle particles of air, thereby transferring energy to them. In this way heat flows from the hotter to the cooler. Energy is redistributed from the iron to the air until the iron is at the same temperature as the air, at which point there is no net energy flow between them.

To better understand the significance of seeing heat in terms of the motions of particles, we will differentiate between coherent motions of particles and random, incoherent, thermal motions of particles (Atkins 1994). A gas stove takes the chemical energy in gas and converts it into heat energy. When gas burns, energy disperses through incoherent, random motions of particles. These particles jostle particles in the pan on the stove, which disperse energy by transferring it to the water molecules in the pan. As these jostle faster, the water gets hot, and you can make tea.

By contrast, consider a car. When a piston in a cylinder goes up and down, there is a net movement up and down of the particles making up the piston as well. These are coherent motions. When we get work from such a system, it is because we are able to use energy to induce and sustain coherent motions of the particles making up the car engine. Thus, coherent motions in one part (the reciprocating motion of the pistons in the engine block) are converted through coherent motions in other parts (cranks and gears) into coherent, rotary motions of the wheels. In virtue of these coupled, coherent motions, by burning gasoline, you can drive yourself to the store to buy tea.

Cars work because they are physical systems whose parts (made of tiny particles) stand in appropriate structural relationships to each other so that coherent motions in one part can cause appropriate coherent motions in other parts. But even the best cars are subject to thermal wear and tear. As the chemical energy in gasoline is consumed to run the car, frictional heating causes brake pads to wear out. Electrical heating wears out spark plugs. Metals get fatigued (structural changes occur as particles vibrate and change locations), and parts drop off. As the particles that make up the car's parts change location and jostle each other, the car gradually loses its structural coherence and eventually suffers catastrophic failure. This is what it means to say that the entropy of the car increases over time.

How, then, can self-organization possibly occur? How can natural mechanisms operating in accord with the laws of nature bring about entropy reduc-

tion and give rise to order and information without the intervention of an intelligent designer to both organize things and keep them organized?

Self-Organization and the Emergence of Order

To find out how order forms, we must distinguish between closed systems, which have no exchanges with their surrounding environments, and open-dissipative systems, which have such exchanges. Our universe contains many open-dissipative systems. When energy and matter flow into and out of open-dissipative systems, they can drive the formation and maintenance of coherent structures and coherent dynamical processes in systems by inducing coherent, coordinated motions in matter—that is, in atoms and molecules. The processes by which these coordinated motions of matter are induced are known as self-organizing processes (since they involve no external designing agency). The complex organization that results from these processes is generated by energy-driven interactions among the components internal to open-dissipative systems.

In accord with the first law, the law of conservation of energy, the work involved in the formation and maintenance of coherent structures in open-dissipative systems happens as a result of energy flowing through the system. Nature does not give something for nothing, and there is no energetic free lunch. The entropy reduction involved in the formation and maintenance of coherent structures and processes must, in accord with the second law, be more than offset by an increase in the entropy of the environment with which it interacts. This last statement means that the formation and maintenance of coherent structures and processes involve the corruption of usable energy in the universe, where the universe is a system currently teeming with usable energy.

To get self-organization, several conditions need to be satisfied. These include the following.

A COLLECTION OF SUITABLE COMPONENTS

The components come in all shapes and sizes. They can be of differing kinds. They may be atoms or molecules (water will do); they may be cells; they may be organisms (for example, an insect in an insect society); they may even be the stellar components of galaxies self-organizing through gravitational energy into giant rotating spirals.

A FLOW OF USABLE ENERGY THROUGH THE SYSTEM

This flow of energy drives mechanisms that give rise to the formation of self-organizing systems. The flow of energy into and out of the system must continue

to sustain the system by driving interactions among its components. A self-organizing system starved of sustaining energy will sink back into the environment from which it emerged as it loses its structural and dynamical coherence. The flow of warm, moist air that drives the formation and sustenance of large self-organized structures such as hurricanes (visible from space as rotating spirals) is disrupted by landfall, whereupon the weather system settles down, spawning self-organizing tornadoes in its death throes. For self-organized creatures like us, as the great nineteenth-century physiologist Claude Bernard was among the first to emphasize, equilibrium is death.

LOCAL COUPLING MECHANISMS

The components must be able to couple their behaviors in accord with local mechanisms. The locality condition means that interactions giving rise to self-organization take place between proximate components of a system with no broader view to the integrated, complex system than may result from many such purely local interactions. The integration of the components of self-organizing systems into organized, complex systems arises from chains of local interactions (as when ants interact with each other through intermediaries—possibly other ants, possibly a pheromone trail laid down by an ant no longer present). This coupling of the behaviors of the components lies at the heart of self-organization. Self-organizing systems are systems of many interacting parts whose interactions with each other give rise to the global, collective behavior of the entire system of interacting components.

