GENERAL FEATURES OF COMPLEX SYSTEMS

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Summary

From biochemical reactions to global development, complexity has arisen as a unifying feature of our world. In this arena of complex systems, new approaches are central to advancing our understanding and capabilities. These approaches include recognizing the importance of patterns of behavior; the space of possibilities; and adaptive processes that select effective behaviors for a complex world. As a discipline, complex systems is a new field of science studying how parts of a system and their relationships give rise to the collective behaviors of the system, and how the system interrelates with its environment. Social systems formed (in part) out of people, the brain formed out of neurons, molecules formed out of atoms, the weather formed out of air flows are all examples of complex systems. The field of complex systems cuts across all traditional disciplines of science, as well as engineering, medicine and management.

The excitement of scientists as well as the public about this new field reflects its potential impact on our ability to understand questions that affect everyday life, perspectives on the world around us, fundamental philosophical disputes, and issues of public concern including major societal challenges, the dynamics of social networks, the Internet and the World Wide Web, biomedical concerns, psychology, ecology and global development.

In this article we introduce concepts and key insights that guide our understanding of complex systems. We explain these concepts using simple discussions of fads, panics and cliques, and how memory and creativity works. We describe the interplay of collaboration and competition, and the origin of altruism and selfishness. We discuss the

role of control in human organizations and how the growing complexity of human civilization is accompanied by a shift from central to distributed control leading to a transition no less important than the industrial revolution.

1. Overview

1.1. Parts, Wholes and Relationships

In the last few years the obscurity of science has been shattered by a new approach which touches on many immediate and current problems we care about: how our minds work, how family relationships work, how to organize a business, how society works, how the environment can be protected, how to improve medical care, how effective third world development can be achieved. While scientists continue to learn and debate the opportunities that this new approach can yield, many people, both scientists and non-scientists, are reveling in the new perspectives and insights being gained. This guide is an introduction to the simple and powerful perspectives of "complex systems". To understand why this approach can do so much that is new, we have to recognize the strengths and weaknesses of how science has previously approached understanding the world around us.

Scientists look at something and want to understand how it does what it does. One of the most important observations is that everything is made of parts. So, reasonably enough, we say, let's figure out how its parts work; this will help us know how it works. When we look at one of the parts, we realize that it too is made of parts. The next step is to look at the parts that make up the part. This progresses until we have often forgotten what it was that we were trying to do in the first place. The human body is formed out of nine organ systems; these organ systems are formed of organs, which are formed of tissues, which are formed of cells, which are formed of organelles, which are formed of molecules, which are formed of atoms, which are formed of elementary particles. The same types of molecules form all biological systems. The same types of particles form all matter, living and nonliving. These are powerful and surprising insights that, today, are taken for granted by scientists. Trees and rocks are made of the same building blocks. Physicists take this for granted. People and trees are made of the same building blocks. Biologists take this for granted. Therefore, physicists consider the study of elementary particles to be the study of all of nature. Biologists consider the study of biological molecules to be the study of all life. Science has made great progress by taking things apart. What is left out of this approach is the problem of understanding relationships between the parts. The science of parts has helped us understand the world around us. It is becoming increasingly clear, however, that many important questions can only be addressed by thinking more carefully about relationships. Indeed one of the main problems in answering questions or solving problems is that we think the problem is in the parts, when it is really in the relationships between them.

Scientists generally think that the parts are universal, but the way parts work together is specific to each system. In recent years it has become increasingly clear that how parts work together can also be studied in general and by doing so we gain insight into every kind of system that exists --physical systems like the weather, as well as biological and social systems.

"Complex Systems" is the new approach to science studying how relationships between parts give rise to the collective behaviors of a system, and how the system interacts and forms relationships with its environment. Social systems formed (in part) out of relationships between people, the brain formed out of neurons, molecules formed out of atoms, the weather formed out of air flows are all examples of complex systems. Studying complex systems cuts across all of science, as well as engineering, management, and medicine. It is also relevant to art, history, literature and other humanities. It focuses on certain questions about relationships and how they make parts into wholes. These questions are relevant to all systems that we care about.

There are three interrelated approaches to the modern study of complex systems; (1) how interactions give rise to patterns of behavior, (2) the space of possibilities, and (3) the formation of complex systems through pattern formation and evolution. There are many advances that have made complex systems an exciting area of research today. It is impossible to discuss all of them here, but the taste provided here will hopefully invite further inquiry.

To start things off, in the next two short sections, which are part of the overview, we will introduce the concepts of emergence and interdependence. Sections 2-4 describe each of the three approaches mentioned above.

The second section is about how patterns of behavior arise from interactions. Simple models of local influences give rise to self-organized patterns. Models of influences in more complex networks can be used to study the patterns of behavior of neurons in the brain, or more complex patterns of social behavior. Using these patterns the network structure of the brain can be related to properties of mind. Similar ideas apply to other networks, including social networks.

The third section is about describing complex systems and the way complexity and scale are balanced against each other. Here, the word scale is used just as in phrases like "economies of scale" or "scale of operation" referring to the size of the activity that is taking place. These ideas are related to thinking about the space of possibilities—the possible patterns that can happen, not just the one that is happening. The balance of scale and complexity will help us understand how social systems are organized and how historical changes in society are leading to a networked global society.

The fourth section is about evolution and how making incremental changes can be an effective way to explore the possibilities. It is important to realize that the standard idea that evolution is about competition is not really complete. Cooperation and competition always work together.

1.2. Emergence

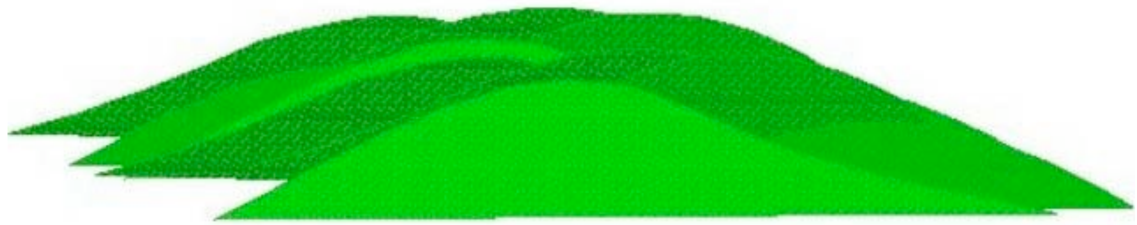

Figure 1: Forest on hills: distant view

In Figure 1 we see a forest on hills. In Figure 2 we see trees, plants and animals. The forest on the hills can be understood as being made up of many trees, animals and other plants. An old expression is "Can't see the forest for the trees". This expression suggests that it is important to have the large-scale view, the long-range perspective. Details get in the way of having this large-scale view. Science has focused on the details, but learning about the long-range view is also important. A forest has its own behaviors; fires and regrowth are part of the natural behavior of a forest. Of course anything that the forest does is made up of many details of what happens to trees and animals and other plants. *Emergence* refers to the relationship between the details and the larger view. It is not about the importance of the details or the importance of the larger view; it is about the relationship between them. Specifically, which details are important for the larger view, and which are not?

Figure 2: Trees, plants, and animals in a forest: closer view

1.3. Interdependence

The study of complex systems helps us recognize and understand indirect effects. Problems that are difficult to solve by traditional approaches are often hard because the causes and effects are not obviously related. Pushing on a complex system "here" often has effects "over there" because the parts are *interdependent*. This has become more and more apparent in our efforts to solve societal problems or avoid ecological disasters caused by our own actions. The field of complex systems provides a number of sophisticated tools, some of them concepts that help us think about these systems, some of them analytical for studying these systems in greater depth, and some of them computer-based for describing, modeling or simulating these systems.

The first issue, however, is just to begin thinking about how parts of a system affect each other. If we take one part of the system away, how will this part be affected, and how will the others be affected? Sometimes the effect is small, sometimes the effect is large; and sometimes there are many effects, sometimes only a few. Consider three examples: a material, like a piece of metal or a liquid, a plant, and an animal.

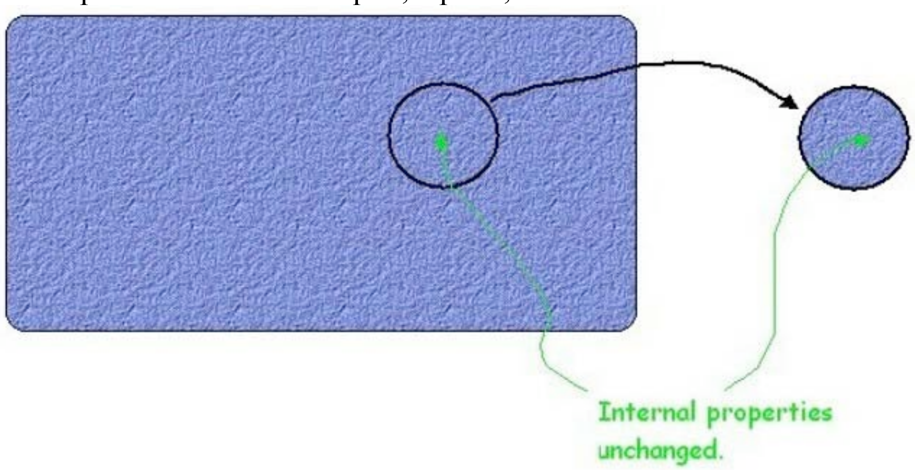

Figure 3: Effects of separation: A piece of material

For the material in Figure 3, the internal properties are not changed, the piece doesn't care, and neither does the rest of the material.

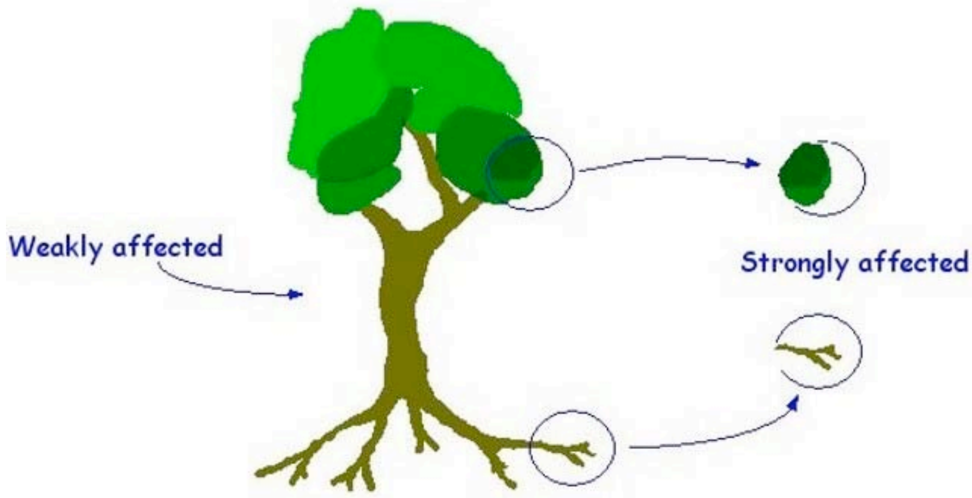

Figure 4: Effects of separation: A plant and its parts

For the plant in Figure 4, if you take a part of it away, like a branch or some roots, typically the plant will continue to grow more or less the way it would otherwise. There are exceptions, like cutting a lateral part of the trunk, but generally the plant is not strongly affected. On the other hand the part of the plant that is cut away is strongly affected. It will generally die unless it is placed in very special conditions.

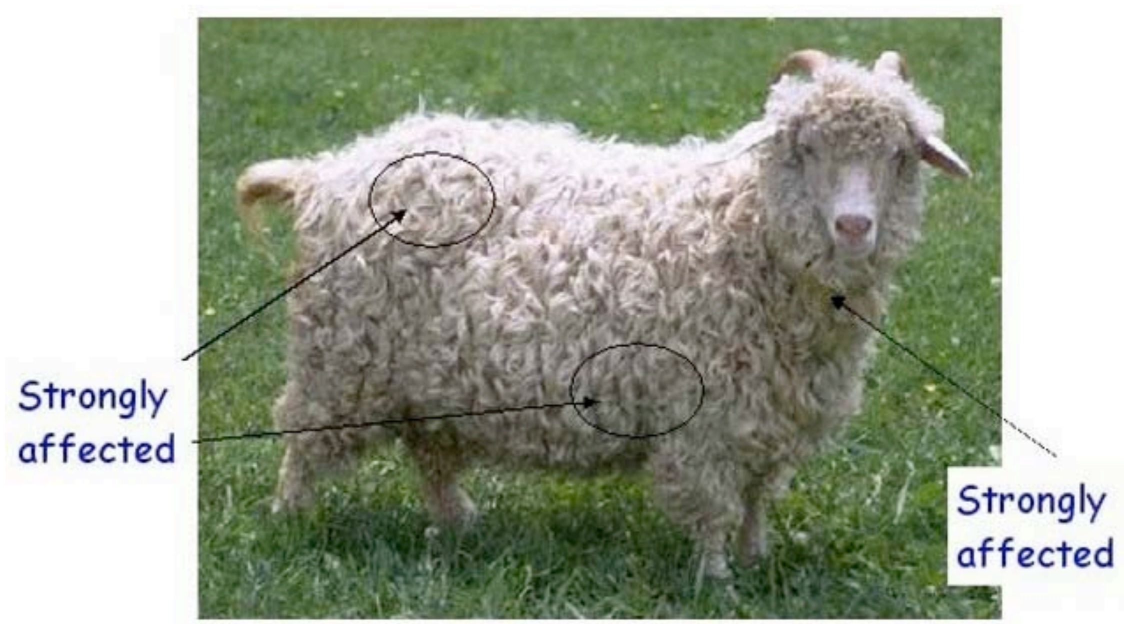

Figure 5: Effects of separation: An animal and its parts

Compare this with an animal in Figure 5. We are not talking about removing part of the wool of the sheep. Taking part of the animal away will have devastating effects both on the part and on the rest of the animal.

These three examples show very different kinds of interdependence. Recognizing that these different behaviors exist is an important part of characterizing all of the systems we are interested in. Consider the family or organization you are part of. How strong are the dependencies between the parts? What would happen if a part were taken away? Does it matter which part? These questions are key questions for understanding the system and how we might affect it by our actions.

2. Self-Organizing Patterns

2.1. What is Pattern Formation?

When people make something, like a car, they put each part in a particular place to make a specific structure that will do a specific task. When someone paints a picture, they place each patch of paint in a particular place to make the picture. In nature we notice that there are patterns that form without someone putting each part in a particular place. The pattern seems simply to happen by itself. It *self-organizes*. Sometimes these patterns are regular, like ripples of sand on a beach or in the desert (see Figure 6).

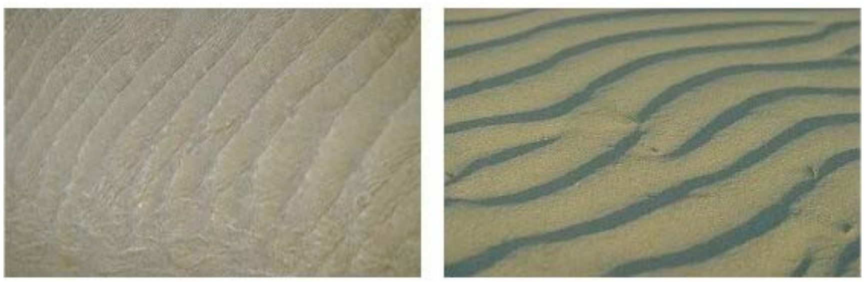

Figure 6: Patterns of sand on a beach and in the desert

Sometimes they are very intricate and have an intricate functioning. One of the most remarkable patterns is the human body itself, which forms from a single cell by a process of *development*. This process is similar to the one that happens for animals, as illustrated in Figure 7 for a mouse (images courtesy of Brad Smith, Elwood Linney and the Center for In Vivo Microscopy at Duke University [A National Center for Research Resources, NIH]). The first two rows at the top are schematic drawings, the bottom two are images of developing mice. During development, some of the cells form the heart, some form the liver, and some form the bones. There is no agent that puts each part in its place. Still, when the process is done the parts work together. How do the cells know where to go, or what form and function to take in each place?

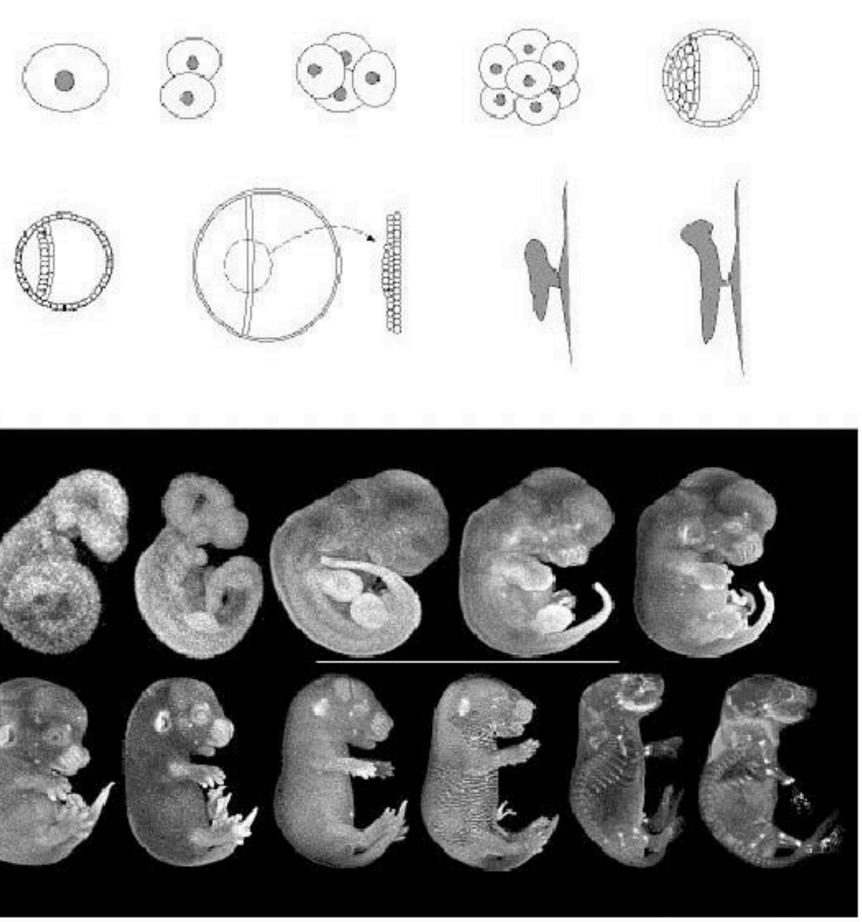

Figure 7: Pattern formation: schematic beginning and images of the development of a mouse fetus

At one time it was thought that there is a small human being in the first cell, a "homunculus" that simply grew in size. We now know that this is not correct. There is a kind of process that is in part directed by the information in the initial cell. Much of this information is found in the DNA in the nucleus of the cell. People still often call DNA a "blueprint" but this is also a mistake, just like the idea of a homunculus is a mistake. A blueprint is a picture of the structure with each part shown. There isn't a picture of a human being there. The DNA information is not in the shape of a human being. In some way, a way we do not really understand, the DNA tells the cell how it should talk to other cells. As they talk to each other, they form the structures of the body. Imagine giving instructions to a brick, about how to talk to other bricks, walking away and coming back to find a house in place with all of the windows, plumbing and electrical systems in place. Even if we had a brick that could move around and morph into plumbing and electrical wires, it is not easy to imagine how this could be done.

