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Diversity and Complexity

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I have many people and places to thank for their assistance with my efforts on this book. A decision by the Santa Fe Institute and Princeton University Press to create a series of books demonstrating the advances in the science of complexity was the impetus for this particular book. Elementary physics informs us that a slight push can have a large effect provided that the object sits atop a big hill. For me, that hill (literally) was a year spent at the Center for Advanced Studies in the Behavioral Sciences at Stanford. The center afforded me the time and space needed to complete a rough draft. My return to the University of Michigan provided a yearlong "author meets critics" session that improved the text that follows. A USAF MURI grant and NSF IGERT and HSD grants provided funding to allow me to workshop portions of the text as well.

In researching this book, I gained renewed respect for the scholarship of many people, most notably, Simon Levin, Steven Frank, Rick Riolo, David Krakauer, Jenna Bednar, Bobbi Low, Melanie Mitchell, and Martin Weitzman. A book of this scope demands broad strokes and limited detail. Many times, I felt as though I stood before a paint by numbers canvas holding a spray gun. One cannot help but feel one's own sweeping attempt to contribute to be inadequate by comparison with the detailed care with which these scholars approach questions.

I wish to especially thank John Miller, whose vision inspired this series, and Chuck Myers, for cracking the whip and editing the text. Without Chuck, this project might not have been finished until May 2014. Throughout the writing, Howard Oishi and Mita Gibson prevented me from spiraling into an administrative abyss. Without the suggestions, critiques, and ideas of many friends and colleagues who've contributed to this project, I doubt I'd have finished it. Simon Levin, Rajiv Sethi, Bill Clark, Sarah Cherng, Jenna Bednar, and P. J. Lamberson commented on earlier drafts of this book and found some glaring errors in fact and logic. Andrea Jones-Rooy worked through the entire text and relieved the reader of twenty-seven and a half tedious paragraphs and two hundred and sixteen unnecessary flowery adjectives. Evan Economo gave a near final draft a thorough reading and identified no fewer than eleven places where I would have offended natural scientists. Thanks to all.

I've dedicated this book to a diverse, complex pair of muses: Stan Reiter and Carl Simon. Over the years, Stan and Carl, along with their partners Nina and Bobbi, have offered guidance, wisdom, patience, and love to me and to my family.

To Orrie and Cooper, my constant reminders of the complexity that diversity can produce, I marvel at your abilities to find and produce joy. And to Jenna, as our continuous lives increase in dimensionality and depth, you remain the helium in my balloons, the peach in my cobbler, and the warm home at the end of the prairie's winding path.

DIVERSITY AND COMPLEXITY

PRELUDE: THE MEANING OF DIVERSITY

The diversity of the phenomena of nature is so great, and the treasures hidden in the heavens so rich, precisely in order that the human mind shall never be lacking in fresh nourishment.

—JOHANNES KEPLER

In writing this book, I have been fortunate to be guided and motivated by the efforts of an incredible collection of scholars. The study of diversity and complexity attracts a vast array of scholars from multiple disciplines whose passion, intelligence, and energy inspire awe. In what follows, I attempt to pull together ideas, concepts, models, and results that intersect with the topics of diversity and complexity, and to make sense of research from multiple disciplines. It proves a daunting, humbling, and ultimately, exciting task.

The book combines illustrative examples, formal models, and bits of data to produce an overview of the interplay between diversity and complexity. The relationship between the two is not always easy to understand. Diversity and complexity lie at the core of many of the challenges that we currently face: managing ecosystems, organizations, and economies. Progress in these domains or, more modestly, continued survival can only benefit from a more nuanced understanding of diversity in complex systems, and that requires naming the parts and learning how those parts combine. It means that we must go beyond stories and analogies. We have to test intuitions and metaphors against logic and empirical reality. For example, it's not enough to say "diversity enhances robustness." If we are to take intelligent action, we need to define our terms precisely—what is diversity? and what is robustness?