For example, a self-organized structure such as a hurricane has air molecules and water molecules as components. It is an entity whose formation is driven by heat energy flowing from the ocean to the upper atmosphere. A hurricane begins with a tropical depression (a point of low air pressure) that draws in warm moist air from the immediate surroundings. The water vapor in the air condenses and falls as rain as the air is drawn into the region of low pressure. As water changes from vapor to liquid, it releases energy as latent heat. This heat causes the air to rise at the center of the emerging structure, helping to form the eye of the storm, thereby drawing in more warm, moist air from below and ultimately from outside the system. This air in turn surrenders its water vapor and rises up the wall of the eye. The resulting coordination of air flows contributes to the emergence of global behaviors of the entire system: organized, rotating, spiral patterns that can be seen from space.

The local coupling of components (in our hurricane, air rising up the wall of the eye drawing in more air from below, which in turn draws in air from outside the system) constrains their behavior and thus their freedom to respond to changes in their immediate environments. This feature of self-

organizing systems is important for understanding how energy flows through a system can induce the coordinated, coherent motions that result in the organization exhibited by such systems. (The local coupling of components also influences how environmental influences will usually be able to propagate through the system. The extent of the propagation will depend on the presence or absence of amplification mechanisms, damping mechanisms, and other factors—for example, how tightly the components are coupled.)

The dynamical stability of self-organizing systems is due to regulatory mechanisms. Positive feedback will make a system grow by amplifying initial effects. An important positive-feedback mechanism is autocatalysis, where the very presence of something, given a source of usable energy, promotes the formation of more of itself. Autocatalysis plays important roles in physics, chemistry, and biology (Shanks 2001). For a simple example, take rabbits and add grass for energy. The result, in the fullness of developmental time, is more rabbits than you began with.

But we do not see arbitrary, uncontrolled growth in the rabbit population, so positive feedback must be balanced by negative feedback. A growing rabbit population, for example, draws the attention of foxes, who eat the rabbits—and produce more foxes in consequence. The rising fox population leads to overpredation of the rabbit population, and this in turn causes the rabbit population to collapse. With a diminished food source, the fox population will shortly collapse and enable the rabbit population to grow again. The result, over time, will be two coupled populations, whose numbers will rise and fall together. We will in fact have a biological oscillator.

Bénard-Cell Convection

Consider a thin layer of water sandwiched between two horizontal glass plates. Suppose the system is at room temperature and in thermal equilibrium with its surroundings. One region of water looks pretty much the same as any other. If the water is now warmed from below so that energy is allowed to flow through the system and back into the environment above, the system will become self-organized above a certain critical temperature. If you look down at the system, you will see a structured, honeycomb pattern in the water (see figure 7.1).

The cells in the honeycomb—often shaped like hexagons or pentagons—are known as Bénard cells and are rotating convection cells. Water warmed at the bottom rises; as it rises it cools and starts to sink again to the bottom to be rewarmed, thereby repeating the process. Water cannot both rise and fall in the same place, so regions where water rises become differentiated from

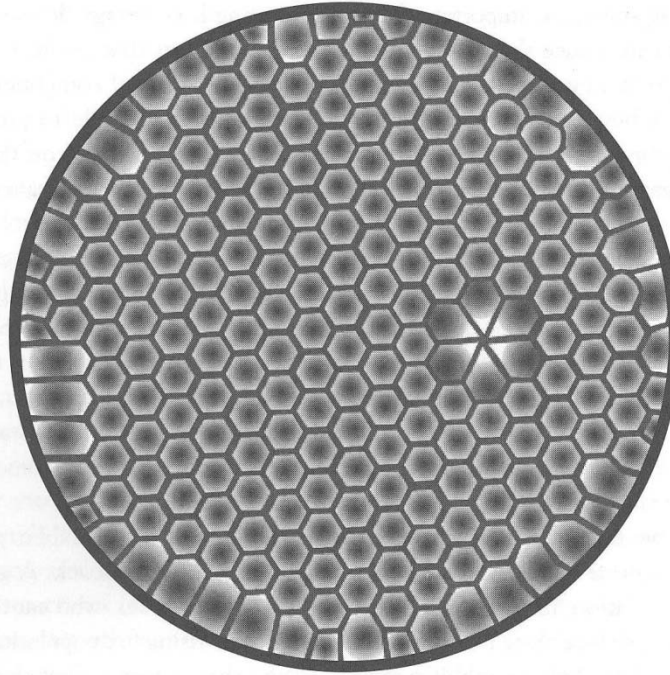


Figure 7.1. Simulation of Bénard convection cells in a Petri dish. The cells have similar size, except on the border. Although the shapes of the cells vary somewhat, they approach a hexagonal structure commonly called honeycomb. The emergence of an organized structure from a homogeneous medium such as water or oil is startling.

regions where it falls. This differentiation gives rise to the cells. Seen from the top, the cells have a dimpled appearance, since water rises up the walls of the cell and flows toward the center dimple to flow back down again, completing the convective circulation (see figure 7.2).

The cells are visible because of the effects of temperature on the refraction of light. The way in which one cell rotates influences the ways in which its immediate neighbors rotate; in turn, the first cell is influenced by them. By adding thermal energy to water, we have brought about the spontaneous emergence of a complex system of interacting convection cells. The spatial and temporal order we can see in the behavior of this self-organizing system is not imposed from outside. The environment merely provides the energy to run the process. Chance, in the form of environmental fluctuations, provides the initial local inhomogeneities that serve as seeds for the emergence of the system from an initially homogeneous aqueous medium. The Bénard-cell patterns result from the energy-driven interactions of the components (water mol-

ecules) internal to the system. Bénard cells are not just an artificial phenomenon: astronomers have seen these cells on the surface of the sun.