As scientists, we would like to understand how this self-organizing process takes place. We would like to understand the mechanism by which patterns form. We would also like to understand how the pattern that arises is determined. This could lead to a revolution in engineering and in management. The idea is that instead of specifying each of the parts of a system we want to build, we can specify a process that will create the system that we want to make. This process would use the natural dynamics of the world to help us create what we want to make.

There is another motivation for understanding self-organizing patterns. Patterns of behavior of human beings in economic and social systems also cannot be explained directly from external forces. External forces cannot explain fads of people buying products, and price changes in stock markets where prices change dramatically from day to day or even minute to minute. Traditional economics tries to understand how behavior is related to external forces. The interactions between people are, however, important in creating fads and market panics as well as day-to-day fluctuations. These are self-organizing patterns. Without understanding how patterns arise from the interactions inside a system we cannot understand these behaviors.

2.2. Examples of Simple Patterns

When different parts of a system act in ways that depend on each other, patterns form. As a first example, consider kindergarten children at circle time who discuss with each other buying Pokemon cards or Beanie babies. Each child starts with what he/she wants to buy, indicated as red or green in Figure 8 (for simplicity shown in a row). Talking with his/her neighbors, the child will change his mind if both neighbors are planning to do the opposite because he/she wants someone to talk to, but otherwise will stay the same. The figure shows what happens over time to the children's decisions as they form patches of Pokemon or Beanie baby buyers. Once they form, these patches are stable over time. Similar dynamics could be relevant to models of other situations, like votes for a president in a two-party election system in the US, or buying and selling in a stock market. As people talk to each other their opinions change. If we placed people in a row and allowed them only to talk to their nearby neighbors, recording what the vote of each person would be, it might also form patches like those in the figure.

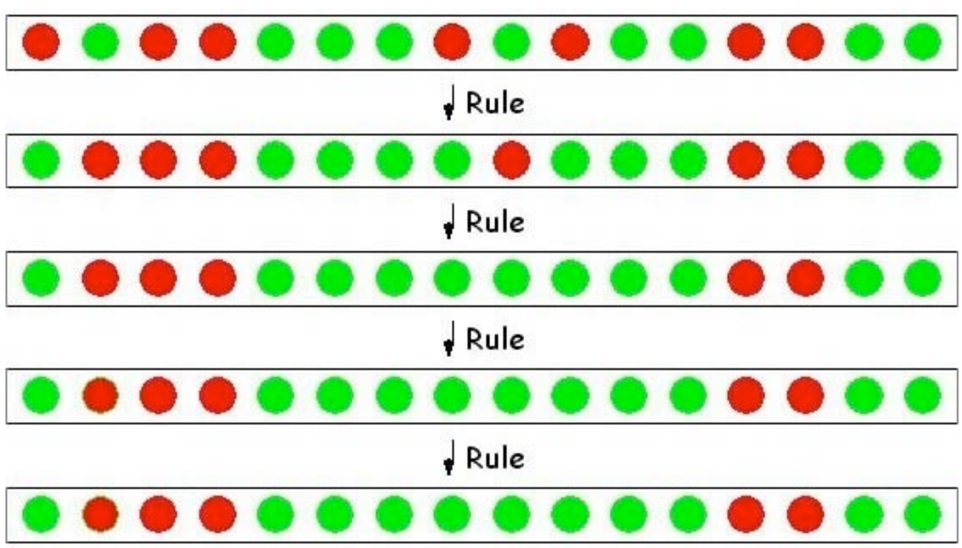

Figure 8: Pattern formation by local communication and influence (the local majority rule)

We can also consider people sitting in an auditorium and talking to each other both in the same row and in front and behind. To be more specific we might consider a model of panic. If there are enough people panicking around a person, the person will tend to panic. So imagine someone yells "Fire!" Depending on how he yells, some fraction of the people in the room will tend to panic. In regions of the auditorium where there are more of these people, the panic will spread. In regions where there are fewer it will tend to disappear. Will the panic spread throughout the room or not? Figure 9 shows a simulation of this rule. Each small cell represents a person and white/black corresponds to non-panic/panic. The first six frames are for the first six intervals of time.

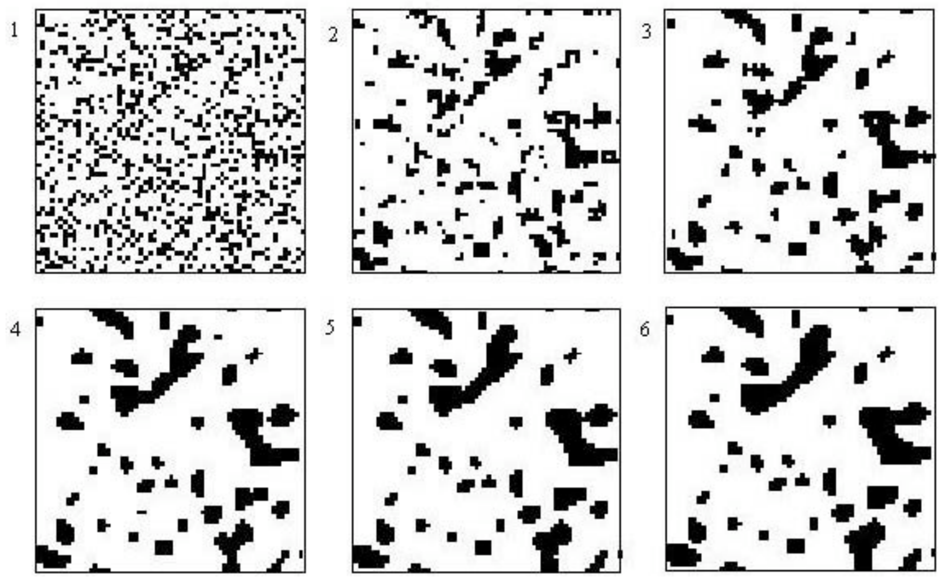

Figure 9: A simple model simulation of the spread of panic —the first six time steps

The next six in Figure 10 are after ten intervals of time.

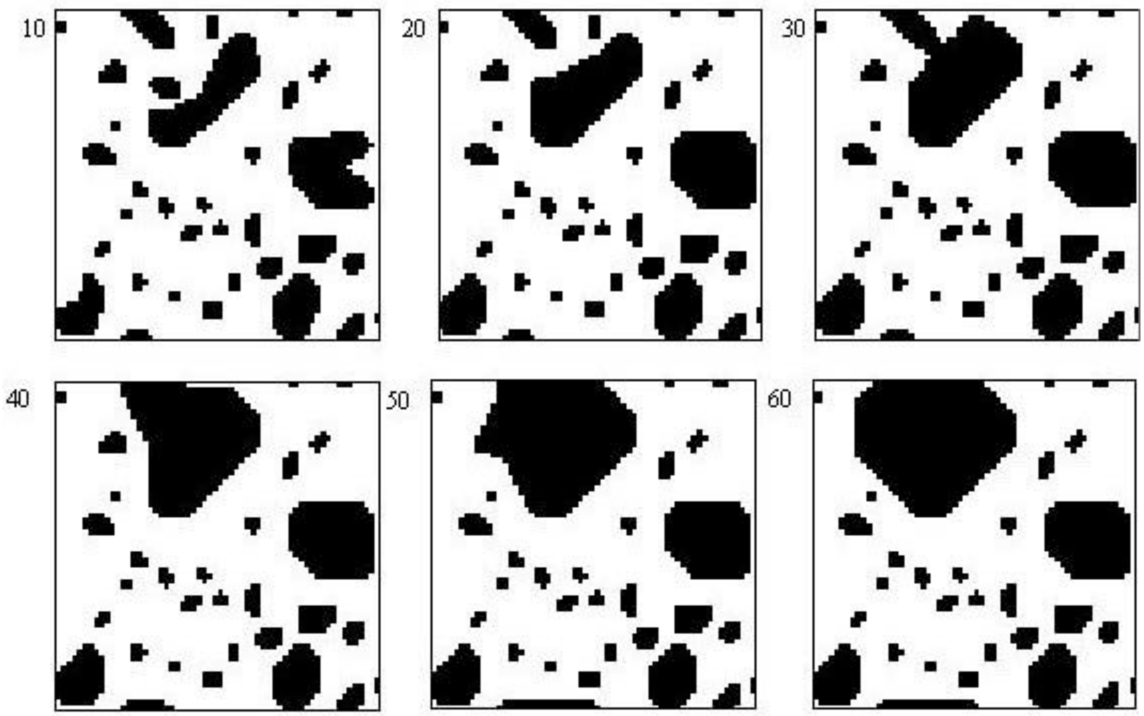

Figure 10: Continuation of a simulation of the spread of panic from Figure 9. Each image is separated from the last by ten time steps

Over the first few updates, the random arrangement of dots resolves into areas of panic. Isolated panickers calm down and regions of higher density become the areas of panic. Then over a longer time, the panicking areas grow and reach a stable configuration. We can try this from a different initial arrangement of panickers. In some cases the panicking areas grow until they combine and fill the entire space. For this rule, in this size space, starting from more than a quarter of the people panicked (black) the panic will grow to cover the space, while for less than this the panic will stay isolated. We can think about this more generally as a model of fads, mobs and hysteria. This model illustrates an important point—the existence of transitions in collective patterns of behavior. Sometimes behaviors feed on each other and involve many people, and sometimes they don't. Understanding exactly what the difference is can be quite hard, but it definitely has to do with the interactions between people, the conditions in which the people are interacting with each other, and the triggering influence (if any).

For a third example, we can consider the patterns that are often found on the fur of both predator and prey mammals: Zebras, giraffes, tigers, and leopards (see Figure 11).

The color patterns of animals have spots or bands of color, which are much larger than the size of a single biological cell. If the pattern were of the size of the cells we would see them as gray. These patterns are formed by cells influencing each other by emitting chemicals into the fluid between them. The chemicals affect not only the cells that are immediately adjacent, but all the cells in an area determined by how fast the chemical moves (diffuses).

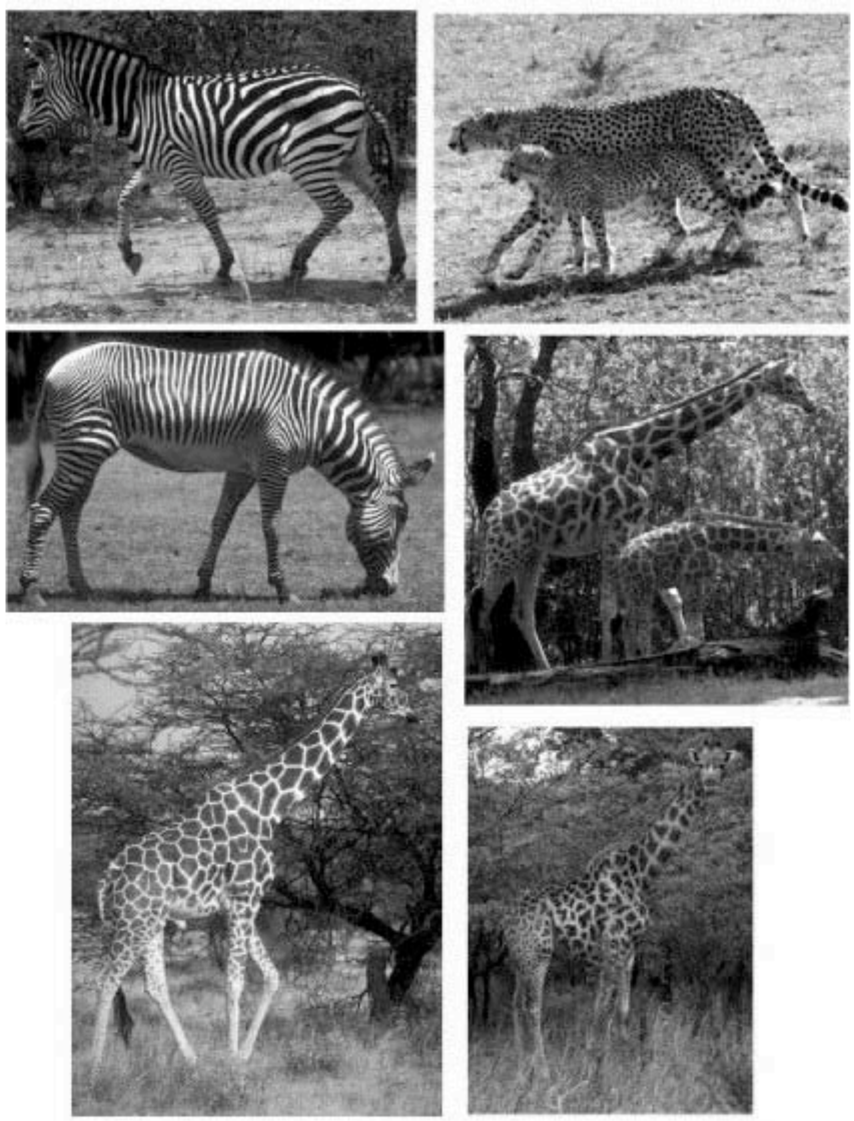

Figure 11: Patterns on animal skins

There are two possible types of interactions, *activating* and *inhibiting*. When a cell producing pigment causes other cells to produce pigment we say that the interaction is activating. When a cell producing pigment causes others not to produce pigment we say that it is inhibiting. The former causes cells to behave the same way, and the latter causes cells to behave the opposite way. To achieve the spotted or striped patterns, there is a local interaction that is activating, and a longer-range interaction that is inhibiting. The dynamics of this model is shown in Figure 12.

Actually, several different types of patterns can be formed. The different patterns arise from a bias that can make cells have a greater tendency towards having more black or white cells. By changing the bias in Figure 13 we can move from having white spots on a black background to black spots on a white background. In the middle of the range are stripy patterns. Local-activation long-range-inhibition models help us understand how patterns in many contexts form. Among them are domains in magnets, clouds, waves on the ocean, traffic jams, and even heartbeats. Social cliques and other groups are another example. People tend to join in groups and cliques and influence each other's behavior to be similar. However, people tend to want to exclude, or behave in different ways from, people who they consider to be different. This causes a kind of patchy local group structure, which is reminiscent of the patterns we are discussing.

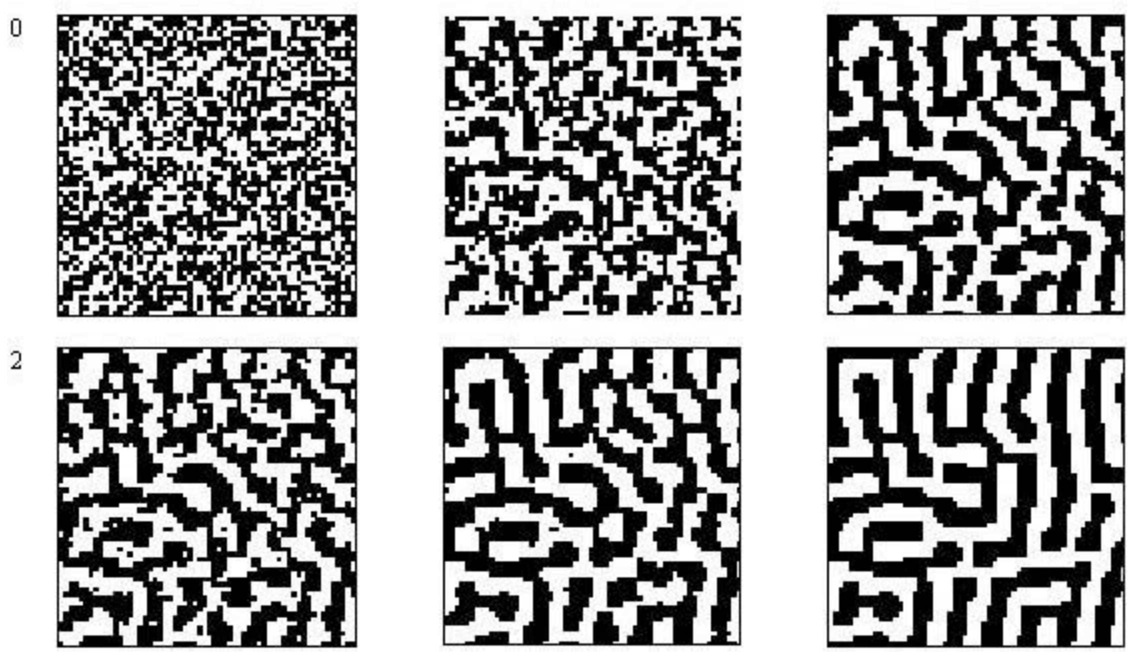

Figure 12: Simulation of the local activation and long-range inhibition model of pattern formation

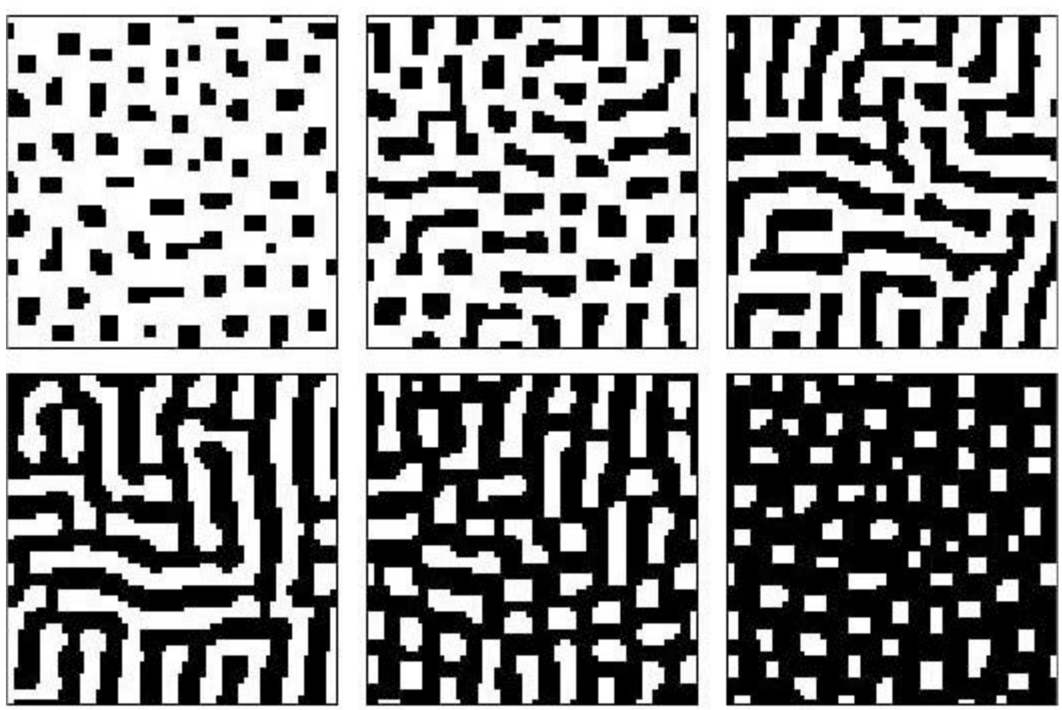

Figure 13: Change in the final pattern due to bias in the local activation long-range inhibition model

When we think about the patterns on animal skins, we can recognize that they are formed during development, but they seem very simple compared to the intricate patterns of tissues and organs that are also formed during development. However, these simple patterns capture an important aspect of all pattern formation—differentiation. Development starts from a single type of cell and creates different types in particular places. The simple ideas of how patterns on animal skins form can be found in ideas about any process of differentiation.