For those people who feel diversity to be of paramount importance for the continued flourishing of societies, economies, and ecosystems, I hope that this book provides theoretical foundations to support that passion. A warning though: the book challenges the naïve assumption that we should always prefer more diversity to less. Too much diversity, as I show in several places, can produce catastrophe or inefficiency. Rotating the presidency of the European Council between a few countries has advantages. Leadership diversity produces innovative policies and prevents the concentration of power. Rotating it among dozens of countries, though, may create policy instability (Kollman 2003). Even if on balance diversity's a good thing, we can have too much of it.

For those people who do deep scientific work within a particular discipline, accept my apologies that this book covers a lot of territory that you already know. But it will also, I hope, introduce a few new measures, concepts, models, and theories from other disciplines that spark new ideas. Working across the disciplines requires translating formal language (one person's epistatic interaction is another person's externality or spillover), suffering through notational conventions, and learning implicit assumptions. My not so secret hope is that this book introduces some ideas that "jump the silo" of their home discipline and advance interdisciplinary science.

The title of this prelude, "the meaning of diversity", should evoke three interpretations: *importance*, *essence*, and *averaging*. The importance of diversity in complex systems is the central theme of this book. Why does diversity matter? What roles does it play? I show that diversity has many roles and effects. Diversity can provide insurance, improve productivity, spur innovation, enhance robustness, produce collective knowledge, and, perhaps most important in light of these other effects, sustain further diversity. But diversity, for all its benefits, is no panacea: It can contribute to collapse, conflict, and incomprehensible mangles.

As for essence, in the next chapter I struggle with how to categorize types of diversity. Eventually, I distinguish between three types: *variation within* a type, differences *across* types, and differences *between* communities or systems. Each of these types can be measured in several ways and each has distinct functions within complex systems. Variation allows for local search, provides responsiveness to minor changes in the environment, and serves as an engine for diversity of types. Diversity across types creates synergies. It allows the whole to be more than the parts. And diversity between communities provides robustness to major changes.

As for averaging, I mean to provoke. Empirical scientists—be they social, physical, or natural—often rely on statistical techniques to make sense of the world. Statistical regressions, for the most part, report means (averages). Means reveal general tendencies that can be misleading. For that reason, economists, especially those interested in policy effects, have increasingly turned to quantile regression techniques (Koenker and Hallock 2001). Quantile regression enables empirical scientists to estimate effects in different parts of the distribution. For example, the average effect of an increase in the gasoline tax can be determined for different segments of the income distribution. Rather than estimate a society-wide mean effect, quantile regression can estimate the effect on the median person in the bottom fifth of the distribution, the next fifth, and so on.

In a complex system with feedbacks, the system generally cannot be approximated by an aggregate variable (Osgood 2008; Iwasa, Andreasen, and Levin 1987). If 1 percent of the population earns 50 percent of the income, an increase in average income need not be indicative of broadly improving welfare. It might just mean that the rich have become richer. A book, such as this, that focuses on diversity pushes back against the tendency toward averaging both for pragmatic reasons—to highlight the value of looking beyond means—and for aesthetics—to call attention to what Janet Malcolm (2008) calls "the gorgeousness of the particulars of the things that are alive in the world."

This book is about diversity and complexity. I'll start with diversity. The single word that jumps to mind in thinking about diversity is *wonder*. When I read research by ecologists who document the diversity of ants and orchids or studies by anthropologists that richly describe differences in human cultures, experiences, and languages, I have a common reaction. I'm awed by the beauty and the intricacies of those differences, and by the curious balance of randomness and assembly. Take humans. We combine idiosyncratic frozen accidents (why not six toes?) and highly functional parts like the lung and the brain. Some differences seem necessary; other differences seem, well, like oddities.

My analysis of diversity starts with two questions: what is it, and why do we see it? To tackle the first question, I survey various measures of diversity. Ecologists, physicists, and statisticians measure diversity differently. By putting all the measures in a common framework, I make it easier to see the strengths and biases of each. I found attempting to answer the second question—why we see diversity and why we don't—to be a lot of fun. We accept without much thought that at restaurants soda pop comes in three sizes, beer comes in two, and wine comes in one. But why?

One day on the University of Michigan's Central Campus, I decided to look at the diversity in the color of male students' pants. I found that over 90 percent wore either blue, black, or khaki pants. By any measure of diversity (and I present a bunch in the text) that's not much. If I were to do the same experiment in Amsterdam, I'd get much more diversity. Why? Or, consider that entomologists have identified nearly 15,000 species of ants and estimate double that number exist, but chemistry identifies fewer than two hundred elements. Again, why?