Self-organizing systems, such as the Bénard-cell system, constitute a threat to Dembski's creationist enterprise because, although these systems are both undesigned and naturalistically explicable, they manifest complex specified information and thereby give the misleading appearance of being the fruits of intelligent design.

Apparently aware of the threat posed by self-organization of this kind to his claims about intelligent design, Dembski (2002b) initially accuses those who study these phenomena of trying to get a free lunch:

Bargains are all fine and good, and if you can get something for nothing, go for it. But there is an alternative tendency in science that says that you get what you pay for and that at the end of the day there has to be an accounting of the books. Some areas of science are open to bargain-hunting and some are not. Self-organizing complex systems, for instance, are a great place for scientific bargain-hunters to shop. Bénard-cell convection, Belousov-Zhabotinsky reactions, and a host of other self-organizing systems offer complex organized structures apparently for free. But there are other areas of science that frown on bargain-hunting. The conservation laws of physics, for instance, allow no bargains. (23)

Yet Bénard cells occur in nature (for example, in the sun) as well as in the laboratory. Their existence is certainly consistent with known conservation laws.

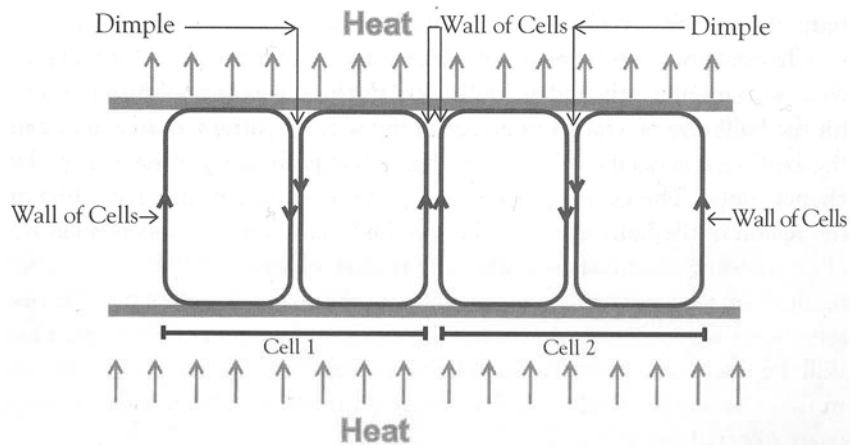


Figure 7.2. Cross-section of Bénard convection cells. Warm water rises up the wall of the cell, cools, and sinks down at the dimple in the middle of the cell.

The matter is made all the murkier because Dembski says elsewhere that he finds the existence of Bénard cells to be unproblematic (which seems to contradict his suggestion that they violate the conservation laws of physics). Thus, he observes:

Bénard-cell convection, for instance, happens repeatedly and reliably so long as the appropriate fluid is sufficiently heated in the appropriate vessel. We may not understand what it is about the properties of the fluid that makes it organize into hexagonal cells, but the causal antecedents that produce the hexagonal patterns are clearly specified. So long as we have causal specificity, emergence is a perfectly legitimate concept. (243)

Here Dembski is guilty of gross oversimplification in his attempt at an easy rebuttal of a difficult problem.

What actually happens “repeatedly and reliably” is a pattern involving some arrangement of rotating convection cells (often involving both hexagons and pentagons), where the rotation of one cell reflects and is in turn reflected by the rotations of its neighbors. But we do not get the same pattern (including rotation dynamics) each time we run the experiment. The actual pattern generated in a given trial reflects both the Bénard-cell convection mechanism and the effects of chance inhomogeneities and fluctuations in the fluid medium. In consequence, the precise patterns generated in a sequence of trials exhibit a high degree of variation. These contingent patterns are nothing like the results of an automatic pattern-generating mechanism that gives the same result repeatedly and reliably, time after time: the Bénard-cell patterns also exhibit complex specified information.

To see this, consider once again the patterns generated by Dembski’s archer, who intelligently and skillfully designs the trajectories of his arrows to hit the bull’s-eye of a target from a great distance. A pattern of several hits in the bull’s-eye is complex because it has a low probability of happening by chance alone. The general form of the pattern—a pattern involving hits in the region of the bull’s-eye—can be specified in advance (or independently) of the shooting of the arrows. That the pattern of hits is skillful and not the result of an automatic pattern-generating mechanism is manifested in the observation that, whenever the archer shoots several arrows to demonstrate his skill, he does not repeatedly and reliably get exactly the same pattern of hits in the region of the bull’s-eye. The actual patterns of hits generated in a sequence of trials are contingent.