2.3. Patterns in Networks

When we look around ourselves, the patterns in the world become related to patterns in our brains. The relationship between patterns in the world and patterns in our brain gives meaning to the patterns in our brain. The patterns in our brain are different from the patterns we have been talking about because the simple elements of the brain—neurons—are not just connected to nearby neighbors but are connected also to neurons that are farther away. We generally call this more complicated way of connection a network. We can discuss how the patterns in the brain work and learn from this also how patterns in other complicated networks, including social networks, can work.

Neurons in the brain have many diverse forms. For our purposes their behavior can be simplified to two states: active and quiet ("quiescent"). Neurons affect each other through connections called synapses (see Figure 14). Synapses can be either excitatory or inhibitory. These are like the activating or inhibiting interactions of color cells discussed earlier.

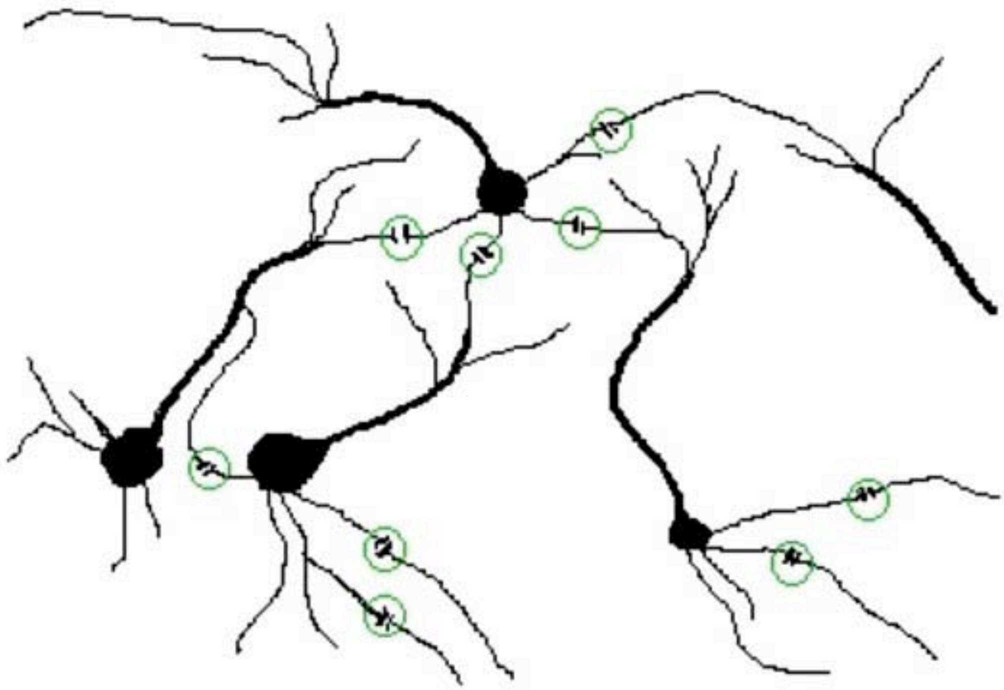

Figure 14: Schematic illustrations of neurons and the synapses between them.

An active neuron will tend to cause another neuron to be more likely to be active through an excitatory synapse and less likely to be active through an inhibitory synapse. Thus, the neural network is quite similar to the models of animal skin patterns. The main difference is that synapses can connect cells that are far apart and the excitatory and inhibitory synapses are not arranged in as straightforward a way as in the local activation long range inhibition case. Nevertheless, we can still talk about the pattern of firing of the neurons at one instant like the pattern of pigment at one instant. Indeed, we can consider the "state of the mind" at a particular time to be described by the activities of all the neurons—the pattern of neural activity. Imagine the pattern of lights that are on or off in a city at night. If you could see into your brain, this is what the activity pattern of neurons would look like (see Figure 15). The pattern of firing of the neurons changes, just like the models of animal skin patterns, because of the influences that neurons have on each other.

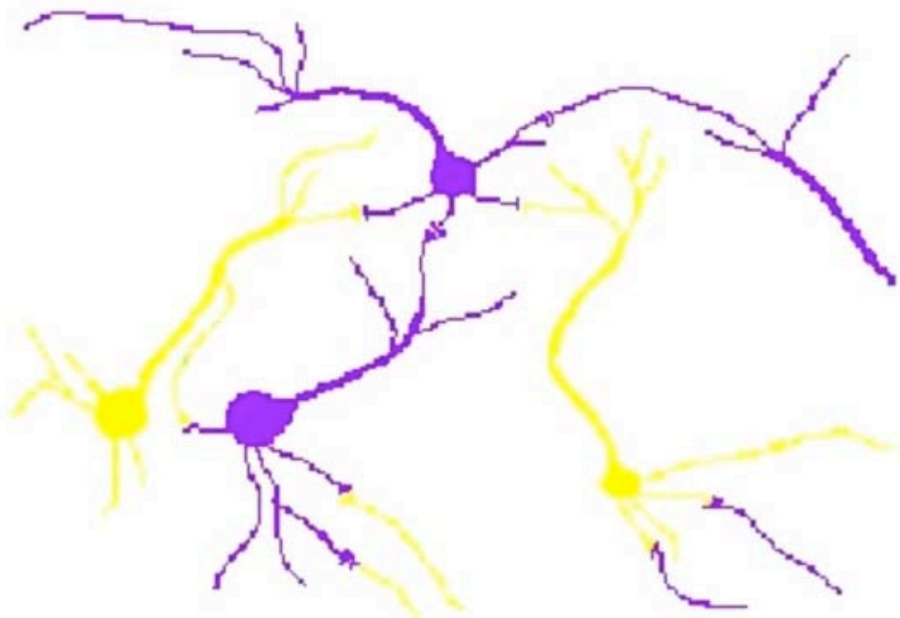

Figure 15: Neural activity pattern

The pattern of firing of the neurons is also influenced by the external world through the activity of sensory neurons that are affected by sensory receptors. These include the five usual senses—sight, hearing, touch, taste, and smell. Actions of the person are effected by the influence of motor-neuron activity on the muscle cells. This means that certain neurons are related to the actions of the muscles. Thus, if we specify the activity pattern of the neurons we are also specifying the behavior of the person.

The synapses through which neurons affect each other are in part "hard-wired" when we are born, but memory and experience also change them. The simplest version of adaptive learning, called *Hebbian imprinting*, can be readily understood. When two neurons are both active at a particular time, an excitatory synapse between them is strengthened and an inhibitory synapse is weakened. The same would happen if both were not active. However, when one is active and the other is not the inhibitory synapse is strengthened and the excitatory synapse is weakened. Intuitively, the synapses become more "consistent" with the pattern. This results in the possibility of reconstructing the neural activity pattern from a part of it, because the synapses have been modified to reinforce the pattern. The imprinted pattern of neural activity becomes a memory.

To think about how this works as a memory, imagine that a picture is imprinted on the network (see Figure 16). Then part of it is shown to the network but the rest is different. The network will, through the influence between neurons, retrieve the original imprinted picture and thus "remember" the rest of the picture. It doesn't matter which part of the picture is shown to the network: as long as enough of it is shown, the rest will be recovered.

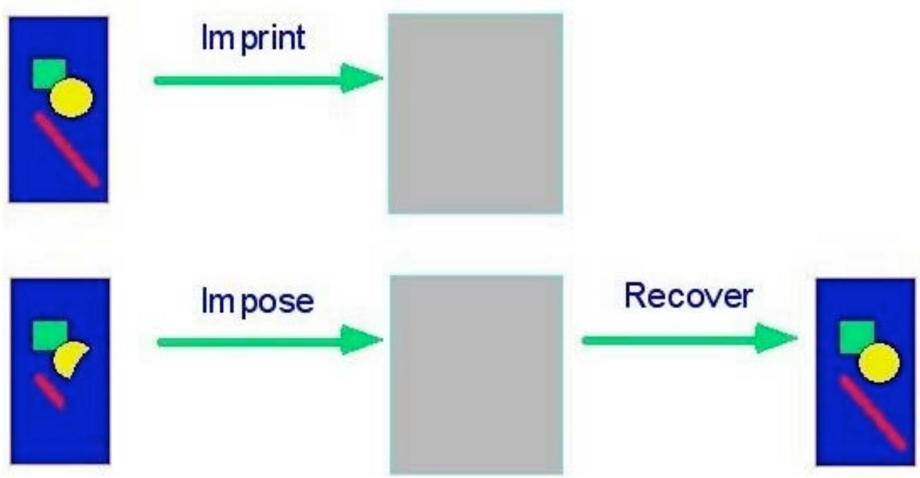

Figure 16: Retrieval from content addressable / associative memory

This neural network memory is called an associative or a content addressable memory. The imprinted state is retrieved using part of itself. Recovering the original pattern "associates" the reconstructed part of the pattern with the part of the pattern that was imposed. There are many patterns that will trigger the same memory; they are all the ones with slight differences from the original one (see Figure 17).

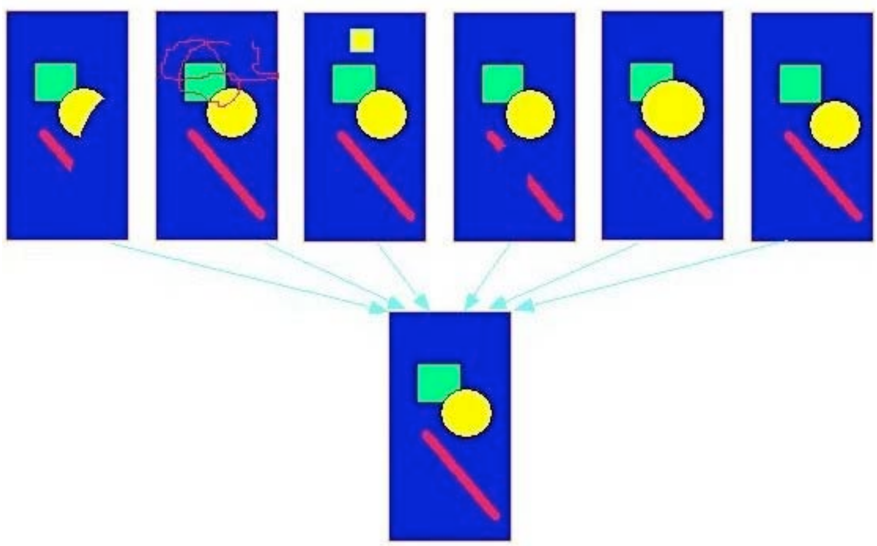

Figure 17: Images that trigger the same memory

This is how advertisers get you to think about their product. By imprinting it on your brain strongly and repeatedly, they cause you to remember it when you see something similar (or anything having to do with their advertisement).

Contrast the properties of the network memory with a computer memory. In a computer the memory is accessed by an address that specifies the location of a particular piece of information. In order to retrieve information it is necessary to have the address, or to search systematically through the possibilities. For a person it is easier to complete the sentence "To be or not to be …" than to quote line 64 from act 3, scene 1, of Hamlet, by

William Shakespeare. A computer would have a much easier time doing the latter because it stores according to address. The way a network memory is similar to how human beings work has led to a lot of excitement about the possibilities of understanding human thought using such model networks.

One of the important properties of a memory is its capacity. If we try to imprint more than one pattern on the network, the basin of attraction of each pattern takes up part of the space of all possible patterns. There is a limit to how many patterns we can imprint before the basins of attraction will interfere destructively with each other. When the destructive interference is complete, the basins of attraction disappear. The network capacity grows with the number of connections (synapses) in the network. If all of the neurons are connected to each other, then taking a network that is twice as large, leads to many more connections, enough so that the network can store twice as many independent images.

2.4. Subdivision and Creativity

The storage of the neural network depends on the existence of connections. If we reduce the number of connections then the ability to store patterns will decrease. More generally, when we think about networks we think that having more connections is better. The brain is a network, but it is not a completely connected network. Instead the brain has subdivisions that have particular functions, like the visual, auditory, and motor areas. Having subdivisions means that there are fewer connections between subdivisions than we would expect from a fully connected network. Why is the brain organized this way? The reason is that when aspects of the world around us are partially independent, then it is much better to store them and act on them using partially independent parts of the brain. This is an important part of understanding how systems should be organized. To examine this more carefully we can consider two examples of memory in the brain. By learning about subdivision we will also learn how creativity works.

For the first example we can consider the main part of the brain that is related to vision: the visual cortex. The visual cortex is separated into three parallel channels. Roughly speaking these are for color, shape and motion (see Figure 18).

The reason is that these are partially independent. Different shapes can have the same colors; the same shapes can have different colors. Moving objects can have many different colors and shapes.

Because of this it makes sense to describe objects using three attributes—color, shape and action/motion. There are many possibilities for each of them:
Color: RED, GREEN, BLUE, ORANGE, PURPLE, WHITE, BLACK …
Shape: ROUND, OVAL, SQUARE, FLAT, TALL …
Action/motion: STATIONARY, MOVING-LEFT, MOVING-RIGHT, RISING, FALLING, GROWING, SHRINKING…

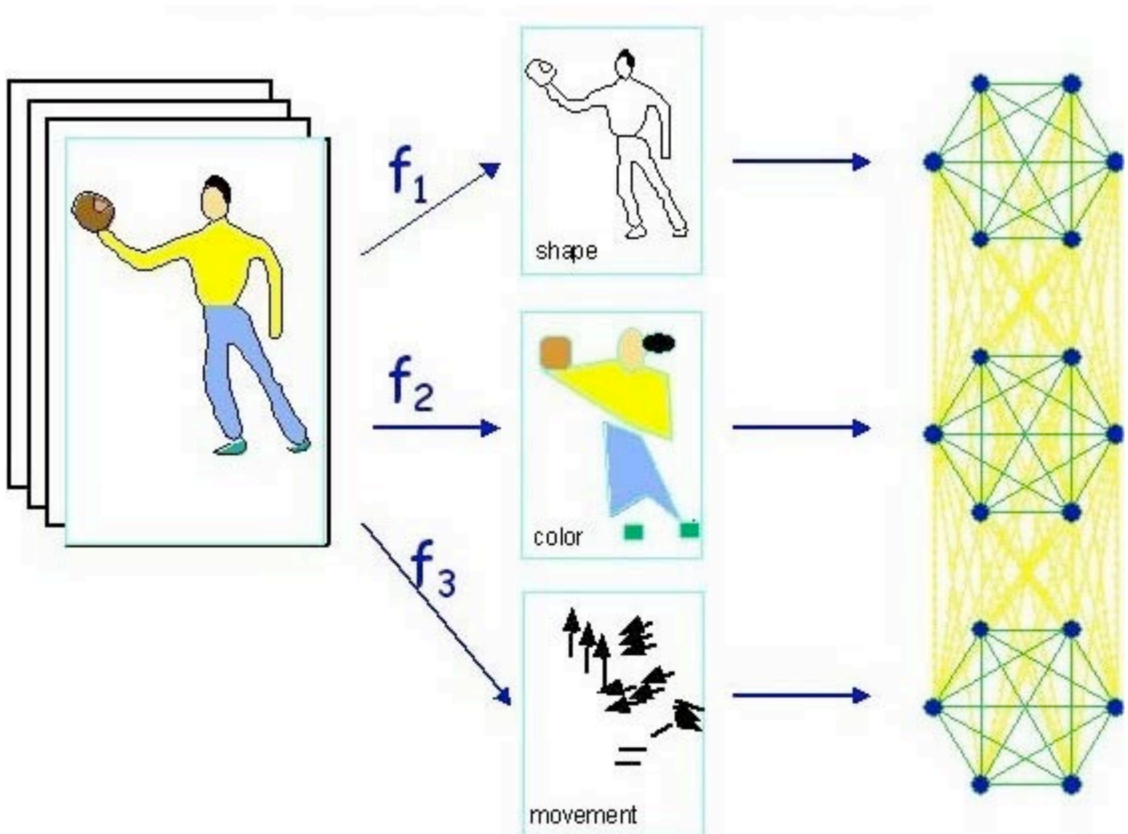

Figure 18: Three channels of the visual cortex of the brain

Separating the color information to one subnetwork, the shape information to the second, and the movement information to the third, lets us use *composite* patterns to identify objects: RED ROUND MOVING-LEFT, and RED ROUND FALLING, BLUE SQUARE MOVING-LEFT, and BLUE ROUND FALLING. The pattern of neural activity in the color network identifies the color, the pattern of neural activity in the shape network identifies the shape, and the pattern of neural activity in the motion network identifies the motion.

Shape, color and motion are not entirely independent. Tree trunks don't move the same way or have the same color as leaves on the tree. Synapses that connect neurons in the different parts of the brain allow us to learn that certain shapes move in certain ways, or have certain colors.

The second example is language. Consider storing simple sentences in a network (see Figure 19). In the first case we store the sentences in a fully connected network. In the second onto a network divided into three parts.