I end up dividing the "why do we see diversity" question into two parts. I first consider the causes of diversity. How does it get produced? I cover a complete set of causes in the text, but will mention two here. In human systems, one obvious cause is slippage (Bednar 2006). Mistakes happen. Those mistakes create variation and variations accumulate into difference. Another cause is creation. People just think up the coolest stuff: the Fosbury Flop, the sonnet, and that miniature three-legged plastic table that keeps the pizza box top from collapsing.

I then consider constraints. Given the many sources of diversity, without constraints we'd have too much of it. These constraints transcend disciplines. For any type of entity, there exists a size of the possible. One can imagine many types of houses but not many types of ball bearings. Physics also constrains diversity. The bones needed to support a five-hundred-foot tall human would weigh so much, the person couldn't move. So, we can't (as much as I used to like to think it) be living in a *Horton Hears a Who* world, in which we reside on a speck on a dandelion in a much larger world. I cover other constraints in the book. Here, I just want to make clear that it's possible to construct logic that partly explains why we see the diversity that we do.

After writing what amounts to a brief, interdisciplinary primer on diversity, I then turn to understanding the functions of diversity in complex systems. At this point, I should provide some background on complexity and complex systems (Miller and Page 2008; Epstein 2006; Mitchell 2009). By complexity, I mean elaborate temporal and spatial patterns and structures. Complex phenomena are hard to describe, explain, or predict—like the weather or the economy. I provide formal definitions of complexity in greater detail later, but these will do for now.

To get a feel for complex phenomena, we also need to understand the systems that produce them. Complex systems are collections of diverse, connected, interdependent entities whose behavior is determined by rules, which may adapt, but need not. The interactions of these entities often produce phenomena that are more than the parts. These phenomena are called *emergent*. Given this characterization, the brain would count as a complex system, so would a rainforest, and so would the city of Baltimore. Each contains diverse, connected entities that interact. Each produces outcomes that exceed the capacities of its component parts. Neurons are simple. Brains are complex.

By way of comparison, a calculus exam and a blender would not be complex, though for different reasons. The parts of a calculus exam—the questions—don't interact. It's a fixed set of problems, so it may be *difficult* but it won't be complex (Page 2008). The blender won't be complex either, but for a different reason. It cannot adapt. Yes, it has diverse parts, and those parts follow rules governed by physical and mechanical laws, but those rules don't allow it to respond to the environment. As a result, the blender itself is a fixed-number-of-tricks pony: blend, puree, and liquefy. It cannot toast bread or make french fries. A blender, like most machines, is therefore *complicated*. The line dividing complex and complicated gets blurry in places. I would classify Boeing's 787 airplane, which uses flight guidance software, as complex. Others might see it as complicated.

Unlike blenders, most complex systems are not predictable. Owing to the interdependence of actions, complex systems can be predicted only in the very short run. Maps from genotype to phenotype, weather patterns, and economies are all complex and not easily forecast even with abundant data (Orrell 2007). The particulars that emerge within complex systems are also difficult to predict. Who could have expected the koala, the macarena, or Super Mario Brothers? As for stability, though often robust, complex systems are also capable of producing large events, such as mass extinctions (Erwin 2006; Newman 1997) and stock market crashes. Owing to the interactions between entities, complex systems produce these large events far more often than would be predicted by "normal" that is, Gaussian fluctuations.

As a result, complexity creates problems for analysis. In systems that produce static equilibria, we can gauge the effect of changing levels of diversity by performing *comparative static analysis*. We can measure how the equilibrium changes when diversity is increased or decreased, and we can quantify the effect. We can say things like "increasing the diversity of preferences results in price increases." In systems that produce complex outcomes, such as long transients with emergent patterns, we cannot make such simple comparisons. For that reason, examples in which diversity has isolatable, direct effects prove rare. And any foray into scholarly research on the impact of diversity in complex systems proves a humbling experience.