Bénard-cell patterns are complex: they involve the coordinated motions of trillions of water molecules, and the probability that they would form by

chance alone is minuscule. As with the archer, the general form of the pattern, involving some arrangement of rotating hexagons and pentagons, is specifiable in advance (and independently) of any given trial. As with the archer, the actual pattern generated on any given trial is contingent. You do not get exactly the same pattern repeatedly and reliably each time you run the experiment. The crucial difference between the Bénard-cell pattern and the archer's pattern of hits is that the Bénard-cell pattern does not require intelligent design or skillful manipulation for its appearance, only the combined effects of a dumb pattern-generating mechanism and mindless chance in the form of fluctuations and inhomogeneities in the fluid medium.

The problems posed by Bénard-cell patterns for intelligent-design theorists such as Dembski do not end here. As we saw at the beginning of this chapter, Dembski claims that information is the inverse of entropy. The emergence of the Bénard-cell patterns involves a local decrease in entropy (that is, a decrease of disorder or an increase of order). It follows from Dembski's claim that, when Bénard cells form, as entropy decreases, information increases. But this increase of information does not involve any input or use of complex specified information arising from intelligent causes, be they natural or supernatural. All that is needed are unintelligent, natural mechanisms operating in accord with the laws of physics.

Dembski claims that his law of conservation of specified information precludes the formation of complex systems through natural causes. But the universe we live in has lots of usable energy and is far from thermodynamical equilibrium. (At equilibrium both entropy and information would remain constant, on average.) The universe also contains many open-dissipative systems as subsystems. For example, our planet is warmed by a large hot star that provides plenty of usable energy, and the universe, not to mention our planet, is teeming with open systems that exploit this usable energy. Self-organization, resulting in decreases in the entropy of local, open systems, points clearly to the conclusion that we can indeed get CSI through self-organization resulting from unintelligent natural causes and that no invisible supernatural hand operating outside a system of purely natural causes is needed. Self-organization is indeed a great scientific bargain when compared with evidentially empty promissory notes concerning supernatural design from outside our natural universe.

Self-Organization As a Pathway to Irreducible Complexity

Michael Behe, a creationist biochemist and a leading light in the intelligent-design movement, has argued that there is a kind of complexity in nature called

irreducible complexity that can exist only as the result of the activity of an intelligent designer (see chapter 4 in this book). An irreducibly complex system is one consisting of several components, all of which must be present if the system as a whole is to achieve its function. Dembski (1999, 149) has attempted to bolster these claims by arguing that irreducibly complex systems also manifest complex specified information, which, as we have seen, he takes as the hallmark of intelligent design.

Behe has illustrated his idea of irreducible complexity with the example of a mousetrap (1996; 2000; 2001a, 90–101; also see chapter 2 in this book). The mousetrap is a device that has several components, all of which are necessary to catch mice. Assume for the sake of argument that Behe is right about all this. He tells us that, although it is easy to see how such a complex, structured system could arise by intelligent design and construction (it is, after all, a human artifact), it is hard to see how it could have formed through the operation of unintelligent, natural mechanisms. The components of mousetraps will not self-assemble into a functioning mousetrap. Yet Behe intends the mousetrap to serve as a metaphor to illustrate the complexity of chemical reactions. It is far from obvious that chemical reactions with the property of irreducible complexity necessarily result from intelligent design.

In chemistry, self-assembly and self-organization are well-studied phenomena. One of the most famous and well-studied self-organizing chemical systems is the Belousov-Zhabotinski (BZ) reaction. The BZ reaction refers to a set of chemical reactions in which an organic substrate is oxidized in the presence of acid by bromate ions in the presence of a transition metal ion (Tyson 1994, 569–87).

The version of the reaction that one of us (Niall Shanks) has used in classroom demonstrations has the following ingredients: potassium bromate, malonic acid, potassium bromide, cerium ammonium nitrate, and sulfuric acid. When the ingredients are placed in a beaker, the system self-organizes to perform a repeating cycle of reactions. It behaves as a chemical oscillator, and the oscillations can be monitored through cycles of color changes. You can use it to tell the time: it is a watch that forms in a beaker without the help of a watchmaker.

The oscillations result from the chemical system cycling through its component reaction pathways. What do we mean? Suppose the system starts out with a high concentration of bromide ions. In the first group of reactions, bromate and malonic acid are used in a slow reaction to produce bromomalonic acid and water. Bromous acid is one of the reaction intermediates in this pathway. Since the cerium is in the cerous state, the reaction medium remains colorless for this phase of the cycle. As time goes by, the concentration of bromide

ions drops to a point at which bromous acid can initiate another mechanism to produce bromomalonic acid and water.

Here, in a fast reaction, bromate, malonic acid, bromous acid (a reaction intermediate from the first pathway), and cerous ions produce ceric ions, bromomalonic acid, and water. The reaction medium turns yellow as cerium enters the ceric state. The pathway also contains an autocatalytic step in which the very presence of bromous acid catalyzes the production of more of itself, so one molecule of bromous acid makes two molecules of bromous acid (this positive feedback effect is why this pathway is fast). As cerous ions are consumed and ceric ions accumulate, a critical threshold is achieved, and a third pathway opens. This pathway consumes bromomalonic acid, malonic acid, and ceric ions to produce carbon dioxide and bromide ions, and to regenerate cerous ions, thereby setting the system up for a new cycle (Babloyantz 1986).