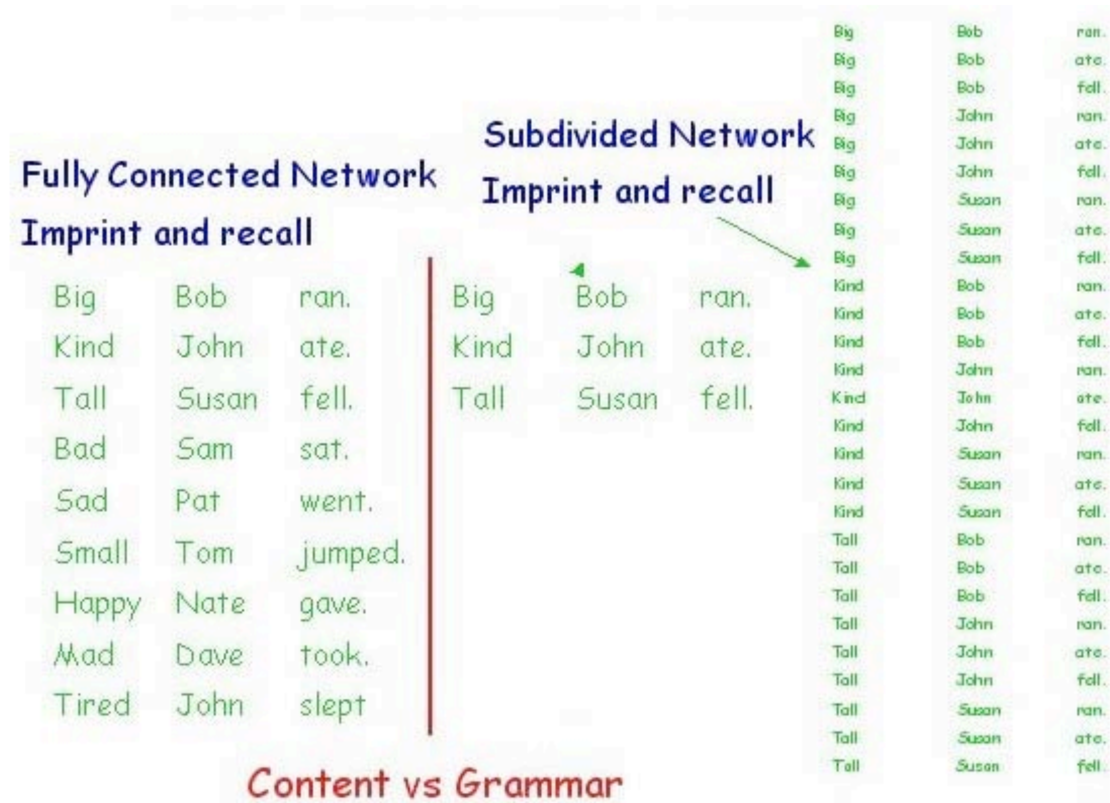

Figure 19: Storage of language: semantic content and grammar

The number of short sentences that can be stored in the first case (nine in the figure) is three times the number of patterns that can be stored in the subdivided network (three in the figure). However, the divided network remembers twenty-seven composite sentences. The first network remembers the specific sentences that are stored, but the second network recognizes all grammatically correct sentences made from these words. Learning only three sentences was enough to learn the many possible grammatically correct possibilities.

The actual process in the human brain lies somewhere between these extremes. Sentences make sense or are "grammatically correct" if properly put together out of interchangeable parts—words. However, a recalled event is described by a specific combination of words. The intermediate case is the result of having some connections between subdivisions that store different parts of speech.

To understand creativity, consider a person who sees a bird flying and a person walking. The shape of the person and the shape of the bird are stored in one part of the brain; the movements of the person and of the bird are stored in a different part of the brain. As a result a composite pattern of the bird and the person can have the person flying. This is the basic notion of creativity: creating new possibilities out of combinations of what already exists. The same notion of creativity applies to many other cases, like the formation of new biological organisms by sexual reproduction.

The key understanding of the role of substructure is the understanding of the role of interdependence in networks in general. Independence is important because it frees each of the parts to respond to independent demands of the environment. Only when the demands on one part are linked to the demands on the other part should the parts of a system be connected to each other. This means that when collective behavior is necessary, the parts should be connected to each other.

3. Complexity, Scale and the Space of Possibilities

3.1. Space of Possibilities

Imagine a flower, a chair, a person. Imagine describing each of them. If words fail you, consider a photograph or a movie. Words, a photograph, or a movie can all be used to answer the question "What does it/he/she look like?" Descriptions underlie everything from science to art. Science explores the descriptions we share (or should share) when we look at the world. Art explores the differences between the descriptions that exist in each of our heads. Thinking is always about descriptions even when we don't realize it; because what we have in our minds is a kind of description, not the system itself.

Even if we have even a simple pattern, like animal skin, it is hard to know exactly how to describe it in words. Saying that we have spots or stripes helps, but what about the details of their locations? What about the details of the shapes? More generally, a complex system is hard to describe and the problem of describing it is central to our ability to understand it. Imagine that we have to study a description of the system. The longer the description, the longer we would have to study it. This makes it natural to define the complexity of an object as the length of the description. An object that is more complex has a longer description. A simpler object has a shorter description.

The idea that complexity is measured by the length of the description seems, however, to suggest that complexity is a very slippery thing. If we are describing something to another person, the length of a description that we need depends on what the other person knows, and even what language we are using. The idea that complexity is not an absolute, but is relative to who is giving the description and who is receiving the description should not discourage us from thinking about complexity. Descriptions are always relative to the observer and this is even recognized in physics.

For example, the speed at which something is moving is relative to the observer. If you are going in a car at 60 miles an hour, and the car that is next to you is also going at 60 miles an hour according to its speedometer, it doesn't seem to be moving at all, as far as you are concerned. On the other hand, a car going in the other direction is going twice as fast. One of the main ideas of Mechanics (the study of objects in motion based on Newton's Laws) is that we can relate what one moving observer sees to what another observer sees, even when what they see is different because they are not moving at the same speed.

The idea of relating what different observers see was made into a principle by Einstein in his theories of relativity. He thought about observers who were not only moving at different speeds (the subject of special relativity) but also speeding up or slowing down. Accelerating upwards (like in an elevator or in a rocket) makes a person feel like the gravity is changing. This relationship between accelerating observers and gravity is the basic idea behind general relativity.

If complexity is relative, then our job will be to relate what different observers consider the complexity to be. In this section we will consider what happens when observers use different languages, or when observers share certain knowledge with the person receiving the message.

Fifty years ago, Claude Shannon, a mathematician at Bell Labs, discussed the problem of communication in a way that is still the basis of our understanding today. He answered the question of how long messages in different languages have to be to say the same thing. (Strictly, Shannon considered the case when there is a definite way of translating between the languages.) Shannon found that messages in one language are longer or shorter than messages in a second language in a way that we can determine by counting the number of possible messages of a certain length. The idea of thinking about all of the possible messages (the space of possibilities) instead of just a specific one is a key idea. If you have a message in one language, say English, and you want to translate it into another language, say Japanese, how long will the new message be? Count how many sentences there are in English that are the same length as your message. Then figure out how long sentences in Japanese have to be in order to have the same number of possibilities. This is the length that the translated message should be. Does this seem like a roundabout way to figure out how long the translation will be? Of course, for one case it is roundabout, but it answers the question once and for all for all possible messages. His discussion of possibilities (the space of possibilities) is helpful in understanding many issues. We can apply it more directly to complexity.

Consider the problem that you have in describing something to a friend (see Figure 20). In front of you is an object. If you want to describe this object, you have to identify it out of the many possible objects that could be in front of you. In order to be able to identify this one out of all the possible objects, the number of possible descriptions has to equal the number of possible objects. Then each of the possible objects can correspond to one of the possible descriptions. Let us say that there are M possible objects: how long does the description have to be so that we will have enough possibilities?

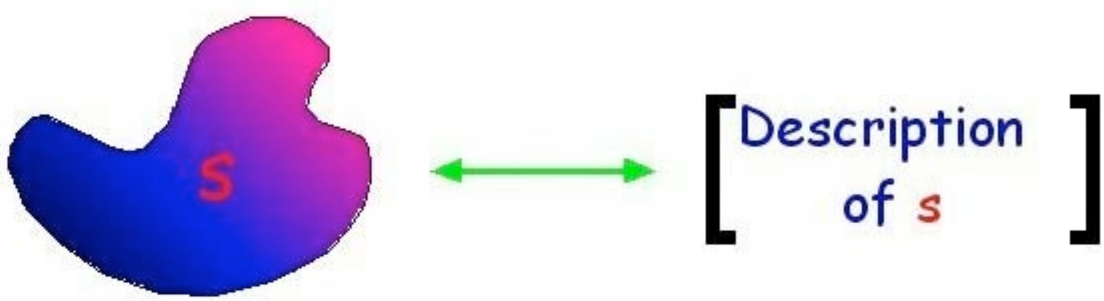

Figure 20: An object, its description and the length of the description (complexity)

The length of a description is related to the number of possibilities. The longer the description the more possibilities you have. Today, we often think of storing information in computers. Computers store information in "bits." Bits are like light switches that can be on or off. Each bit has two possibilities. Two bits have four possibilities. Three bits have eight possibilities. Four bits have sixteen possibilities. Every bit we add increases the number of possibilities to twice as many as before. Multiplying rather than adding means that the number of possibilities grows very rapidly. One hundred bits gives about 1 000 000 000 000 000 000 000 000 000 000 possibilities.

What happens when we use sentences in English to describe something? It turns out that if we only count the sentences that make sense, the number of possible sentences also increases by roughly a factor of two for each additional English character. You might think that because there are many more letters than just two there would be more sentences than this. However, using real words, grammar and generally making sense limits the number of possibilities significantly. This means that writing 100 English characters gives the same huge number of possibilities as 100 bits. Thinking about how many possible books there are is mind-boggling, but this is the kind of complexity that people's minds can absorb.

So, if you want to characterize the complexity of an object, think about how much you would have to write in order to describe it. Would it take a sentence, a paragraph, a few pages, a book, or many books? Count the number of characters in the description. This is its complexity.

3.2. Complexity and Scale

As I mentioned in the previous section, in the context of complexity we have to discuss observers that see with different degrees of precision. The length of a description depends on how much detail we can see (see Figure 21). If we are far away from an object, we can't see many details. The description would then be much shorter than if we were close to the object. Think of using a zoom lens to take a picture. If we zoom in on a person we see a lot more detail than if we don't. If we are far enough away, a person looks just like a speck.

Figure 21: The description length depends on the level of detail

The dependence of the complexity on the amount of detail is important enough that we will discuss several different cases, shown by the red, blue, and green curves in Figure 22. The horizontal axis indicates how far away you are from the object you are describing. Better yet, it indicates the scale (precision) of the description. The vertical axis indicates the complexity of what you are describing.

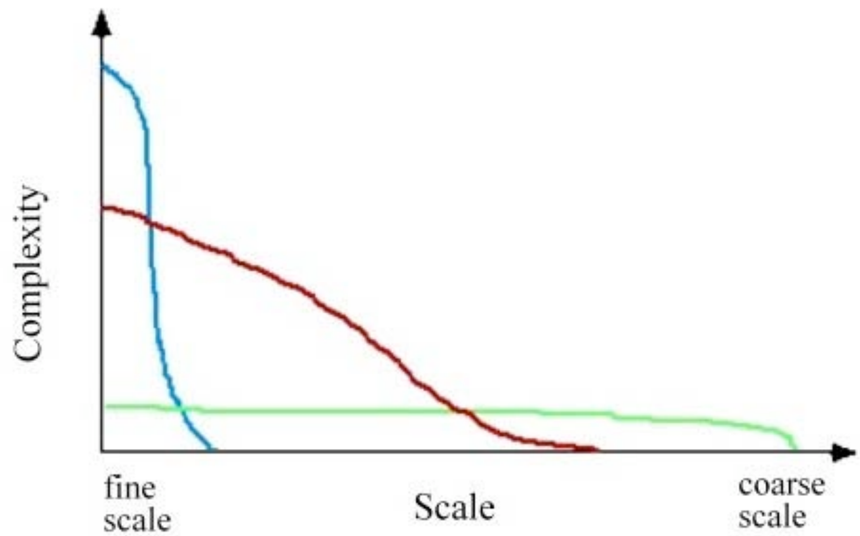

Figure 22: Complexity as a function of scale

The red curve shows what would happen if we described a person. The closer we get, the more detail there is, and the longer the description. It is better if we think not only about describing a person at a moment, but describing a movie of the person over, say, a day. Also we need to be able to ignore (see right through) the things that are around the person that might block our view.

When we are far away from the person, we would see only a point moving around. We might see the person go from home to work and back, going out to dinner or to the movies, and we would see if the person went on a trip by airplane, but not much else. This would be interesting to a sociologist thinking about how people travel from place to place.

If we are closer, we would see all of this, but we could also see the person's legs and arms moving, walking around the room, going from room to room at home, or walking between places at work.

Still closer, we would see the person's mouth moving, hear what he/she is saying, see his/her facial expression, what his/her fingers are doing. This is the detail that we normally see when we are at a distance in which we find it natural to talk with the person.

For the purpose of considering complexity we don't have to limit ourselves to this distance, we can consider much closer distances that are not generally practical. We also don't have to limit ourselves to using a regular camera, we can think of using a magnifying glass, or even a microscope.

Usually, when we think of a magnifying glass or a microscope, we look at only a small thing. But for thinking about the complexity of the person, when we are making a movie of the person with a magnifying glass, we still want the whole person in the movie. It would take a really large screen to do this. It means that with a magnifying glass we can see all of the pores and hairs on a person's skin. When we describe the person with this level of detail we have to describe each and every one of the pores and hairs. Of course this description would be very long.

It is even better to think about this like a CAT scan where we can see all of the internal parts of the person and what these parts are doing. Depending on whether we are looking with a magnifying glass or a microscope (how much magnification we use), we can see all of the organs of the body, or all of the cells of the body, or all of the molecules, or even all of the atoms. By the time we are thinking about writing a description of all of the atoms, it would take a remarkably long time to write the description. From physics we actually know how long a description this would be. If we cut up the entire earth into little pieces the size of grains of sand and wrote one English character on each grain of sand, there would be barely enough characters to write this description.

This is clearly a long description. However, while it is very long, it is still "finite." This means that even if we describe a person atom by atom, there is a limited amount of information that we need. The reason this is true originates in quantum physics, which tells us that each atom has some uncertainty built in to it. So we only need to say where it is with certain accuracy, and that's enough.

The blue curve in Figure 23 shows a different case. This would be the case if we took a person and mixed up all the atoms so that they were not organized in any way. The atoms would also not be moving in a particular direction, but in any direction. Each of the parts is acting randomly. If we put these atoms into a large vat, it would look like dirty water. This is what physicists call "*equilibrium*." Looking at it from far away there isn't much to describe because it doesn't go anywhere. Even if we look much closer, it looks boring. The reason is that when we mix it all up, all the parts of it look the same. This is true until we reach the scale of describing what each of the atoms is doing. What is special about this case is that all the atoms are moving independently. So when we want to describe what all the atoms are doing, then we actually have a longer description than the one of the person. The equilibrium liquid is "more complex" than a person when we describe all the atoms. However, this is only true when we describe the atoms. Otherwise the person is much more complex. The blue curve is higher than the red curve for very small scales, but otherwise it is lower.

The third case (shown in green) is what would happen if we took the same atoms and organized them so that they were all moving in the same direction. It may surprise you to know that if your atoms were all moving in the same direction, you would move at a speed of about 2000 miles per hour. The reason we don't move that fast is that the atoms are constantly bouncing against each other, and they are tied to each other by various kinds of chemical bonding. Of course, if we did organize them to move in the same direction, the motion would be visible from far away! This case we can call *coherent motion*.

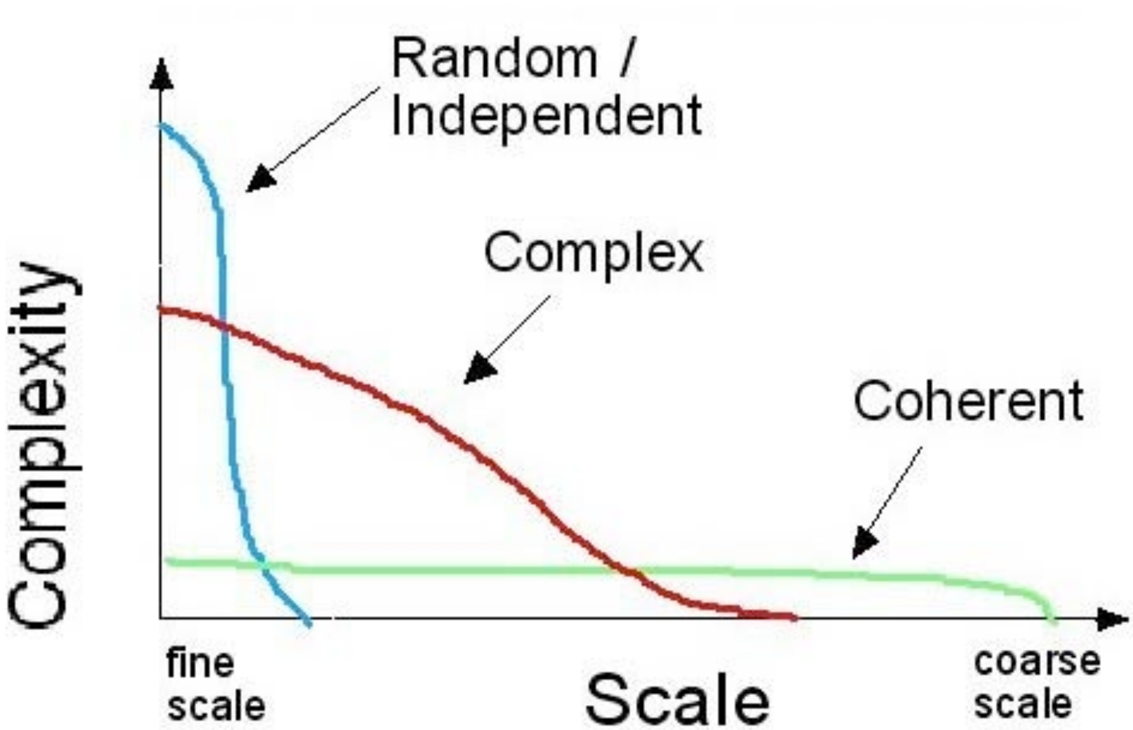

Figure 23: The cases of random, coherent and complex system organization

The three cases—random, coherent and what we normally think of as complex—illustrate how the way a system is organized affects how it is seen at different scales. Visible at a large scale means that things are organized. In order for us to see behavior at a large scale, the parts must be moving together. We can see this in how a muscle works. Muscles have many cells doing the same thing at the same time. Because of the actions of a muscle we perform motions that are visible at a large scale compared to the size of the individual cells. A human being has various groups of atoms organized to work together. The groups are of many different sizes. Depending on the size of the group of atoms working together, we see what they are doing on a different scale. This is why there is more and more to see as we get closer.