That said, some broad general claims do appear to hold across contexts. First, diversity often enhances the robustness of complex systems. By robustness, I mean the ability to maintain functionality (Jen 2005) rather than analytic stability. Systems that lack diversity can lose functionality. History has many examples of failure through lack of diversity, the potato famine being among the more notable.[1] The potato must be counted among the most precious of the gifts introduced into Europe during the age of exploration. Of the thousands of varieties of potato grown in Central and South America at their disposal, the Europeans imported primarily two. This lack of genetic variation presented a huge target for parasites. When the potato blight hit, it found field upon field of genetically similar potatoes. Though nearly a million Irish perished, even more relocated to America. Diversity at the community level—America had a different mix of crops from Ireland—minimized the global impact of the blight. Had every country been subsisting on potatoes as Ireland had, the famine would have been an even worse calamity.

Second, diversity drives innovation and productivity. In biology, the forces of mutation and recombination are well known to be primary sources of innovation. In economies, variation and experimentation also lead to innovation, and, as Arthur (2009) convincingly shows, so does recombination. In fact, recombination may be the biggest driver of economic and scientific innovation. As for productivity, I've covered some of this terrain in an earlier book (Page 2007a), but it's worth repeating. Whether one looks at ecosystems, empires, or cities, greater diversity for the most part correlates with greater productivity. Cities that are more diverse are more productive and more innovative.

The productivity and efficiency of ecosystems are harder to measure. Among other approaches, the efficiency of ecosystems can be measured by how effectively they degrade energy. A barren rocky flat degrades energy from the sun less effectively than a forest (Schneider and Kay 1994). I'm taking an aggregate view here. In the case of ecosystem productivity, the relationship varies depending on the scale of the ecosystems and other factors. The same holds for cities: size matters. Thus, any broad claim of correlation such as these will have many counterexamples.

To show how diversity produces benefits, we need not identify synergies and superadditivities. As I show in the book, diversity improves productivity for two rather mundane reasons: averaging and diminishing returns to type. Averaging enables diverse systems to perform well regardless of the state of the world.

Diminishing returns are a widespread phenomenon. Whether one looks at ecosystems and frequency-dependent fitness or firms and diminishing returns to scale, one finds that at some point having more of the same produces diminishing productivity. And, given that diminishing returns implies a benefit to diversity, we should not be at all surprised that productivity correlates with diversity. In fact, I might even go so far as to say that when we don't see diversity producing benefits—such as in some diverse groups of people—we should go looking for a cause. To wit, diverse groups sometimes perform poorly. Often, their failure can be attributed to an inability to communicate or a lack of trust.

Finally, to step away for a moment from objective scientific criteria, diversity merits attention because, at least subjectively, it makes systems more interesting. Diversity is why London or New York is more exciting than Duluth. Why the earth is more interesting than the moon. Why the Amazon rainforest is more interesting than a field of soybeans and an opera is more interesting than a ballad. Diversity alone, though, is not enough. Interestingness requires the right connections and interactions. And those have to be assembled through evolution or through judicious practice (Alexander 2001). Otherwise, we just get gray goo—an incomprehensible mess.

The salience of diversity and complexity in the modern, connected world provides a reason to read this book. Many of the challenges that we presently face—climate change, epidemics, terrorism, segregation, global economic disparities, financial markets, and international policy—involve complex systems. Each challenge involves anticipating and harnessing diverse, adaptive entities, with interdependent actions. These entities interact within contact structures or networks. Actions taken at one time and place often echo across networks of relationships. Small events can trigger large reactions—a football fan forgets a camera, runs back through airport security, and delays hundreds of flights across the United States. And, as mentioned above, within diverse complex systems, large events can often be absorbed with minimal loss of function. For example, the 2009 earthquake near L'Aquila, Italy, wiped out buildings and roads, leaving 70,000 people homeless. Italy's economy, though already in bad shape, took a hit but did not collapse.