Neither the law of conservation of energy nor the second law is violated. To get the oscillations, the system begins far from chemical equilibrium. The oscillations continue until equilibrium is reached: the period gradually gets longer and the color changes become less pronounced as equilibrium is approached. Like more familiar mechanical watches, it runs down unless it is rewound by the addition of more reagents. We have had the system oscillate for more than an hour in typical classroom demonstrations. That the reaction manifests self-organization means nothing more than that the invisible hand of the chemical interactions between molecules, in accord with the laws of chemistry, brings about highly ordered, organized behavior of the system as a whole in the form of regular temporal oscillations. This behavior does not require the intervention of a supernatural intelligence.

The reaction is important because advocates of intelligent-design theory claim that irreducible complexity can appear only as the result of the actions of an intelligent designer who takes the components of the system and assembles them into a functioning whole. In saying this, they evidently mean that they cannot see how unguided mechanisms operating in accord with the laws of nature could give rise to this type of complexity. But the BZ system manifests irreducible complexity, and it does so without any help from intelligent designers (Shanks and Joplin 1999, 2001; Shanks 2001). How can this be so?

Behe (1996, 2000) tells us that three conditions must be satisfied if a system is to be irreducibly complex: (1) the system must have a function, (2) the system must consist of several components, and (3) all the components must be required for the achievement of function. The function of the BZ reaction is to oscillate. The BZ system consists of several key reactions. The key components of the BZ reaction are all needed for the oscillatory cycle to

exist. The disruption of any of these key reactions results in the catastrophic failure of the system. The BZ system manifests the same irreducible complexity found in a mousetrap, yet it requires no intelligent designer to arrange the parts into a functioning whole. Apparently, the unguided laws of chemistry will generate irreducibly complex systems.

Yet Behe (2000) has objected to this example. He observes, "Although it does have interacting parts that are required for the reaction, the system lacks the crucial feature—the components are not well-matched" (157). This charge has been reiterated by Dembski (2002b), who tells us that being well-matched means being like the fan belt of a car: "specifically adapted to the cooling fan" (283). Behe (2000) thus objects that the reagents used in the BZ reaction have a wide variety of uses. In his terminology, they have low specificity (158). For example, one ingredient, sodium bromate, is a general-purpose oxidizing agent; and ingredients other than those we mentioned can be substituted. As we have noted, the term *BZ reaction* refers to a family of chemical reactions.

If Behe is right, then mousetraps are not irreducibly complex either. Their components also have low specificity. The steel used in their construction has a wide range of uses, as does the wood used for the base. You can substitute plastic for wood and any number of metals for the spring and hammer. Mousetraps are easy to make (which is why they are cheap) and will work with metals manifesting a wide range of tensile strengths. Either the BZ system is an irreducibly complex system, or the mousetrap is not a model for irreducible complexity. Take your pick, because you cannot have it both ways.

Moreover, crucial components of Behe's own biochemical examples of irreducible complexity have multiple uses and lack substrate specificity (interact with a wide variety of substrates). For example, plasminogen (a component of the irreducibly complex blood-clotting cascade) has been documented to play a role in a wide variety of physiological processes, ranging from tissue remodeling, cell migration, embryonic development, and angiogenesis as well as wound healing (Bugge et al. 1996). And although Behe (1996) tells us that plasmin (the activated form of plasminogen) "acts as scissors specifically to cut up fibrin clots" (88), we learn in one of the very papers he cites that "plasmin has a relatively low substrate specificity and is known to degrade several common extracellular-matrix glycoproteins *in vitro*" (Bugge et al. 1996, 709). This component of an irreducibly complex system is evidently nothing like the fan belt of a car "specifically adapted to the cooling fan."

Nor, for that matter, are all the components of the clotting pathway necessary for function. Plasminogen-deficient (*Plg*^{-/-}) mice (hence, mice lack-

ing plasmin) have been studied. As noted, plasmin is needed for clot degradation, yet as Bugge et al. (1996) comment,

Plasmin is probably one member of a team of carefully regulated and specialized matrix-degrading enzymes, including serine-, metallo-, and other classes of proteases, which together serve in matrix remodeling and cellular reorganization of wound fields. . . . However, despite slow progress in wound repair, wounds in Plg^{-/-} mice eventually resolve with an outcome that is generally comparable to that of control mice. Thus an interesting and unresolved question is what protease(s) contributes to fibrin clearance in the absence of Plg? (717)

The reasonable conclusion is that, if Behe's examples are indeed examples of irreducibly complex systems, then so is the BZ system. Hence, self-organization is evidently a pathway to irreducible complexity and one that involves no intelligent design, supernatural or otherwise.

Construction without Intelligence

Looking at the pyramids of Giza, we see huge, intelligently designed, complicated structures built by humans about 4000 years ago. These are structures with a definite function. They are not natural formations; thousands of people built them over many decades. The work was carefully planned and executed. The structure is a result of the planning of architects, the blueprints of engineers, the organization of bureaucratic and military commanders, and the work of many laborers.