Thinking about random, coherent and complex systems applies to any kind of system, physical, biological or social. For example, a liquid in a cup is a physical system where atoms are moving randomly, a cannonball has atoms moving in an organized way, and the atoms of a snowflake are organized so that there is structure on many different scales. In biological organisms cells in a pond tend to move randomly, a bacterial infection involves many cells working together, and the cells of a human being are organized to have structure on many different scales. In social systems people in a crowd move aimlessly, a mob or an army moves coherently, and a corporation has people organized to have structure on many different scales. Thinking about the case of people moving in all directions, when one person moves one way, another person moves the other way. If we look from far away nothing seems to happen. In the case of a mob or an army we can see what is happening from very far away because the motions of the individuals add together. In the case of an organization, as we get closer we see more and more details about what is going on.

These examples all show a tradeoff between large scale behavior and fine scale complexity. When parts are acting independently, the fine scale behavior is more complex. When they are working together the fine scale complexity is much smaller, but the behavior is a larger scale behavior. This means that complexity is always a tradeoff, complex at a large scale means simple at a fine scale. This tradeoff is a basic idea that we need in order to understand complex systems.

In the next section we will devote more attention to the subject of social systems and how we can understand them using the properties of complexity and scale. Before we do this, let's consider again the complexity of a human being. This time let's think about how one person describes another (see Figure 24). The person doing the describing is going to use his own senses (not a microscope) and is going to be located a distance away, of say a meter or two, which is how we usually interact with each other in social contexts. How much information would be necessary for this description?

We can estimate this by using the amount of memory needed to store a movie made by a regular video camera. These cameras are designed with people in mind, how sensitive our eyes are, and how sensitive our ears are to sound. It is easy today to take a digital video camera and plug it into a computer to see how much memory space a video would take. It turns out that about five minutes fills a gigabyte (a billion bytes) of memory; since a byte is about 10 bits this is about 10 gigabits of memory, which is also about the space on a CD-ROM and about 10-20 per cent of the size of a DVD. This would suggest that a DVD can only store about 25 minutes of video. Actually, it can store about 2 hours of video by using compression, eliminating the recording of parts of the picture that are not changing. If we extended a movie to a day, we would have enough video to fill about 10 DVDs or about 4000 gigabits. To describe a person over a lifetime we would multiply this number by a typical number of days in a lifetime of 80 years, about 30 000. So it would take about 300 000 DVDs to store a description of a human being. Of course, a person repeats many things that he/she does, so we could make a shorter description if we tried to. Nevertheless, this gives an idea of the complexity of a person as far as other people are concerned.

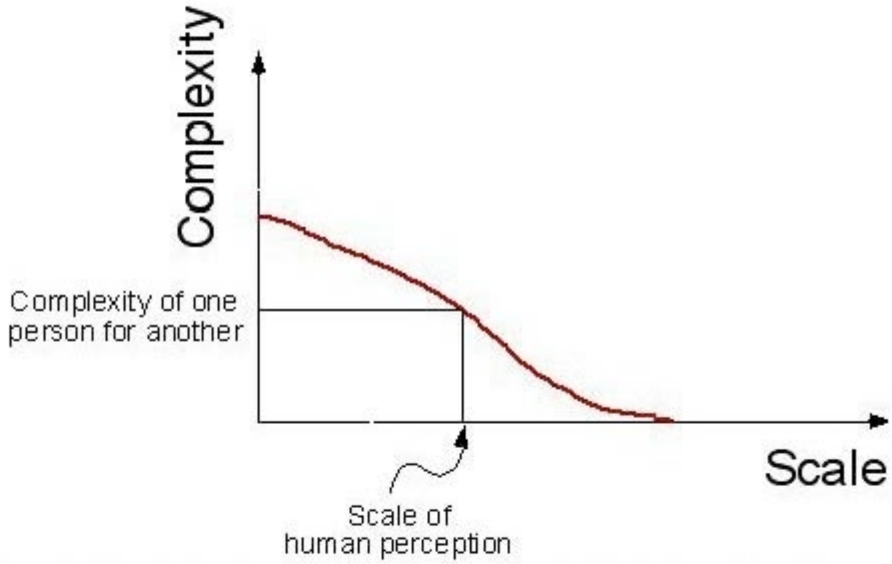

Figure 24: Complexity of a person as a function of scale. The horizontal line indicates the complexity of a person at the scale of perception of another person

While the specific description length is not essential, the idea that the complexity of a human being is limited will be important when we discuss how complexity applies to social systems.

3.3. Complexity of Social Systems

The dependence of complexity on scale can be discussed for many different kinds of systems. Rather than thinking about the usual systems that are studied in science, it is particularly exciting to think about systems that conventional science doesn't have many tools to think about. Instead of working on systems that are studied by the science of parts, let's see what we can say about the most complex largest scale systems we know about: human organizations and human civilization as a complex system.

Why should we think about human civilization? Aside from the obvious, that we are all part of it, there is a specific reason to consider the complexity of human civilization. Everyone seems to be complaining about how complex life is becoming. This complexity is not due to any dramatic change in the natural environment. Trees haven't all of a sudden become harder to understand. What has become more complex is our social and economic system. What can we say about the complexity of society?

To start thinking about this problem we might notice that the world has become much more interdependent. This is what we mean by talking about the "global economy." The interdependence means that something happening in one place in the world can, and often does, affect things happening in another place, even in many places around the world. If things are more interdependent, then the complexity of the world at larger scales has increased. Simply put, if we want to describe the world, we need to mention all of the things that have impact on a lot of people. Since there are many such things, there is a lot to describe.

Another approach to thinking about the complexity of society is considering how the interdependence arises. What are the ways that people influence each other? We think of influence between people as control, not necessarily coercive control, but control nevertheless. Traditionally, the way people influence/control each other is in organizations. This suggests that we consider how control works in companies, governments, and other social organizations. In traditional organizations control is exercised in a specific way---in a hierarchy. For about 3000 years, hierarchies have been the generic form of human organizations. It would be helpful for us to understand how a hierarchy works and what this means for the complexity of a social system.

To help us think about a hierarchy it is useful to focus on an idealized hierarchy like that shown in Figure 25. In an ideal hierarchy, the only way people talk to each other is up and down the hierarchy. If you want to do something with someone in the office next door, you talk to your boss, and your boss tells the other person what to do. If the person is not supervised by your boss, then your boss talks to his boss, his boss talks to the boss of the person in the office next door, and that boss tells him what to do. Of course, the bosses don't need to wait for someone in the ranks to suggest something; they might just tell a bunch of people what to do. Another way to think about the communication through the hierarchy is that the communication up the hierarchy filters the information that is needed for the bosses, while the communication down the hierarchy provides details that are needed for the workers.

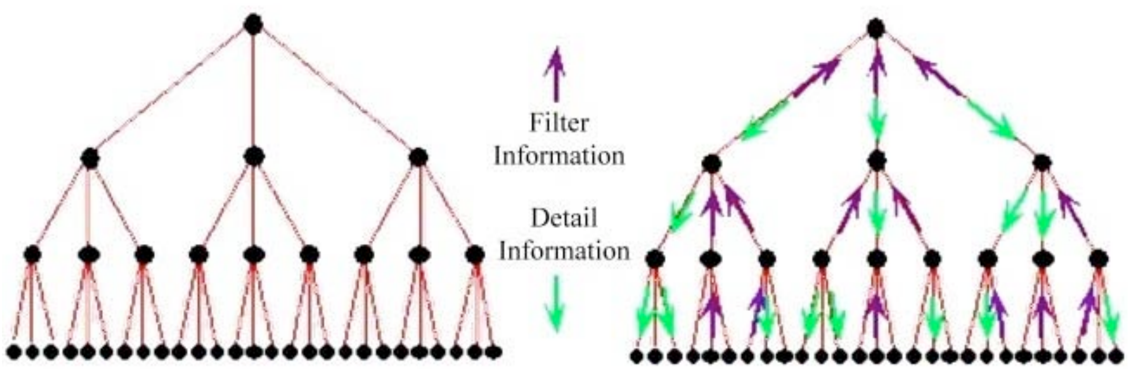

Figure 25: A control hierarchy

Hierarchies can differ from each other, particularly in how many individuals are supervised by a single boss (see Figure 26).

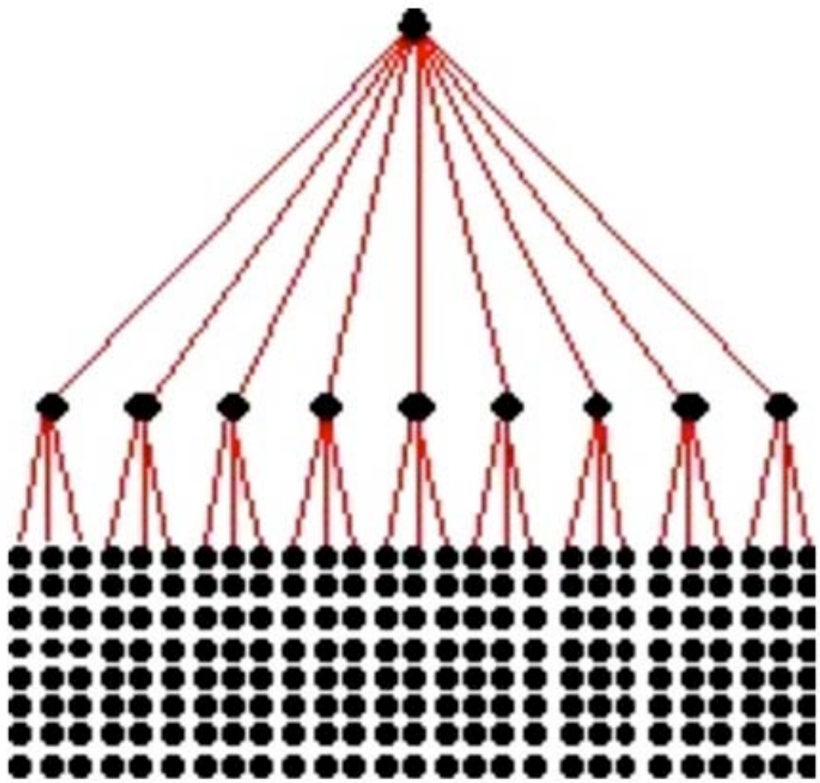

Figure 26: A hierarchy with a larger number of individuals supervised by a single boss

To help us think about hierarchies, we need some examples. A couple of simple examples are military force and factory production. As with the ideal hierarchy, we will consider a simple and generic version of each of these.

For the case of a military force consider ancient armies that conquered much of the ancient world, specifically Alexander the Great's Phalanxes or Roman Legions (see Figure 27). These military forces are almost like the idea of coherent motion we were discussing before. The behavior is characterized by long marches with many individuals doing the same thing at one time, and repeating it many times. The behavior of each individual is very simplified. Here we see the tradeoff between complexity and scale. The construction of the Phalanx or the Legion is designed for large-scale impact. Indeed, the scale of impact of these forces was remarkable even by today's standards. Still, the military force has to respond to what is going on around it. For this there is a control hierarchy that determines what direction to march in. In this hierarchy many individuals can be under the supervision of a single commander.

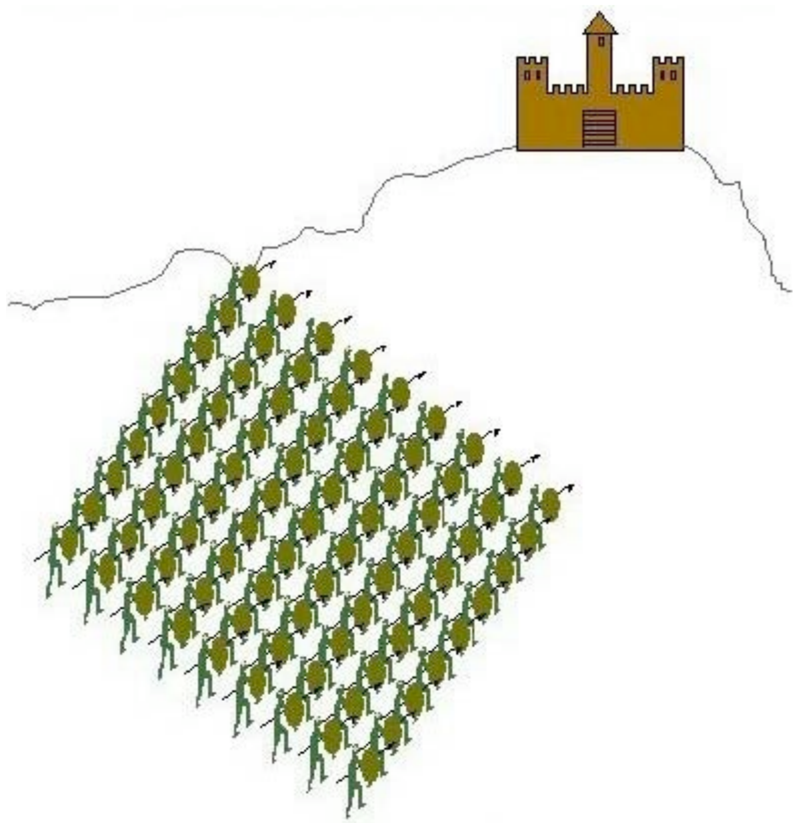

Figure 27: Greek Phalanx or Roman Legion

For the next example consider a factory, specifically a Model-T Ford factory (see Figure 28). The basic idea of Ford was to simplify what each individual had to do. Each person performed a simple task and repeated it many times. Different people performed different tasks. These were coordinated to produce a single product. The product could be quite complex, like a car, but the key idea was that the number of cars could be large. The scale is large because of the repetition of simplified tasks. Again we see the tradeoff between complexity and scale. In addition to the tradeoff between scale and complexity of what each individual is doing, we can also see the role of the control hierarchy. The hierarchy coordinates the tasks of different individuals. Because individuals are doing different things, the control hierarchy has to give many more instructions than in the case of the military. Intuitively, this means that there must be fewer individuals directly supervised by a boss than in the military case.

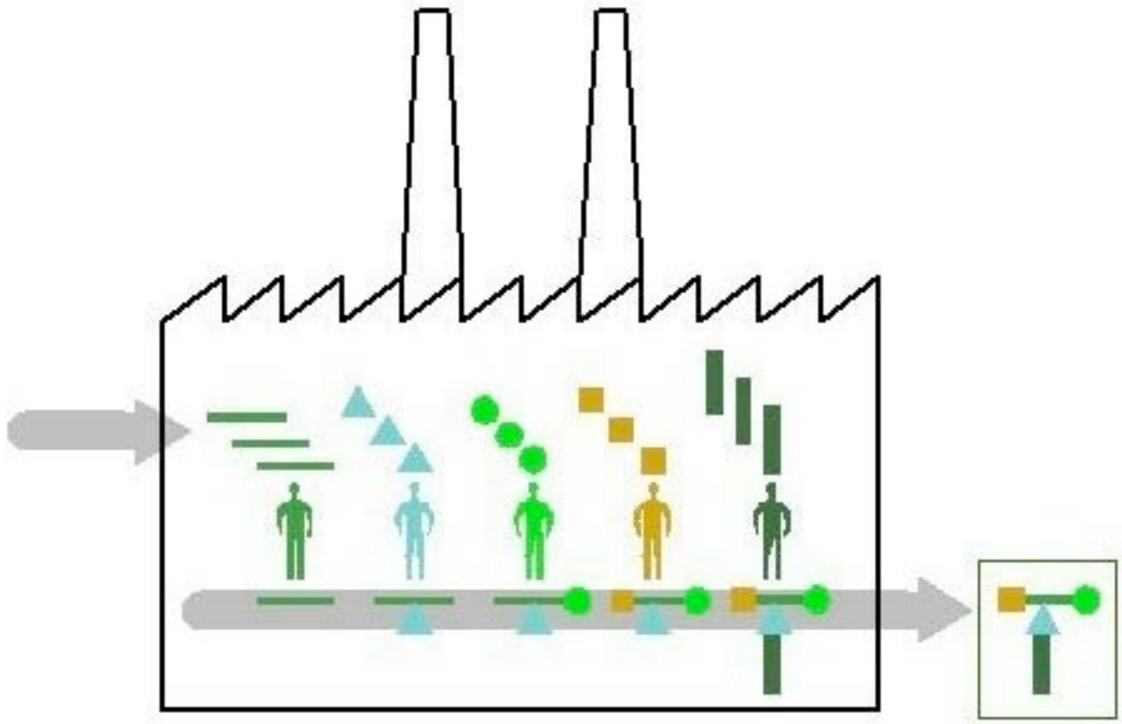

Figure 28: Production line in a traditional factory

Now that we have seen a couple of examples of hierarchies, let's consider the basic nature of the hierarchy itself (see Figure 29). We can see that the hierarchy enables a single individual (the commander or CEO) to control large-scale behaviors. The CEO needs to know something about what individuals in the organization are doing. However, he/she does not need to know everything about it. Specifically, the CEO does not need to know every detail about what every person does every minute of every day. It is necessary for the CEO to know or to control matters that affect a large proportion of the organization, the large scale behaviors.

Another way to see this is to consider the communication through the hierarchy. Any communication that involves people in well-separated parts of the organization (the blue groups in the figure) must go through the CEO or commander. This would be true of almost all large-scale behaviors.

We've arrived at an important conclusion. Since the large-scale behaviors are communicated through the CEO, there is a limit to how complex they can be. The large-scale behaviors cannot be more complex than the CEO. This complexity is large, as large as a single human being, but it is limited. At most 10 DVDs of information are needed to describe what the CEO does in one day. This is a lot, but it is still a finite amount of information.