The complexity of our challenges arises from the increasing connectedness of the human world. When interactions were few and far between—when farmers went to market a couple of times a year, when armies and crusaders moved by foot and wagon, and when ideas spread primarily by word of mouth, the resulting systems were more episodic than complex. The transition from episodic histories—from brief encounters to multilayered interactions—has been gradual and inexorable (Diamond 1999). I don't mean to imply that ideas and technologies did not spread. They surely did, but the spread was much slower. Technology has reduced distances between people. We cannot help but bump into other people who look, behave, and think differently. Today, as Thomas Friedman so aptly puts it, the world is flat—everything interacts with everything else, at least potentially.[2] The resulting complexity, whether it works for us or against us, depends to a large extent on the amount of diversity.

explore. Understanding the relevance of diversity—especially to robustness—often requires thinking about complexity. By studying diversity and complexity together, we can start to say things about *what kind* of diversity, *when*, and *under what conditions* produces good outcomes (robustness) in systems with *what kinds* of characteristics.

That's not to say that a broad strokes approach such as this doesn't have limitations. Ideas and insights won't always transfer across contexts. An economy is not an ecosystem, and the human brain is not the Internet. The Internet doesn't have a frontal lobe and the human brain doesn't have email (at least not yet).

A critic could argue that because complex systems differ in their particulars, we cannot expect that the functions of diversity in one complex system translate to others. My first response to that position is that we should not aim for a theory that gets the details correct in every specific case, but instead pursue the more modest goal of identifying core functions of diversity—as responsiveness, as fuel, as insurance, etc. Those core insights will fan out across disciplines; they will apply within economies, ecosystems, and biological systems alike. To the extent my belief holds true, the pages that follow have greater value. My second response is that even if the attempt fails, the effort may be worthwhile. By pursuing common principles, we learn which particulars matter.

Furthermore, and this may be equally important, by studying diverse disciplines, we may find concepts and tools that we can apply fruitfully to our own. I cannot resist mentioning research by one of my colleagues at Michigan, Mercedes Pascual. She and Stefano Allesina decided to take Google's PageRank algorithm and apply it to ecosystems

(Allesina and Pascual 2009). They found that a species' PageRank was an excellent predictor of the likelihood that the extinction of that species would lead to secondary extinctions within an ecosystem. Their research can be seen as an example of *horizontal transfer*, which occurs when an idea or solution jumps from one domain to another. Horizontal transfer will be one of many ways in which diversity arises in complex systems. It can also be one of the ways that science advances.

I had two audiences in mind when writing this book. As mentioned, one is that large group of people who care deeply about diversity but who pick up technical journal articles and find themselves overwhelmed by jargon and notation. The second group consists of academics. That group can be divided into subgroups. One consists of individuals who work on issues related to diversity within a single discipline. Diversity spurs the interests of a variety of scholars: sociologists, political scientists, biologists, ecologists, and economists, to name just a few. Learning how other disciplines approach similar and related problems has been eye opening, and at times eye popping. I expect it will be for others as well. The second consists of scholars interested in complex systems who haven't unpacked the contributions of diversity to complexity. A third consists of undergraduate and graduate students looking for interesting research ideas. This book asks more question than it answers. I worry on its completion whether I've accomplished more than depositing puzzle pieces on the floor. If that turns out to be true, I hold out hope that young scholars with passion and vision will read this book and put some of those pieces together.

1

ON DIVERSITY AND COMPLEXITY

Armageddon is not around the corner. This is only what the people of violence want us to believe. The complexity and diversity of the world is the hope for the future.
—MONTY PYTHON'S MICHAEL PALIN

In this chapter, I pose and answer some basic questions. What is diversity? What is complexity? And, why link diversity and complexity—what does one have to do with the other? First, diversity. Diversity applies to populations or collections of entities. A ball bearing cannot be diverse. Nor can a flower. Diversity requires multitudes. Cities are diverse; they contain many people, organizations, buildings, roads, etcetera. Ecosystems are diverse because they contain multiple types of flora and fauna.

When scientists speak of diversity, they can mean any of three characteristics of a population. They can mean *variation* in some attribute, such as differences in the length of finches' beaks. They can mean *diversity* of types, such as different types of stores in a mall. Or they can mean differences in *configuration*, such as different connections between atoms in a molecule.