Social wasps construct paper nests with complexity and relative size that is similar to that seen in structures of intelligent human construction. Where are the blueprints, the engineers, and the hierarchical chain of command in the execution? As Maurice Maeterlinck (1927) asked, "What is it that governs here? What is it that issues orders, foresees future, elaborates plans and preserves equilibrium?" (137)

These are interesting questions, because the structure built by insects with their tiny brains and limited intelligence seems to be beautifully regular and complicated even for us human beings. It seems certain, however, that no wasp possesses knowledge of the ultimate form of the structure, and the duration of the building process generally spans several lifetimes of an individual. Apparently, coordinated construction activity does not depend on supervisors. As biologist Thomas Seeley (2002) has observed, "The biblical King Solomon was correct when he noted [in Proverbs 6:7], in reference to ant colonies, there is no guide, overseer or ruler" (315).

Organizing construction activity among humans generally requires a well-informed leader who directs the building activity of the group, providing each group member with detailed instructions about what to do to contribute to the global result. A group of unskilled workers building a barn under the command of a master carpenter is a good example. The resulting barn is not the result of self-organization, because we can halt the construction by removing the master carpenter or by blocking the information flow from the master carpenter to the other workers.

Construction of more-sophisticated structures generally requires something more than a construction leader. These activities also require blueprints. Blueprints are compact representations of the spatiotemporal relationships of the parts of structures. A blueprint may be a small replica (a scale model) or a detailed drawing, perhaps accompanied by explanations.

Blueprints result from the creative acts of intelligent designers. They typically require skilled on-site interpretation. They also enable the construction workers to produce a more-sophisticated structure than they could without the blueprint. Simply following a set of instructions is similar in several respects to using a blueprint. A set of instructions provides step-by-step construction procedures that typically do not require skilled interpretation. A good example is the construction of an elaborate Lego structure, following the directions of an enclosed booklet that shows which kinds of blocks have to be attached to the incipient structure and in what order. None of these approaches to the construction of structures is based on self-organization. Removing the blueprint or the set of instructions will stop the construction or lead to disaster.

Humans also use templates to construct simple items. Templates are different from blueprints and sets of detailed instructions: rather than functioning as an aid for workers to carry out complicated construction, templates ensure the production of consistent and reproducible units such as bricks. There are numerous analogs of these human approaches to the design and construction of structures in the nonhuman, biological world (Camazine et al. 2001).

Social wasps build nests to keep their carnivorous larvae in one location yet separate them from each other. Early analysis of construction behavior involved little more than division of the behavior into acts of instinct and acts of intelligence. Thorpe (1963), for example, went so far as to claim that wasps use a mental blueprint to guide nest construction. Results of further experiments and perturbation of the construction behavior suggested that, instead of a mental image, the construction behavior was driven by an inherited building program: a set of instructions coded in the wasps' genes (Evans 1966).

The main problem with these early ideas was that they did not include any analysis of the role of ongoing inspection of the changing state or condition of the incipient structure and the subsequent use of this information to modify the behavioral states of the insects involved in nest construction. It was also assumed that “the more complex the nest construction becomes . . . the more sophisticated the building programme must be. Hierarchical level of evaluation, subroutines within the building programme, and learning capabilities appear to be the ways of achieving this sophistication” (Downing and Jeanne 1990, 105). Learning, along with use of construction leaders, blueprints, and sets of instructions, is costly and may require developed cognitive abilities. With the possible exception of learning, these other approaches to construction are often highly sensitive to small errors whose consequences can rapidly become catastrophic.

In fact, it now looks as though social insects rely on simple self-organizing construction processes that do not require sophisticated cognitive abilities and are also error-tolerant. The explanation we will provide here is based on decentralized coordination, in which individuals respond to stimuli provided through the common medium of the emergent nest. In the case of the collective building of a wasp nest, where many individuals contribute to the construction, stimuli provided by the emerging structure itself can be a rich source of information for a given individual. The term *stigmergy* (Grassé 1959) describes the situation in which the product of previously accomplished work, rather than direct communication among the builders, induces the wasps to perform additional labor.

In a stigmergic account of nest construction, the completed nest is a complex structure whose specifiable morphology reflects the behavioral repertoires of the insect builders as they respond to a multiplicity of chance encounters with a changeable, contingent environment during the construction. The construction is thus not the unfolding of a preordained plan—intelligent, genetic, or otherwise. As environmental encounters vary, so do the shapes of the nests constructed. Construction is not teleological; it occurs with no view to the future.

Moreover, even when two nests have more or less the same shape, they are not built in exactly the same way, repeatedly and reliably, as if by an automatic, preprogrammed process. Stigmergic accounts of nest construction recognize that there are many construction pathways to a nest of a given general shape. The pathway actually taken (which wasp does what in response to local cues and when) reflects both the internal states of the wasps and the many chancy, unpredictable contingencies associated with the actual construction.

The result of this dumb process is a complex structure that gives the misleading appearance of being intelligently designed. Here is how it happens.

Hexagonal cells are the basic unit of the wasp comb. Hexagonal cells are a very efficient way to fill a two-dimensional space and also very economical. But how, exactly, do these regular structures emerge? Detailed observations show that hexagonal forms are a predictable by-product of cell-building activity and do not require any higher-level rule or information (West Eberhard 1969, Karsai and Theraulaz 1995).