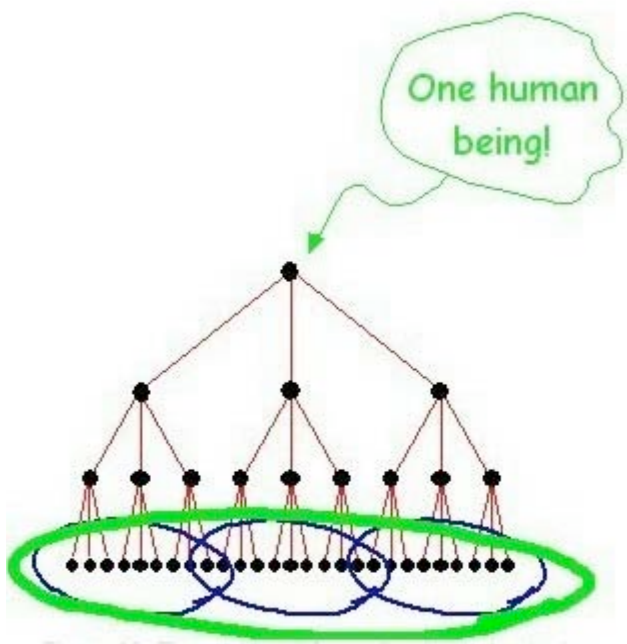

Figure 29: The problem of coordinating behavior in a hierarchy

Let's compare the hierarchy with other organizational structures (see Figure 30). Another structure we can think about is a network, like the network of neurons in the brain. When we discussed the brain as a network, we did not think that one of the neurons was responsible for the large-scale behavior of the system. Each neuron could be simple and yet we could have very complex behavior of the network as a whole. We shouldn't think that any randomly connected network behaves in a complex way. Still, it is possible to have a network that together is more complex than its parts. This is not true of the hierarchy. We see that the hierarchy is good at amplifying, increasing the scale of behavior of, an individual. However, it is not able to make a system have a larger complexity than its parts.

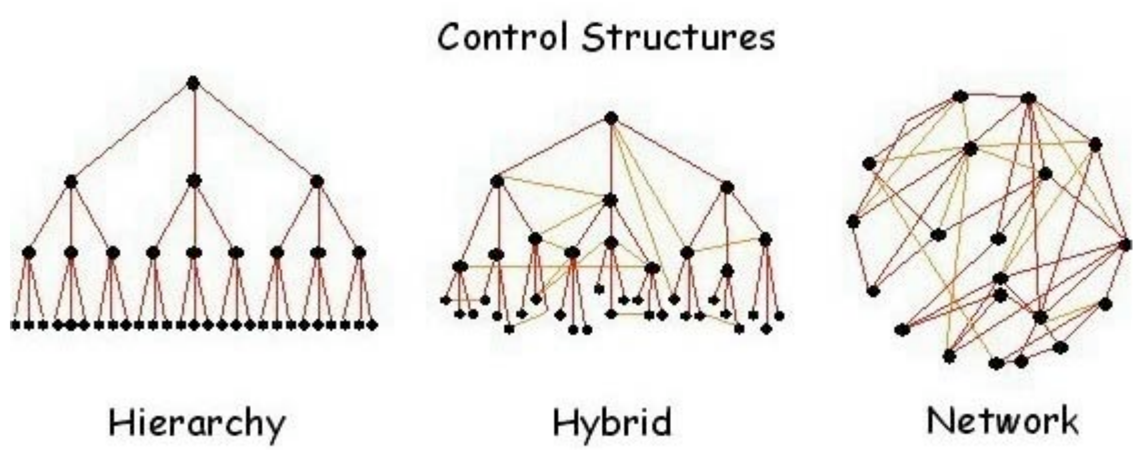

Figure 30: Organization structures: Hierarchy, network and an intermediate hybrid case

Real organizations today are not pure hierarchies. There are many lateral connections corresponding to people talking to each other and deciding what to do. Nevertheless, we can learn from this discussion that to the extent that a single individual is in control of an organization, that is the extent to which the organization is limited in complexity to the complexity of a single human being. Is this important? To answer this we need to understand why an organization (or any other system) needs to be complex.

3.4. Why Complexity?

Why is it helpful to be complex? The answer is that being complex is the only way to succeed in a complex environment. What is a complex environment? One that demands that we pick the right choice in order to succeed. If there are many possibilities that are wrong, and only a few that are right, we have to be able to distinguish the right ones. This requires a high complexity.

We can see what happens with different types of biological organism. Most types of animals have many offspring. The number of offspring that survive to adulthood tells us something about how complex their environment is compared to their own complexity. Mammals have several to dozens of offspring, frogs have thousands, fish have millions and insects can have as many as billions. In each case, only about one offspring per parent survives to have offspring. The others made wrong choices because the number of possible right choices is small. Darwin's theory of evolution discusses how the fitter ones tend to survive, but most of the reason for an offspring to survive is chance, because of the many possible wrong choices for each right choice. The more complex is the organism the more options it has in its own behavior and this enables it to make more right choices. We can tell how much more complex the environment is than the organism by how many offspring they have. Mammals are almost as complex as their environments, frogs are much less complex, fish and insects are still less complex when compared with their environments.

Scale also matters. In general, larger scale challenges should be met by larger scale responses. The rule of thumb is that the complexity of the organism has to match the complexity of the environment at all scales in order to be likely to survive.

The same argument can be used in the context of economic systems. If the environment of a corporation is very complex, it means that there are many decisions that must be made correctly in order to succeed. These decisions might include product choices, price decisions, investment choices, resource allocation, hiring policies, mergers and acquisitions, and so on. Students of economics and management are taught how to make such choices in order to increase the likelihood that they will make the choices that lead to success. The best a single person can do, however, is limited by his/her complexity.

A key to the problem of corporate success is that companies are competing with each other. This means that if one company makes better choices than another, then it will succeed and the other will tend to go out of business. Both scale and complexity matter; larger scale companies and more complex companies will tend to succeed. This leads to a kind of "arms race" where companies that increase their scale or complexity tend to succeed at the expense of other companies.

The same ideas apply to military power and the appearance of ancient empires. Why did one country take over another country to become an empire? Because it had a larger scale or more complex military. Among the ways that complexity shows up is in military tactics and strategies. We can combine thinking about scale and complexity using the curves we discussed that show the complexity as a function of scale.

3.5. Historical Complexity

The large-scale complexity "arms race" between organizations leads to a progressively increasing complexity at the large scale (see Figure 31).

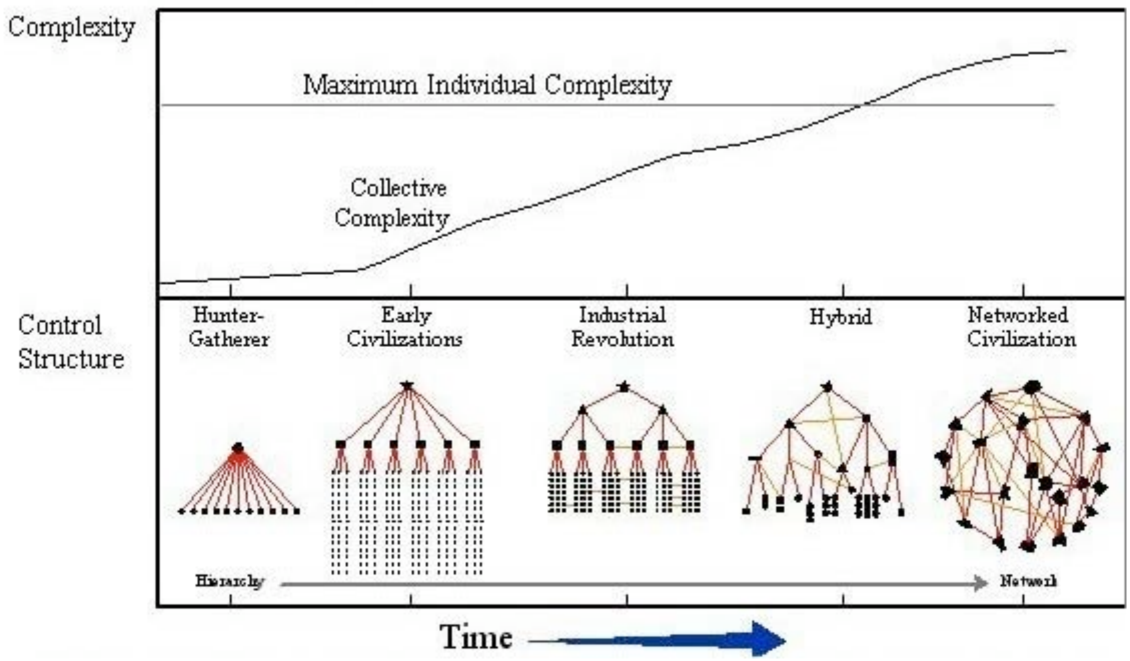

Figure 31: Increasing large scale complexity as a historical trend along with the related organizational structures.

The increase in large-scale complexity over history is what we see as historical progress. From our discussion of complexity in organizations, there is a problem however. The complexity of organizations can become larger than the complexity of a human being. If this were to happen, organizations that are mostly hierarchical would no longer be able to compete. Organizations with more distributed structures would become dominant.

We will argue that this transition in complexity has already happened. Specifically, it appears from historical evidence to have happened in the 1970s. During this time there were major changes in many aspects of the world. The global conflict between the US and the USSR was replaced with the global economy. The industrial society was replaced with a post-industrial, service or information economy. There are many ways people have characterized this transition. Our discussion of this transition suggests that complexity is the key to understanding what happened. (It may seem coincidental that scientists are studying complexity just as a complexity transition is taking place in society. This is not a coincidence at all since the complexity of society is one of the main reasons that scientists and people everywhere are interested in complexity.) There are three key observations to support this claim. The evidence can be found in both political and economic contexts.

First, all of the dictatorships in the western hemisphere, except one, disappeared during this decade. Before 1970 there were governments that switched back and forth between dictatorships of various kinds and representative democracies of various kinds. During the 1970s, with one exception, they became some form of democracy. The one exception, Cuba, is a country that is largely isolated and has a highly simplified social and economic system characteristic of what was going on in other places many years ago.

What is particularly significant about the changes in government during the 1970s is that they often did not follow the historical pattern of revolutions. The historical pattern can be seen in the French revolution at the end of the eighteenth century or the Russian revolution at the beginning of the twentieth century. A classic revolution begins with an effort to reform a government that is not functioning well. The reform process becomes more radical, and then there is a bloody revolution, which leads to a restoration of central control. This dynamic suggests that despite the limitations of central control, it was the stable form of government in the face of social disorder. By contrast, many of the more recent changes of government have been peaceful. The individual or individuals in control simply "give up" this control.

Table 1 is a list of mainland Central and South American countries and the date and kind of their most recent major change of government. Until the late 1970s a patchwork of military dictatorships and democracies existed. By the early 1990s a transition had occurred to almost universal democratic governments. A tilde (~) before the word Democracy indicates significant control is still exercised by military leaders within the democratic regime. For countries whose government has not changed since the early 1970s, no transition is indicated. While not part of the Americas we added Greece, South Africa and the Philippines at the bottom of the list. Their most recent governmental changes were also not characteristic of the historical process of revolutions.

Country	Before Change	After Change	Year of Change	Manner of Change
Argentina	Military Dict	Democracy	1983	Peaceful
Belize	Colony	Democracy	1981	Peaceful
Bolivia	Military Dict	~Democracy	1979	Peaceful
Brazil	Military Dict	Democracy	1985	Peaceful
Chile	Military Dict	Democracy	1990	Peaceful
Columbia	Democracy			
Costa Rica	Democracy			
Cuba	Military Dict			
Ecuador	Military Dict	Democracy	1979	Peaceful
El Salvador	Military Dict	~Democracy	1980-1992	Bloody
French Guiana	Possession			
Guatemala	Military Dict	~Democracy	1985	Background violence
Guyana	Democracy			
Nicaragua	Dictatorship	Democracy	1978-1990	Bloody
Panama	Military Dict	Democracy	1989	US Military Intervention
Paraguay	Military Dict	Democracy	1989	Peaceful
Peru	Military Dict	~Democracy	1980	Peaceful
Suriname	Military Dict	~Democracy	1985	Peaceful
Uruguay	Military Dict	Democracy	1984	Peaceful
Venezuela	Democracy			
Greece	Military Dict	Democracy	1974	Peaceful
Philippines	Dictatorship	Democracy	1986	Peaceful
South Africa	Apartheid	Democracy	1991	Peaceful

Table 1: Central and South American countries with major changes in government during the 1980s (and three other interesting cases).

The second major piece of evidence is the collapse of the Soviet Union. This is the largest scale at which governmental change took place. The Soviet Union simply stopped existing toward the end of the 1970s. Along with the collapse of the Soviet Union the centralized communist governments, like the dictatorships, seemed simply to give up. Very few people anticipated this collapse, and it is entirely inconsistent with historical patterns. Even with the many problems that the Soviet Union faced, the historical precedent is that governments continue to fight for their existence even when their people are starving or rebelling. In this case, the government simply stepped aside. The result was the breakup of the Soviet Union into many smaller countries shown by the area in white in Figure 32. Other countries in Eastern Europe (dark color) also changed away from communist central control.

While China continues to be, in part, a centrally controlled communist system, there have been dramatic changes there as well. These changes were initiated at the beginning of the 1980s through the possibility of private corporations in China. This and other government policies have led to dramatic growth of an economy that is no longer subject to the same kind of central control as it was.

The third piece of evidence has to do with changes in corporate structure and control in the US. Management change became a major factor starting in the early 1980s with the widespread adoption of Total Quality Management (TQM). The principles of TQM lead to a change in perspective about management. The main point from our perspective is that teams of individuals become responsible for decisions rather than the CEO. Thus, beginning in the 1980s and continuing through the 1990s, TQM and other approaches such as the Learning Organization, Re-engineering, High Performance Organization, and Lean Manufacturing have led organizations to adopt structures that are more distributed in control, and where information passes laterally through the organization instead of up and down the hierarchy. More recently the concepts of distributed networks and self-organization have become central to Management change.

Figure 32: Break up of the former Soviet Union

We might be concerned that companies are getting larger and larger through mergers and acquisitions, and that this means more centralization of control. If the control in these organizations is distributed then the size of the organization doesn't matter as much as it once did. It is also clear that increased scale is being used as a competitive advantage. It is the competition between organizations that is responsible for the evolutionary process we have been describing. If a company becomes so large that their scale enables them to beat all competitors, this is what is called a monopoly. In this case the importance of complexity is reduced and corporations that are centrally controlled may still be successful. The observation that monopolies prevent evolutionary development by stopping competition is precisely the reason that there are regulations against monopolies.

The dramatic changes in control in governments, both Dictatorships and Communist, and the similarly widespread changes in corporate control suggest that the large-scale complexity of human organizations has reached the point where it is larger than that of a single human being. This conclusion is consistent with our more intuitive feeling that society is becoming more complex. The reason we feel this complexity in an intense way is that when the complexity is larger than a human being, then it becomes difficult to understand; indeed it becomes impossible to understand fully what is going on in society. This is why government and corporate leaders have made the decision to transfer their control to others in a systematic way. If they could figure out what to do, they would not have done so.

We can also take a different tack to seeing the way central control doesn’t work for complex systems. Consider a system that is not controlled centrally which is highly complex, like the supply of food to a large city, say Boston. Think of all the different kinds of food, the different ways food is delivered, trucks, trains, ships, and airplanes. Some of it is refrigerated; much of it has to arrive within a limited time. Think of all the storage facilities that are involved. Also, think of all the different places it goes: supermarkets, restaurants and institutions. The right things have to arrive at the right time in the right amounts, and so on. What would happen if we tried to control this centrally? The answer is that we would have to limit the number of types of food, the number of places that it arrived; even then things would arrive at the wrong times in the wrong quantities. Indeed, this is reminiscent of the food supply in Moscow before the breakup of the Soviet Union.

3.6. Complexity Around Us

What can we learn about the world from the arguments about large-scale complexity of society and human organizations?

We can learn, as we know already, that the complexity of society is increasing. For managers this may be disturbing, because control is not possible. For others, including academics, it may be disturbing because complete understanding is not possible. Complete control or understanding by an individual is not necessary, however, for us to continue to do and learn together what we cannot do and learn as individuals. We can also realize that as individuals we are being protected from the full complexity. In order for society to be more complex than a person, we must be protected. This is just like the cells inside our body are protected from the complex environment that our bodies as a whole are able to face. The evidence that we, as individuals, are being protected is also clear. The increasing life spans, and reduction in disease and accidents are examples of how society is protecting individuals. There are other more subtle ways in how people can specialize in work, and choose communities to live in with compatible lifestyles.

We can also learn that the change in central control is going to continue. The world, with billions of people, can become much more complex than a human being. We should expect that complexity will continue to increase, and this means that organizations will be less and less recognizable as hierarchies. We see this in many ways, even by considering how informal distributed organizations like the open-source movement are challenging innovative but conventional organizations like Microsoft. People will work in teams and control over what happens will be distributed widely. Governments should be expected to have less and less importance. This is not a victory of democracy over communism. Both democracy and communism are forms of government. We are talking about a different option, a complex collective, an organism, which is quite different from either democracy or communism.

Finally, we can be amazed at the idea that human beings as a collective are more complex than an individual human being. We tend to be focused on the importance of the individual. Human togetherness is real. Human beings together are a complex organism. Individuals are no longer the principal actor; human civilization, all of us together, is.

4. Evolution (Simple to Complex Patterns)

4.1. Selection and Competition

The basic idea of evolution is that the collection of all living organisms changes over time. The change is incremental, a little bit at a time. The key to this incremental process is natural selection. To understand natural selection, consider what happens if people choose to mate cows that have more milk. Over generations, the cows that are born have more and more milk on average. This is the practice of breeding. The ideas of breeding and inheritance of traits from generation to generation are known, in some form, as far back as there are records. Darwin connected this process to the natural change of species through selection by nature. Organisms that succeed to reproduce are more fit, by definition, than those that do not. This leads their traits, whatever they are, to become more prominent in succeeding generations. As we look back in history, and especially bearing in mind the fossil records, the incremental process of change suggests that life originated from a very simple primitive organism on Earth; and the diverse forms we see arose over time in a diverging "tree" of species.

Since its inception, the theory of evolution has been challenged by people who believe in a literal view of the Bible. Their view is that life as we know it was formed, quite similar to the way it is today, by the direct action of God. This debate has been the focus of scientific/religious controversy. We are not concerned here with this debate, but rather with how evolution helps us understand all complex systems, not just biological ones.

The framework of evolution provides an important insight into the process by which any complex system can be formed or changed. The reason that understanding the origin of complex systems is a problem, is the very reason that the origin of life is such a profound mystery. It is impossible for complex systems simply to appear out of nowhere. At one point, scientists thought that life could start "spontaneously." According to this view, whenever conditions are right, living organisms appear at once. We now know that this is not correct. Living organisms only arise from living organisms of very similar kind. The same can be said of other types of complex systems. Like living organisms, they arise from previously existing complex systems.