Complexity proves to be a much more problematic concept. As mentioned in the Prelude, complexity can be loosely thought of as interesting structures and patterns that are not easily described or predicted. Systems that produce complexity consist of *diverse* rule-following entities whose behaviors are *interdependent*. Those entities interact over a *contact structure* or *network*. In addition, the entities often *adapt*. That adaptation can be learning in a social system, or natural selection in an ecological system. I find it helpful to think of complex systems as "large" in Walt Whitman's sense of containing contradictions. They tend to be robust and at the same time capable of producing large events. They can attain equilibria, both fixed points and simple patterns, as well as produce long random sequences.

To provide an example of the type of analysis that follows, I begin with an example of how diversity contributes to complexity in economics. Imagine an exchange market—a bazaar in which people bring wheelbarrows of goods to trade. This example demonstrates how diversity can reduce volatility in a system and also produce complexity. In an exchange market, diversity can enter in three ways: (1) in what the agents bring to buy and sell, their *endowments*; (2) in the agents' *preferences* for the different goods; and (3) in the ways the agents *adapt* to information, specifically prices.

If the market had no diversity, not much would happen. If everyone had identical endowments and preferences, then no one would have any reason to trade. So, we need diversity on at least one of these dimensions just to make the market come to life. Let's add diversity to both endowments and preferences so that agents bring different goods to market and desire different bundles of goods as well. In such a market, we need some mechanism for prices to form. Following standard economics, let's assume that there exists a market maker, who calls out prices with the intent of producing equilibrium trades.

Once we introduce the market maker, we have to take into account how agents respond to prices. Let's start by assuming no diversity. If all of the agents react in the same way, then prices will be volatile. They'll jump all over the place. This volatility results from everyone reacting in the same way to a price that's too low, resulting in a massive increase in demand and a similar rise in price. Gintis (2007) shows that diversity in the learning rules reduces this volatility. Later in the book, I provide a simple model involving negative and positive feedbacks that explains the stabilizing effect of variability in responses. Here, I just wish to raise the point that diversity can stabilize.

This model can be made even more complex. Kirman and Vriend (2001) add realism by dispensing with the market maker. Instead, they allow individual buyers and sellers to strike up relationships with one another. With this added realism, diversity has more subtle effects. If buyers differ in the price at which they value the goods, then buyers with relatively high values tend to pay higher prices. Furthermore, high value buyers exhibit less loyalty than buyers with low values. In this model, diversity produces complexity through the web of connections and reputations that emerge from the system. Without diversity, nothing interesting happens. With diversity, we get relatively stable market prices, but when we look at the agents and how they behave, we see a complex system.

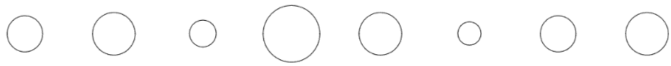


Figure 1.1. Variation: Diversity within a type.

This trichotomy will prove helpful throughout the book as I analyze the effects of diversity. Like most classifications, this one seems great if you don't think about it too deeply. Once you do, problems begin to arise. Take the length of finches' beaks. These differences would seem to fall into the category of variation. However, an ecologist will counter with the fact that finches with different sized beaks eat different types of seeds and nuts and therefore occupy different places in the food network. So, perhaps, we might also think of them as different types. In sum, this categorization won't be perfect, but it provides enough structure for us to move forward.

Variation

Diversity within a type, or variation, is often defined along dimensions, such as length, width, height, circumference, or color. Suppose that you go on a scavenger hunt and find eight marbles. If you measure the diameters of those marbles, you would probably find that they are not all the same. They exhibit *variation* in their diameters.

Variation within a type plays important roles in the adaptability and robustness of complex systems. As I just mentioned, members of the same species exhibit variation in wing size and beak length, and those differences allow them to

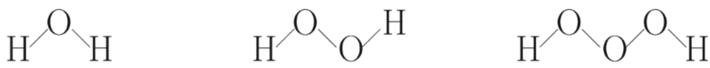
Figure 1.2. Diversity across types.

occupy distinct niches. Not only can the differences produce a fitness or survivability advantage for some members of that species, they also allow the species to adapt to a changing environment.

Differences of Types

When people speak of diversity, they tend to mean differences of types. Suppose that instead of asking you to gather marbles, I asked you to search your house for circular objects. You might find a frisbee, a pizza pan, a dinner plate, and a quarter. This collection would contain *diverse types* of objects even though they are all circular.