The hexagonal cells emerge from wasps' attempts to make conelike structures. When a wasp lengthens a given cell, it also tries to increase its diameter. Imagine that the wasp builds a cone by adding a small quantity of material to the lower edge of the cone. Several cones are linked, however; and if the wasp detects another cell adjacent to the cell it is building, it slightly modifies its posture and does not extend the cell in that direction. The result of this behavior can be seen very clearly in the cells that are on the periphery of the comb. They have two or three neighbors, and all sides facing outward are curved (see figure 7.3). Later, when new cells are added to the comb, these outer cells become inner cells and are turned into hexagonal cells. The hexagonal shape emerges without a blueprint, as a result of a simple building rule that is based only on local information. The hexagonal cell is just one of the

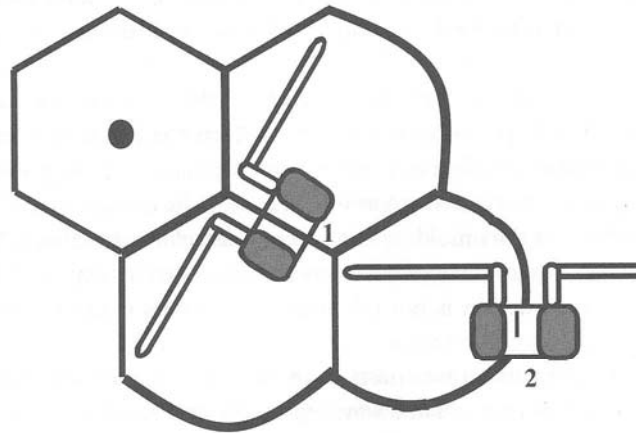


Figure 7.3. Cell shaping by wasps (head shown only, view from below). The cell with the black dot has six neighbors (just two are drawn) and has a perfect hexagonal shape. Peripheral cells have a straight border with their neighbors, but neighborless sides are curved. In these cells, wasp 2 increases the diameter of the cell by pushing the building material outward while its head is tilted. When a cell wall is built between two cells, the head of wasp 1 is not tilted, and the cell wall becomes a straight line.

emergent regular characteristics of the wasp nests. These cells form a comb, which has a definite (generally regular) structure. One of the most common comb shapes is a hexagonally symmetrical shape (see figure 7.4).

The hexagonally symmetrical comb shape has several adaptive advantages: it requires less material per cell, is better in terms of heat insulation, and, because of its small circumference, can be protected easily. But the adaptive explanation of this compact cell arrangement will not tell us how wasps built this structure. Philip Rau (1929) concluded from his experiment that the hexagonal symmetry is learned. Istvan Karsai and Zsoltan Péntzes (1993) analyzed the nest structures and the behavior of wasps and argued that the construction is based on stigmergy.

In a stigmergic type of construction, the key problem is to understand how stimuli are organized in space and time to ensure coherent building. The hexagonally symmetrical structure emerges as a global pattern without deliberate planning. It is a by-product of simple rules of thumb that are triggered on the basis of local information (the wasps do not experience or conceive the shape of the comb).

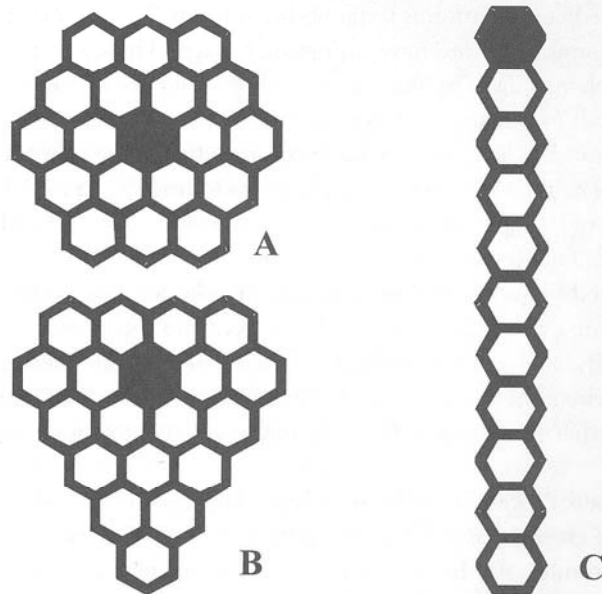


Figure 7.4. Different shapes of wasp combs (view from below, cells drawn as idealized hexagons). Dark cells are the first cell where the comb is attached to the substrate. Type A is the most common hexagonally symmetrical comb; a type-B comb has a single symmetry axis; and type C, the rarest, has a single cell row. The combs can grow much larger while keeping the same form.