The field of complex systems, however, has a basic problem with Darwin's theory of evolution. In a sense this is the same problem that complex systems has with the rest of the science of parts. By describing the incremental process of evolution, Darwin took evolution apart. The incremental process, a step-by-step idea of how change takes place, is not enough to understand how evolution as a whole takes place. Putting the steps together is more of a problem than many people realize, just as putting a person together out of his/her atoms is more of a problem, and an interesting scientific puzzle, than many people realize.

When we consider the overall picture of evolution there are immediately questions that are not easily addressed by the incremental process described by Darwin. The first of these is understanding why there exists more than one type of organism. How does one species split into two species? Why do these two species (and others) continue to coexist? These questions can be addressed. Complex systems ideas have contributed to our thinking about these questions in the last few years. The answers add new understanding that goes beyond the basic idea of incremental change.

Modern biology also tends to think about evolution as a process that occurs to the genes that are a basic building block of DNA and the genetic code. The organism is mostly an afterthought. This is consistent with the basic reductionistic approach of science in recent years. (This approach is also the same kind of simplistic notion as the idea that your brain controls your body, or that a CEO controls a company. None of these statements is really true if we think them through.) Instead, we should think of an organism as a pattern—a pattern that exists in the structure of matter and how it behaves over time. The idea of the organism as a pattern connects organisms to the discussion of patterns in Section 2, and of organism change to creativity. If we think about the space of possible organisms, we can also connect the ideas of evolution to the ideas of complexity discussed in the previous section.
Understanding evolution is clearly one of the great challenges in the study of complex systems. Though it is not restricted to biological evolution, biological evolution is a central example. It is impossible to discuss all of the issues involved in this article, but we will start.

The incremental process that Darwin recognized acts on populations of organisms, not on individuals. The change that he described is not the difference between a child and his or her parent, but rather the change in an entire generation. Because of heredity children are similar to their parents. Why, then, is one generation different from its parents' generation (see Figure 33)? Some parents will have more children than others (called differential reproduction) and of these children some of them will grow up to be parents and some of them will not (called differential survival). Overall, if we look at the population a generation later, the effects of "differential reproduction" and "differential survival" (net differential reproduction) results in a different population.

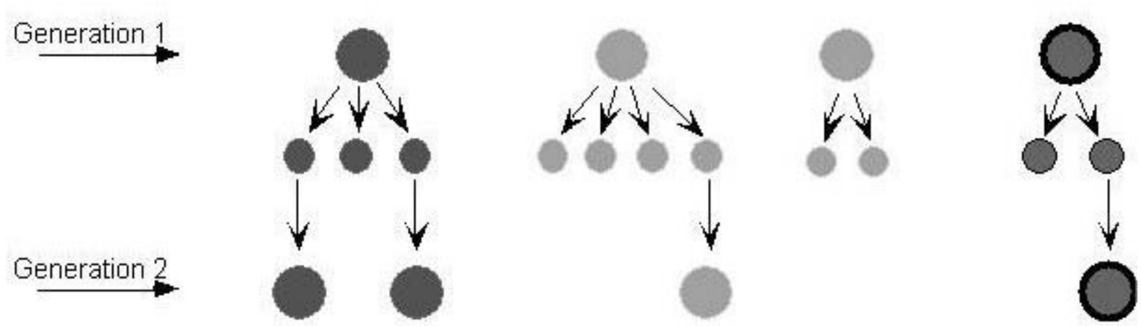

Figure 33: Evolutionary differences between successive generations

After many generations these changes can result in dramatic changes in the population. There are several reasons that the changes due to selection continue to accumulate. One of these is *variation*, that children are not quite the same as parents. The differences between children and parents result from several mechanisms including mutation and the mixing that occurs in sexual reproduction that we mentioned in the first section. This is like the formation of composite patterns in creativity.

The second reason that changes continue to accumulate is that the selection occurs relative to the other organisms that are around at that time. Part of the selection is just what can survive (viability). The other part, which compares one organism with others, depends on how many organisms can exist at one time. These limits have to do with the resources that are available, and also how the organisms interact directly with each other. Because of these limits, the ones that survive are the ones that are better at surviving than others at that time. In the next generation, the situation changes because the population changes and the organisms are compared with each other. At each generation, selection is being made from those that already were selected before. This comparison of organisms can be thought of as a competition. Heredity, variation and competition combine to make selection act as a progression that continues to move forward rather than staying in one place.

The idea of progressive selection implies that selection progressively improves the abilities of the organisms to compete. This idea is not entirely correct, because the situation is different from generation to generation. The environment changes and so does the population (for any one organism the other organisms are also part of the environment) so the competition is somewhat different each time. If the competition is different, a selection in one generation is not necessarily improving on the previous selection. Still, the idea that improvement occurs progressively in evolution is a useful conceptual starting point. This idea is especially important because of the fantastically complex biological organisms that exist. Only by building generation to generation on the selection of the previous generation could such complexity arise.

The ideas of evolution are often used in thinking about how people live in society. At one time it was believed that people should compete with each other for success and the losers should not survive. At the beginning of the industrial revolution this allowed some people to justify to themselves the terrible conditions of poor workers or the unemployed. It still seems to some people that helping each other goes against the basic idea of competition as a positive force in selecting the best. This idea, called Social Darwinism, was partly motivated by the limited understanding of evolution that people had a hundred years ago. Over the course of this section we will explain other aspects of evolution that counter this perspective. The basic problem is understanding how cooperation and competition work together. {Still the basic idea of evolution is that a non-ethical framework is useful in describing nature, noting that what works, works. It turns out, however, that what works is a combination of competition and cooperation.}

4.2. Evolution and Competition in Sports

Selection is also found in competitive sports. In a competition between people running the 100-meter dash, the top few are selected to win prizes. This selection often means that they are eligible to compete in another race with other winners. In a more or less organized fashion, the selection continues until the world champion is identified from the few best racers from various subregions of the world. Selecting just one out of all the world is not really the same as selection in biology. Biology typically has many "survivors" in any one generation giving rise to the next generation. There are many other differences as well. The idea of progressive competition is, however, analogous, since we expect over the many races to identify the best runners.

In sports, there is also an "intergenerational" competition through the keeping of records. Records allow us to compare runners that cannot directly compete with each other because they are at the peak of their capabilities at different times, possibly separated by many years. The conditions are not exactly the same, but this is the idea of keeping records. It is not the same as the evolutionary process between generations.

Heredity also doesn't work exactly the same way in sports as in evolution. Aside from the few cases where children of racers are themselves racers, there is no biological inheritance. There is a different kind of heredity, however, through transmission of knowledge. Knowledge is an important part of capability in sports. This includes knowledge of how to prepare and train, physically and mentally, for competition, as well as how to compete effectively during an event. The biological parent to child heredity is replaced by teacher to student heredity. Unlike the biological case, where there are usually two parents, there can be many teachers for each student, not just many students for a teacher. Similar to heredity in biology, where selection involves increased reproduction as a measure of success, the process of evolution by selection in sports involves learning by copying/emulating the most successful competitors. The transmission of knowledge is true not just in sports, but as part of how society develops as a whole. In general, parents are often also teachers, but there are many other teachers as well.

There is an important way that sport is similar to biology that we haven't spoken about. This is the existence of many different kinds of sports. Each sport, when played at its best, requires a different set of skills and strengths. This means that selecting the best in one sport is not the same as the best in another sport. The same is true in biology. There are many different environments, and many different resources (for example, different types of food or different places to make homes) in these environments. We call a particular environment and set of resources a *niche*. The existence of many different kinds of niches is the main reason there are many different kinds of biological organisms. When there are many niches that are connected to each other, competition, and evolution as a whole can be very different from the process that Darwin thought about.

Historically it has been hard for thinkers about evolution and society to realize that the existence of many different ways to succeed changes the meaning of competition. We can see this by thinking about what has been happening in recent years in society. As we discussed in the last section, the complexity of society is increasing. This also means that the number of different types of jobs and professions—the number of ways to succeed—is increasing so that there are more and more ways to succeed. The many different possible professions require careful selection. One of the problems that we face is not to win a race, but to figure out what race to be in. This is a major reason that people try different jobs, or move from job to job.

4.3. Competition and Cooperation in Sports

Team sports add a new feature to our discussion that will help us develop a more complete picture of evolution itself. This new aspect is the interplay between competition and cooperation.

Whenever discussions of competition and cooperation take place, people usually think of them as opposites. In evolution, the competition that exists between organisms seems to make it impossible for cooperation to exist. Similarly, companies are competing with each other for business. People compete for jobs. This seems to mean that competition is the basis of the free market system. Politics seems to be about competition for power. The notion of "it’s a dog eat dog world out there" captures how people often think about the social world. Figuring out how cooperation fits into this world view seems to be a very difficult problem.

Counter to the traditional perspective, the basic message of this section is that competition and cooperation always exist together.

Using our example of team sports we can see how competition and cooperation work together. Different team sports (baseball, hockey, basketball, football, volleyball, soccer) are different from each other, and so are the ways that competition and cooperation work for each, but there are still general ideas of cooperation and competition that apply for all of them. We can think about each of the different team sports and even the way teams work in gymnastics and track and field. You can take a few minutes and think about how competition and cooperation happen in a sport that you are familiar with. We will take some examples from basketball, when specific examples are needed; if you like a different sport, see if the same points can be made about it.

The simplest view of team sports is that teams compete against each other. Winners are chosen just like in the individual sports. The idea that teams compete with each other, however, is not the whole story. Professional teams are also a business. Together, teams cooperate in forming a league that schedules times of games, and competes for attention with other leagues and other forms of entertainment (see Figure 34). As a business, basketball teams cooperate with each other to maximize their profits: game rules are set and enforced through penalties, officials are selected and assigned to games, new players who come into the league are selected by a lottery system to prevent one team from dominating for many years, and rules are set to determine how players can be traded around. Even in non-professional sports, teams cooperate with each other to decide upon rules and playing times.

The cooperation between teams is part of a different competition, the competition between different sports (baseball, basketball, hockey, football) and other forms of entertainment for the attention of the fans, the players, and financial gain. The competition between sports is made possible by the teams agreeing to rules of the sport, schedules, and other forms of cooperation. The more there is a competition between the different sports, the more the cooperation between teams of a sport has to work well, otherwise it will lose the attention of the fans, and the related income, to other sports.

Figure 34: Competition between sports and collaboration between teams: reinforce each other

Cooperation between teams can be counter to the competition between teams (see Figure 35). This is the basic conflict between competition and cooperation that we usually think about. For example, the more games that are played, the more profits are made by the teams. So there is an incentive in playoff series for the teams to win some games and lose some games. This is true even when one team can win all the games. This suggests that two teams might cooperate to extend the series. Cooperating in arranging victories and defeats to extend a series would be counter to the competition in the sport and is considered against basic ethical behavior. Nevertheless, it is generally believed that some sports, like TV wrestling, do this regularly. In general, sports try to avoid the conflict between their competition and their cooperation, because the competition is part of the reason people are interested in sports and cooperating undermines the competition in a most basic way.

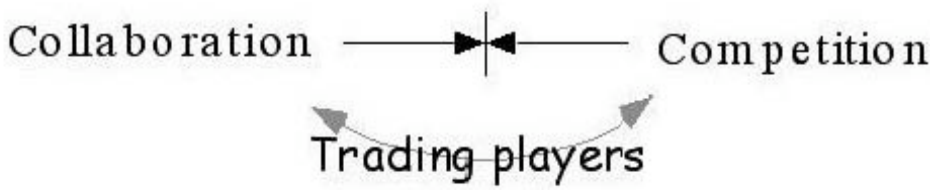

Figure 35: Cooperation between teams can be counter to the competition between teams

There is an important difference between the cases where competition and collaboration support each other, and those when they oppose each other. In the first case the cooperation between teams enables the competition between sports, and the competition between sports promotes the cooperation between teams. The key to thinking about the cooperation between teams and the competition between sports is that they are on different levels of organization. The cooperation between teams is at the level of the teams. The competition is at the higher level of the sports. These interact with each other in a constructive way: competition between sports for financial gain tends to increase collaboration between teams, and collaboration between teams improves their ability to compete with other sports. On the other hand, when we consider the competition between teams and the cooperation between teams we see that this is in conflict. There are ways to lessen the conflict between cooperation and competition between teams. For example, in the trading of players, the teams are competing and cooperating at the same time. It is interesting that teams can find ways to trade players that each team will agree to. The potential conflict in doing so is clear—it would seem that one team would gain and one would loose. Still, trading does go on, showing that competition and collaboration can coexist, even if the relationship is an uneasy one.

The two kinds of relationships between competition and collaboration also hold within a team (see Figure 36). Competition between teams requires cooperation between players on a team. If the players on a team do not cooperate well with each other, their team is not likely to be successful. The competition between teams is what makes the cooperation between the players happen.

We can see this as a kind of evolutionary process that works toward improving the cooperation between players. Just like in biological evolution, there is a process of selection of winners which involves teams competing. Over time, teams change how they behave. Strategies of teams that do well are copied by teams that are doing less well. Over time, teams tend to improve their effectiveness. This means that over time teams become selected for their ability to cooperate internally. The cooperating teams become successful, and the successful teams are models for others how to behave. This shows that competition and collaboration work together. Competition of teams causes more collaboration within the team. The collaboration within the team enables a team to compete effectively. The key to this is that competition and collaboration are at different levels. Competition is between teams, collaboration is between players. In addition to copying the behavior of other teams, teams change by choosing their players, trading players, and changing coaches.

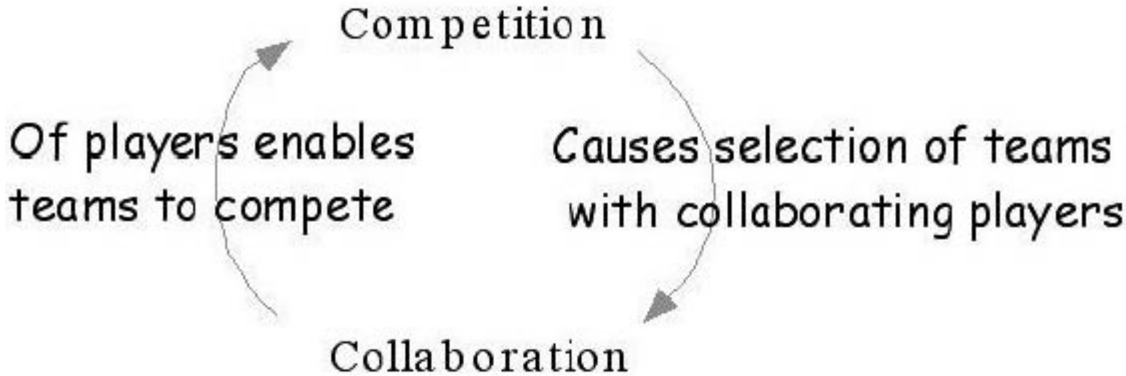

Figure 36: Competition between teams and collaborations between players reinforce each other

We can also think about the competition between players on a team. There are two aspects of this relationship (see Figure 37). The first is that when players on a team compete with each other, they don't tend to collaborate as well. In basketball, when two players are both trying to get baskets in order to show how good they are individually, they don't work together for the benefit of the team, so usually the team doesn't do very well. A recent example of this is the case of Shaquille O'Neill and Kobe Bryant of the Los Angeles Lakers, whose lack of cooperation in the beginning of the 2000 season was a clear cause of the team's poor performance. Once they began to cooperate with each other, the team became almost unbeatable. Team owners, managers and coaches are rewarded for winning and promote the cooperation of team members over their competition, but this conflict still exists.

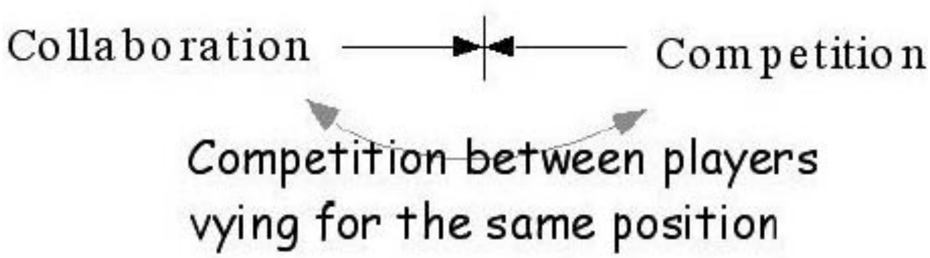

Figure 37: Competition versus collaboration between players on a team

This conflict between collaboration and competition is the one that we often speak about. Still there are important ways that the competition between players is helpful to team cooperation. This is particularly clear when the players are specialized in their position. In this case the players who are playing at one time don't compete as much with each other as with other players that can play that position. In basketball the different positions of center, forward and point guard are not part of the rules of the game. They arise from the realization that these specialized positions are helpful for the team to be successful. There is a competition between different centers for the possibility of playing on the team and for playing time once they are on the team. But there is not as much competition between centers and point guards because they are not competing for the same position. The case of Shaquille and Kobe is an exception: they were competing for attention on the court even though they were playing different positions. Despite this exception, when players are playing different positions, the competition between players competing for the same position on the team causes them to become better collaborators because this is an important part of what makes them better players.

The importance of cooperation between players in basketball can be seen from how the playing of the sport has changed over the years. One of the clearest trends has been the trend from high scoring games, well above 100 points per team, to games that score in the 80s. In basketball, like in other sports, a winning team is the team with the highest score. The simplest way to measure how good a player is is by the number of points made. One would expect that if the players are improving over time, and the teams are improving over time, they would score more and more points and the scores would increase. In the early days of the sport this is indeed what happened, but not in recent years. To understand this, it is helpful to realize that each time a team makes a basket, the other team gets the ball and has a chance to make a basket. If the likelihood of scoring is high, the scores increase but the difference between the scores is very small. Any missed basket becomes very important for winning. Teams can increase the likelihood of a miss by playing better defense. This leads to a very important role of defense, even though defense itself doesn't show up directly in the score. Defense is also much more of a team effort than offense, because it is usually not enough for one player to play good defense to prevent a score. Even if only one player is playing bad defense, the other team can use this to score many points. Eventually, as scores decrease, there becomes a point where the importance of good defense should balance against the importance of good offense. In the meantime the scores still seem to be decreasing.

In order to select good players that can help a team win, it is clear that the number of points they make is not enough. How can teams evaluate and recognize the good players? One way to do this is to measure other qualities in addition to scoring. An important cooperation-related measure is the number of "assists" showing how well one person passes to set up another to make the score. A mixed offense and defense related measure is "rebounds," which counts how many times a player catches the ball when there is a missed basket (whether it is a missed basket of your own team to give your team another chance, or a missed basket of the other team). A measure of defensive ability is "blocked shots," which are direct blocks. Measuring other qualities of defense and more generally of cooperation is harder. This is particularly true since these qualities are not really qualities of a single player but qualities of groups of players, playing together. There are "set plays" that involve several players, like the "pick-and-roll" and the "alley-oop" that work for certain players in particular combinations.