These diverse circular objects have different functions. You could eat dinner off a frisbee, and you could play catch with a dinner plate, but neither would be much fun. The functional differences between quarters and pizza pans are even more extreme. You could cook a pizza on a quarter, but it wouldn't be very filling. And, no matter how hard you tried, you couldn't load a parking meter with a pizza pan. These differences in functionalities make the world more complex, as I shall show.



water *hydrogen peroxide* *trioxidane*

Figure 1.3. Diverse community compositions.

Differences in Community Composition

Finally, diversity can refer to differences in community or population composition. Water (H_2O) hydrogen peroxide (H_2O_2) and trioxidane (H_2O_3) all consist of combinations of hydrogen atoms and oxygen atoms, but differ in their relative amounts.

These differences in composition result in distinct emergent properties. Water has all sorts of interesting emergent properties, such as the tendency to form spheres when placed on a leaf or a freshly waxed surface, and even the ability to climb trees. Hydrogen peroxide, which differs from water by only one oxygen atom, is widely used as a disinfectant and as a whitener. It is also unstable. If exposed to sunlight it will decompose into water and oxygen, which is why it comes in brown bottles. Trioxidane, an oxidant that differs from hydrogen peroxide by only one oxygen atom, is also unstable. In the air it will decompose in a matter of minutes. If placed in water, it will decompose into a simple water molecule and an individual oxygen atom almost instantaneously.

Diversity of composition underpins much of the vast type diversity we observe in biology. The cells of all vertebrates come from only a few hundred or so types of cells. Humans, rats, and camels are comprised of muscle cells, nerve cells, glandular cells, and so on. Humans differ from rats not so much in the types of cells that we have, but in the proportions of those cells and in how those cells are arranged. That vertebrates are built from only a few cell types only moderately restricts the set of possible vertebrates. The vertebrates that presently exist are a tiny sample of what is possible (Jacob 1977).

The concept of diversity of composition provides an entrée into the concept of modularity. Many evolved and created systems are modular. Near the end of the penultimate chapter, I discuss how modularity promotes robustness. It's worth noting as well that modularity also simplifies the creation of diversity. Cars have modularized packages of extras. If you can choose from three engine modules, four stereo and communication modules, three interior models, and four trim modules, then you have a choice of one hundred and forty-four cars. The modularization is intended to guarantee that every one of those cars functions.

Complexity

Complexity has many definitions and measures. In the 1980s, Seth Lloyd began counting up definitions of complexity and stopped at forty or so (Lloyd 1988). The multitude of characterizations that Lloyd discovered reflects less a lack of agreement than an inability of any single approach to capture what scientists mean by complex. A similar problem exists for definitions of culture. Hundreds of definitions exist, and each has strengths and weaknesses. For both complexity and culture, a collection of definitions may well be needed to convey the essence of the term.

In discussing complexity, I will also devote time to describing complex systems. A complex system consists of *diverse* entities that interact in a *network* or *contact structure*—a geographic space, a computer network, or a market. These entities' actions are *interdependent*—what one protein, ant, person, or nation does materially affects others. In navigating within a complex system, entities follow rules, by which I mean prescriptions for certain behaviors in particular circumstances. These rules might be fixed: water molecules follow physical and chemical laws that are constant with respect to context.

Often, scholars distinguish between *complex systems*—systems in which the entities follow fixed rules—and *complex adaptive systems*—systems in which the entities adapt. If the entities adapt, then the system has a greater capacity to respond to changes in the environment. Adaptation occurs at the level of individuals or of types. The system itself doesn't adapt. The parts do; they alter their behaviors leading to system level adaptation.

Note that even if the individuals seek or are selected for better performance, we have no guarantee that the system will perform better, the Tragedy of the Commons (Hardin 1968) in which individual self-interest harms collective performance being the classic example of a disconnect between individual adaptation and community failure.[4]

Systems possessing diverse, connected, interacting and adaptive agents often prove capable of producing *emergent* phenomena as well as *complexity*. Before describing complexity, I take a moment to discuss emergence. Emergence refers to higher order structures and functionalities that arise from the interactions of the entities. Ant bridges, market crashes,