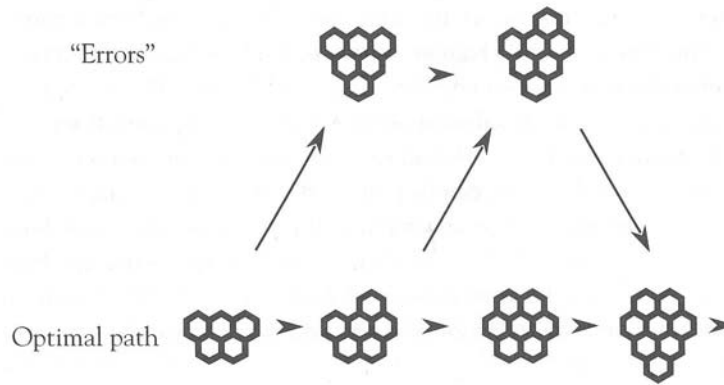


Figure 7.5. Wasp nests grown cell by cell. The optimal way to increase cell number is depicted in the bottom row. In real wasp nests “errors” (suboptimal forms) emerge as well. Faithful use of a blueprint or recipe would not allow errors in the system. The errors indicate that the wasps use a simple rule of thumb to construct their nest. Analysis of these errors helped investigators find the rule of thumb guiding construction.

Karsai and Péntzes (2000) examined several candidate rules of thumb and compared predicted nest forms to natural nest forms. They found that not all of the nest forms in nature have an optimal shape. These suboptimal forms could be explained away as anomalies, or they could be consequences of the rules of thumb (see figure 7.5). Karsai and Péntzes considered these “faulty” nests to be real data and the inevitable consequence of the rule of thumb actually used. The next step in their analysis was to find the rule of thumb that generates all of the optimal shapes as well as the faulty structures (that is, the complete set of natural nests).

Karsai and Péntzes (2000) examined the predictions of several candidate rules of thumb. One of the rules was able to generate the whole set of natural nest forms. The rule can be described in functional terms as follows: construct a new cell, where the summed age of the neighbors of the new cell shows the maximum value (see figure 7.6). This rule gives rise to the maximum age model.

Karsai and Péntzes showed that a beautiful, regular, and adaptive structure emerges even if the builders are unaware of this regularity. The builders follow simple rules. As the nest grows and changes during construction, the nest itself provides new local stimuli to which the rule-following builders respond. As the builders respond to changing local stimuli, a globally ordered structure emerges. It is as if the developing nest governs its own development; the builders are only the tools. The wasps do not follow the ages of cells and sum their ages for their decision. In fact, several parameters correspond to the

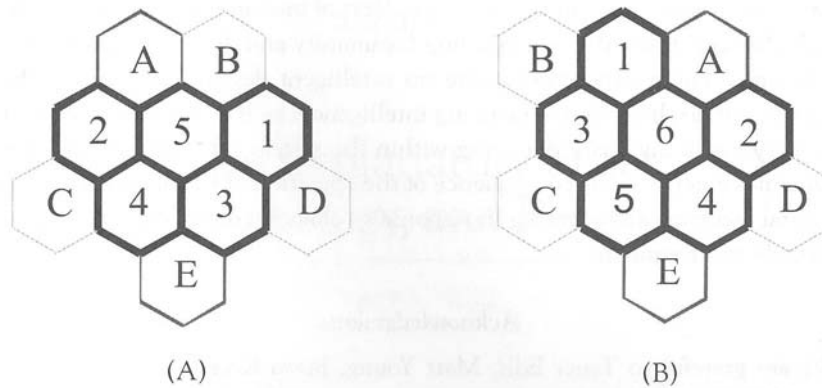


Figure 7.6. Nest building using the rule, “Construct new cell, where the summed age of the neighbors of the new cell show maximum value (that is, a maximum age).” Thick cells show the current structure. Numbers in the cells show their age. (In example [a], the upper middle cell with number 5 is the oldest.) Cells with thin walls and letters in them show the locations of initiation positions in case of random cell initiation. In example I, for positions A (2+5) and E (4+3), the summed age of the neighbor is equal; thus, the maximum age model predicts one of two possible forms to emerge. If position A is chosen for the sixth cell, then we have a six-celled form shown in example (b). Here again, the maximum-age model selects positions A and E with the same stimulus strength (9), which means that two possible forms can emerge again.

age of cells: cells become longer and wider as they age, and they absorb more chemicals. These constitute the local information that can be sensed by the wasps.

Now that we have explained how the regular hexagonally symmetrical comb shape emerges, it is natural to try to understand how other comb shapes emerge (see figure 7.4). Does every shape need a unique rule of thumb? Using the stigmergy approach, Karsai and Péntzes (1998) showed that the variability of comb forms can be deduced from the same construction algorithm. Tweaking a single parameter of the model, the authors generated all forms found in nature and, interestingly, only those. This shows that variability and complexity may emerge in a very simple system in which interacting units follow simple rules and make simple decisions based on the contingencies of local information.

Communities of nest-building wasps are open-dissipative systems. The internal dynamics of these systems is driven by flows of energy through the system and constrained by parameters derived from the environment with which the insects interact. The elaborate, structurally coherent nests are highly improbable forms that could not have arisen by chance. In fact, these orderly,

low-entropy structures emerge as the products of interactions between the insects that constitute the nest-building community and their immediate environments. These structures require no intelligent design from outside the system, nor do they require a guiding intelligence, be it a single individual or collective of individuals, operating within the system. The orderly, complex structures emerge as the consequence of the operation of blind, unintelligent, natural mechanisms operating in response to chancy, contingent, and unpredictable environments.

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