The key idea here is that the property of a "good player" is not only a property of the player. It is really a property of the player in the context of a specific team. There are two contexts in which we could think about the player's qualities in and of themselves. The first is when we have a shooting contest. The second is if we give each player a chance to play with all other players in teams—then we can ask which player does better on average over all of the possibilities. Of course, we can't try all possible combinations. Also, averaging over all of the possible teams is not necessarily as important as picking the specific team that is better, even if the players on that team are not the ones that are good on average. This is one of the places where we see how reductionism does not really work. Biologists often think about the competition between organisms in terms of the competition between genes, and consider the "fitness" of a gene as an evaluation of how good it is, like a player on a sports team. Just like with players in sports, the "fitness" is not really a property of a gene.

The many different important qualities of players are also what lead to the player specialization on teams to different positions. What is the problem with asking for a player to be good at everything? The problem is that different individuals are good at different things. Even in just considering scoring, the main quality of the center is the ability to shoot baskets from very close to the basket, the main quality of a point guard is to shoot baskets from far away. The player qualities that are good for nearby shooting are size, strength (to force through the defense in the small space near the basket) and coordination. The main qualities of a player who is good at shooting from far away are precision and quickness (to avoid defense in the large space far away from the basket). Moreover, devoting energy to one thing (like offense) will reduce energy for other things (like defense).

We can summarize this discussion by recognizing that the competition and collaboration tend to reinforce each other when they are at different levels of organization, but tend to be in conflict with each other when they are at the same level (see Figure 38). The conflict between them at the same level can be reduced by separating the competition and collaboration (as in the competition between players at the same position, while there is cooperation between players at different positions). The idea of competition and cooperation also works when we consider the competition between different organisms in biology or competitors in a non-team sport. In this case the cooperation is between parts of the body. One of the most important qualities of the winner is having the most coordinated parts. This is also important in team sports, so that the best team is the team with the best coordination between the players, and the players with the best coordination of their parts. We can even say that the team has the best coordination of parts of the players. Cooperation is necessary for competition, and competition, through the process of selecting the best, gives rise to cooperation.

Figure 38: Competition and collaboration tend to reinforce each other when they are at different levels of organization, but tend to be in conflict with each other when they are at the same level

When thinking about how it is possible to improve the effectiveness of teams in any context, we can use the sports example. The effectiveness of a team, including the cooperation within a team, is enhanced when teams compete with each other, and when they have the opportunity to change their composition by selecting and trading team members. Teams also will find ways of measuring the capability of their members to help them select the better team members. Just as in basketball this includes various measures both of individual ability and cooperation. Still, cooperation is a property of the team not of the individual, and the particular combination of members matters to the ability of the team. There are a number of ways that the competition between players can be used to help teams perform better. The first is through the effectiveness of the player him-/herself. This has to do with the coordination of the parts of the player. The second has to do with the cooperation in general of the player. The third has to do with how well he cooperates with the specific other members of the team, or how well this particular team plays together.

Finally, there is another way that competition and cooperation interact favorably with each other; this is at different scales in time. Teams that are competing with each other are cooperating in improving their capabilities, increasing their likelihood of success in future competitions. There is a caveat—this kind of competition has to be "non-destructive" so that the teams are strengthened rather than weakened by the competition. In nature, this kind of competition is also present. For example, in the battles between antlered deer, it is believed that under many circumstances they are careful to avoid severe damage to each other. Even though there are consequences of the battles in terms of dominance and mating, the battles appear to follow rules that avoid mutual damage. Presumably the reason is that their strength is needed for later battles, particularly those with other types of animals.

From the discussion of different levels and time scales we see that understanding the relationships between cooperation and competition is part of considering evolution by looking at different levels and relating the behavior at these different levels of organization.

4.4. Selfishness and Altruism

The traditional conflict of competition and cooperation is closely related to the conflict between selfishness and altruism. The ideas of competition and cooperation describe groups of individuals, while selfishness and altruism are ideas that focus on the individual. We can think about cooperation as mutual altruism, competition as mutual selfishness. Selfishness and altruism correspond to one person cooperating and another one competing. Our discussion of competition and cooperation explains how mutual altruism and mutual selfishness work together at different levels of organization. We have not directly addressed what happens when one player cooperates and one player competes. In this context, there is a straightforward answer: In simple cases, when some people are cooperating and some are competing in a team, the team will be better than if all are competing and worse than if all are cooperating. This means that the selection of winning teams (team competition) will tend to promote altruism in the team. This idea is central to our understanding of selfishness and altruism in general. To make this clearer, we can review the philosophical discussions of altruism and selfishness.

Selfishness and altruism have been the subject of discussion by philosophers since the time of the ancient Greeks. The Greek philosophers asked why would/should someone be altruistic? It seemed, and still seems, to many great thinkers that self-advancement is the only rationally justifiable approach to life. This approach is also carried over to conventional evolutionary biology. The idea of selection of those who successfully compete suggests that any act that reduces the likelihood of reproduction and survival should be eliminated by selection. Evolution seems to be a process that should result in completely selfish individuals.

Despite the views of philosophers and biologists, altruism exists in human societies in many obvious ways. It also can be found among many animals. As scientists who would like to interpret animal and human behavior in light of traditional evolutionary theory, biologists are concerned about how altruism can arise.

Many biologists believe that a reductionistic approach solves the paradox of altruism. Reductionism says that the gene, as the smallest hereditary unit, is the object of evolution. The notion of selfishness taken at this level gives rise to the notion of the selfish gene. The idea of the selfish gene seems to explain altruism, by arguing that all altruism arises from a hidden agenda of selfishness. If one individual is altruistic, it is only because there is a way that his/her genes will benefit. The easiest way this can happen is if different individuals are relatives that share genes with each other. Then, when one person helps another, this is just a way of helping the reproduction of his or her genes. Genetic selfishness is the only explanation, they argue, for any appearance of altruistic behavior. While this idea has dominated much of biological thinking, there are real problems with the scientific application of these ideas to actual biological or social systems.

One of the key issues that is not addressed by the reductionistic approach is that genes themselves cooperate much more than they compete. Human beings, and other biological organisms, including single celled organisms, have many genes. These genes, by and large, cooperate with each other. The sports analogy works pretty well—genes are like members of a sports team. The competition between teams only happens because of the cooperation within a team. If we had a problem understanding cooperation in human society, then we still have a problem understanding cooperation between genes. The idea of explaining cooperation between people in terms of competition between genes doesn't work unless you also have an explanation of cooperation between genes.

Is there an explanation of why genes cooperate? The solution to the problem of genes is like the solution to the competition and cooperation puzzle at every level of organization. Competition between organisms reinforces the cooperation between genes and cooperation between genes enables the competition between organisms. The key is realizing that genes, people (or animals) are organized into groups and individuals in groups that have more altruists are often better off.

Indeed, the basic idea that sharing genes gives rise to altruism can be entirely turned around. The reason that we share genes with each other through sexual reproduction is that we are cooperating with each other. Why else would an individual share successful genes with others? Once again, cooperation and competition, altruism and selfishness, are complementary. Selfishness does not explain altruism; they can only exist together.

Why do biologists find this difficult to accept? Why don't philosophers discuss this approach? The main problem is recognizing the many levels of organization of systems: seeing systems on multiple levels at the same time. It is much easier to see one individual person as the subject of philosophy than to see the many levels of family, neighborhood, social context, country, and so on, as the subject of philosophical inquiry. Similarly, if we extend the discussion down to biological molecules, realizing that all levels of organization are engaged in elaborate schemes of cooperation and competition is hard to visualize. Some philosophers have considered the importance of community and they have used this to resolve the paradox of altruism; some biologists have also done so. A more general understanding of levels of organization is harder because they are not as clearly defined as (what seems to be) a clear boundary around a person.

When we look at a person, we think of him/her as having a well-defined structure and size. Social communities seem to be less well defined. It turns out, however, that just like with sports teams that trade around players, groups do not have to be very well defined in order for altruism/cooperation to be a good idea. It is even enough for people to interact in a network. As long as people are more likely to interact with others that they have interacted with before, altruism will tend to win in selection. This is particularly true when there is a possibility of recognizing those that are altruistic and selfish, so that people can choose who to interact with. The example of team sports continues to be a useful one in understanding how this works.

When we think about the role of altruism and selfishness in a general social context it is easy to see that people tend, over time, to find others and develop social groups that are compatible with themselves. While this is not universally true, it need only be a tendency for the principles to apply that justifies the existence and reward of altruism. The most basic response to philosophers who ask: Why should someone be altruistic? is: Because he who is altruistic will join with others who are altruistic and together they will triumph. The significance of the ethical imperative of choosing your friends can be found here.

Still, this argument is not just about altruism winning the battle against selfishness. It is about their interplay at different levels of organization. Note the importance of the word "triumph" in the last paragraph. It is a statement of competition. As with the discussion of competition and cooperation, we see that altruism exists due to the competition/selfishness of groups.

4.5. Social and Political Competition and Cooperation

Competition gives rise to collaboration; collaboration enables competition. The inverse is also generally true: when there is no competition, there is no reason to have collaboration. We can see this in political and social contexts. People tend to band together in the face of competition and threats to their collective survival.

The end of the Cold War between the US and the USSR through the collapse of the USSR left the US without a global competitor. What should we expect as a consequence? The conclusion of this discussion is that we should expect that this would result in more conflict within the US. This is a natural conclusion. As long as the USSR was a threat, people in the US worked together, suppressing their individual aspirations in order to work together to avoid destruction by the outside threat. Once this outside threat was removed, there remained much less reason to cooperate. We should see this particularly at the largest scales of organization, and the natural place to see this is in the centers of power. In the US these centers of power are the executive, legislative and judicial branches of government and in the two party system, the Republicans and the Democrats. Conflicts between these different parts of the government were in existence even during the Cold War. However, it is not difficult to argue that after the end of the Cold War this conflict became much more severe. This tendency to internal conflict was dramatically reduced with the appearance of a new external threat with the destruction of the World Trade Center. These events provide just a hint, but the suggestion that, without an external enemy, internal conflicts become more severe is a reasonable and natural one.

Similarly, if we look at the conflict between the Arabs and the Israelis, we can easily find historical evidence that the Arab nations among themselves tend to be in conflict, and the Israelis have factions that are in conflict, but when they are fighting each other they tend to cooperate internally – and the more severe the conflict, the closer the cooperation.

We can extend this argument to consider what happens with corporations, families or other groups. When there are difficulties or threats from the outside, group members tend to stick together more. When there are fewer external threats they tend to have more internal conflicts. Generally, when people are working together to solve problems arising from outside the group, they overlook problems inside the group. When the external problems go away, the internal problems become the focus of attention.

It is important to realize that the idea that groups cooperate more when there are external competitions/challenges is a tendency rather than a rule. Each of these scenarios happens because cooperation at one scale enables effective competition at a larger scale. Evolution doesn't say that a change in competition will give rise to a change in cooperation of the same entity. Evolution only says that organisms that cooperate better will tend to survive. What we are observing is that evolution has also selected organisms that respond to competition by becoming more cooperative. This is an adaptive rather than an evolutionary response, but the adaptation is consistent with the evolutionary preference for organisms that respond effectively to environmental demands.

4.6. Groups in Evolution

An important aspect of the general process of evolution is the formation of groups at different scales. This is important whether we are considering molecules, organelles, cells, multicellular organisms, hives, herds, prides, families or other social groups. Understanding how such multilevel structures form in evolution is a key part of understanding evolution. Traditional views of evolution consider these transitions to be major revolutions in evolution. The use of the word "revolution" suggests that this process is outside of the usual process by which evolution takes place. The study of evolution from the perspective of considering the different scales of competition and cooperation suggests that the formation of groups is a very natural and essential part of the basic process of evolutionary change.

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Glossary

Adaptive:	An adaptive system (or a complex adaptive system, CAS) is a system that changes its behavior in response to its environment.
Altruism:	quality of promoting gain of others at the expense of self
Coherent:	all doing the same thing
Competition:	behavior of entities promoting exclusive gain
Complexity:	the (minimal) length of a complete description of the system
Cooperation:	behavior of entities promoting mutual gain
Description:	representing the properties of one system in the properties of another system

Development: the process of self-organization that occurs when a single fertilized egg becomes a differentiated multicellular organism

Emergence: the relationship between a description of the system at a fine and large scale

Environment: the context in which the system we are interested in is found

Evolution: a process of change or adaptation that occurs in populations that undergo replication and selection of heritable traits

Feedback: Feedback is a circular process of influence where action has effect on the actor.

Information: the logarithm of the number of possibilities in a message

Interdependence: the existence of relationships between the behaviors of parts of a system

Network: a system that can be partially described as a set of points and line segments that connect them

Observer: a person who makes measurements (observations) on a system to gain information about it

Pattern: a set of relationships that are satisfied by observations of a system, or a collection of systems

Possibilities: the set of possible states of a system

Random: arbitrary within a set of possibilities

Reductionism: considering the properties of the parts of a system as embodying the properties of the whole without regard to the relationships between them or the system's environment

Relationship: When two entities have a relationship then information about one of them also contains information about the other.

Scale: measure of size used to determine level of detail provided in a description

Selfishness: quality of promoting gain of self at the expense of others

Self-organization: the appearance of patterns that are not imposed directly by external forces

State: the condition of a system at a particular time

System: a delineated part of the universe distinguished by an imaginary boundary

Bibligraphy

Axelrod R. M. (1984) *The Evolution of Cooperation*. New York: Basic Books. 256 pages. [Classic research on the evolution of and need for cooperation in human groups]

Bak P. (1996). *How Nature Works: The Science of Self-Organized Criticality*. New York: Copernicus Books. 212 pages. [Popular book explaining the concept of self-organized criticality]

Bar-Yam Y. (2002). Complexity Rising: From Human Beings To Human Civilization, A Complexity Profile, *Encyclopedia of Life Support Systems*.[Exploration of the complexity of human groups and societies]

Bar-Yam Y. (1997). *Dynamics of Complex Systems*. Cambridge, MA: Perseus Press. 848 pages. [Wide ranging description of the study of complex systems including chapters on brain and mind, proteins, evolution and development, and human civilization. These chapters explore the relationship of structure and function, dynamics, self-organization, and complexity.]

Bar-Yam Y., ed. (2000). *Unifying Themes in Complex Systems: Proceedings of the International Conference on Complex Systems*. Cambridge, MA: Perseus Press. 655 pages. [Perspectives and research contributions in the many scientific fields exploring complexity and the themes that apply across these fields]

Bar-Yam Y. and A. Minai, eds. (2002). *Unifying Themes in Complex Systems II: Proceedings of the 2nd International Conference on Complex Systems*. Cambridge, MA: Perseus Press. 722 pages [Second volume of perspectives and research contributions in the many scientific fields exploring complexity and the themes that apply across these fields]

Bar-Yam Y. (in press). *Unifying Principles in Complex Systems, in Converging Technology (NBIC) for Improving Human Performance*, M. C. Roco and W. S. Bainbridge eds.[Overview of the fundamental advances and research opportunities in the study of complex systems]

Darwin C. (1964). *On the Origin of Species (By Means of Natural Selection) (a facsimile of the first edition, 1859).* Cambridge, MA: Harvard University Press. 513 pages. [Darwin's landmark discussion of the evolution of living species]

Gell-Mann M. (1994). *The Quark and the Jaguar*. W H Freeman & Co. 392 pages. [Popular book explaining many aspects of simplicity and complexity.]

Holland J. H. (1992). *Adaptation in Natural and Artificial Systems*, 2d ed. Cambridge, MA: MIT Press. 228 pages. [Evolutionary adaptation and its use in computer-based genetic algorithms]

Kauffman S. A. (1993). *The Origins of Order: Self Organization and Selection in Evolution*. New York: Oxford University Press. 709 pages. [Describes many complex systems insights into biology and evolution]

Shannon C. E. (1948). A Mathematical Theory of Communication, in Bell Systems Technical Journal, July and October 1948; reprinted in C. E. Shannon and W. Weaver. (1963). *The Mathematical Theory of Communication*. Urbana, IL: University of Illinois Press. 125 pages. [The original and highly accessible paper on the theory of communication]

Simon H. A. (1998). *The Sciences of the Artificial*, 3rd ed. Cambridge, MA: MIT Press. 212 pages. [Clearly described insights about natural and artificial complex systems.]

Sober E. and D. S. Wilson. (1999). *Unto Others*. Cambridge, MA: Harvard University Press. 384 pages. [Overview of the scientific argument for the evolutionary value of altruism and group selection]

Sterman J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Irwin Professional. 1008 pages. [Carefully worked out examples demonstrating how systems thinking can be applied to the dynamics of business organizations and decision-making]

Biographical Sketch

Professor **Yaneer Bar-Yam** is founding president of the New England Complex Systems Institute. He received his Ph.D. from MIT in Physics in 1984. He was a Bantrell Postdoctoral Fellow, and a joint postdoctoral fellow at MIT and IBM. After a junior faculty appointment at the Weizmann Institute, he became an Associate Professor of Engineering at Boston University in 1991. He left Boston University in 1997 to become president of the New England Complex Systems Institute. He is also Associate of the Department of Molecular and Cellular Biology of Harvard University.
Prof. Bar-Yam studies the unified properties of complex systems as a systematic strategy for answering basic questions about the world. His research is focused both on formalizing complex systems concepts and relating them to everyday problems. In particular, he studies the relationship between observations at different scales, formal properties of descriptions of systems, the relationship of structure and function, the representation of information as a physical quantity, and quantitative properties of the complexity of real systems. Applications have been to physical, biological and social systems.
Prof. Bar-Yam has made contributions to: the theory of the structural and electronic dynamics of materials; the theory of polymer dynamics and protein folding; the theory of neural networks and structure-function relationships; the theory of quantitative multiscale complexity; and, the theory of evolution.
Prof. Bar-Yam is author of over a hundred scientific articles and the textbook *Dynamics of Complex Systems* (1997) addressing the entire field of complex systems. He is Chairman of the International Conference on Complex Systems and Managing Editor of *InterJournal* -- an on-line electronic journal. He has consulted and given courses for: the World Bank, MITRE, and the US military and intelligence communities. He has taught about complex systems in Canada, China, Columbia, France, Italy, Japan, Korea, Portugal, Russia and many places in the U.S.