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Analyzing the Effectiveness of Social Organizations Using a Quantitative Scientific Understanding of Complexity and Scale

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In the last few years the obscurity of science has been shattered by a new approach that addresses a slew of current questions: how our minds work, how family relationships function, how to protect the environment. The field of "Complex Systems"[1] is an approach to science that uses mathematical modeling to study how relationships between a system's parts give rise to collective behaviors, such as a population formed of animals, the brain formed by neurons, or cells comprised of molecules. These are all examples of complex systems. Though approaches to the study of systems have existed for decades, only recently have formal, mathematical tools been developed to effectively represent, classify, and characterize those systems. 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 to be gained.

Traditionally, the domain of quantitative theories is that of the physical sciences. However, it has become apparent that the scientific theories offered by the complex systems approach can also be applied to the way we organize our social systems, including businesses, governments, and economies. The excitement about the field of complexity science reflects its potential impact on our ability to understand questions that affect our everyday lives, lives that have become increasing complex. The widespread interaction of people across the world makes present day activities intrinsically more complex than they have ever been. As complex systems research demonstrates, [1,2] this increase in global complexity is now requiring human organizations to become equally complex. Technological and economic developments have enabled, and even *required*, a distinct shift from central to distributed control in our organizations. This transition, often referred to as the advent of the “Information Age," should be understood as a complexity transition. While the industrial revolution changed the primary energy sources of our society, as well as the nature of human activity, this new transition is, instead, a change in organizational structures and social forms.

In many of our organizations and communities, decisions are no longer made from the top down. Rather, in order to operate more effectively, our social systems have become less and less hierarchical. This change hasn't necessarily occurred everywhere at the same time, and need not happen everywhere. Still, the study of complex systems provides a map to understand how and where the forces of complexity compel the shift to distributed networks. To scientifically understand this change is to better understand the past evolution--and future trajectory--of our global society. These are among the issues we are studying at The New England Complex Systems Institute (NECSI). We can also apply this basic understanding to more specific systems such as the healthcare system, revealing steps toward solving some of its most pressing problems.

However, before we further discuss how the complex systems approach can help us to address concerns about specific social systems, let us turn to the complex systems approach overall. Specifically, how does it differ from the more traditional science? In brief, the focus of complex systems is on relationships between parts, rather than on the parts themselves. Traditionally, a scientist observes something and attempts to understand how it operates. One of the most important insights to this process is that everything is made up of parts. So, reasonably enough, we say, "let's figure out how its parts function; this will help us know how it works." Yet when we look at one of the parts, we realize that it too is made up of parts. The next logical step, then, is to look at the parts that make up the part. For example, the human body is comprised 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. It is impossible to deny that science has made great progress by taking things apart.

However, what is left out of this approach is the problem of understanding relationships between the parts. Indeed, the importance of this understanding should be self-apparent. If all systems around us were made of the same elementary particles, and their relationships were irrelevant, then all systems would be identical. Obviously, this is not the case. Our quest to understand the parts becomes so detailed that we forget what we were trying to understand at the start. Moreover the strategy of looking at parts may blind us to the way properties of a system arise from the relationships between the components. This reflects itself in what we think about in general. More specifically, it affects how we approach problem solving when we try to solve problems in society. Indeed one of the main difficulties in solving problems is that we think the problem resides in the parts themselves, when, in actuality, it is to be found in the interactions between the parts. As a result, many crucial questions can only be addressed by thinking carefully about connections in a system as a whole.

In order to cultivate an understanding of relationships, we must begin by developing frameworks that allow us to characterize their nature. Systems with many components are all around us. But what is important is developing ways to characterize, classify and describe the nature of their relationships. One difficulty we face when training ourselves to consider the relationship between parts of a system is that not all systems, no matter how many parts they contain, are equally "complex," as we will use the term. One helpful way to understand this issue is to compare natural and engineered systems. An engineered system, such as a microprocessor, is an extremely intricate device with millions of electronic components. The same could be said of a naturally arising system, such as the global economy. However, there are fundamental differences between these two. While the microprocessor was carefully designed and tested by engineers, every component consciously put into place, the global economy is very different. No one person can claim to have designed the global economy. Furthermore, nobody can claim to fully understand or control it. Additionally, while the microprocessor can be augmented only through careful redesign, the economy grows (and shrinks) on its own, without explicit direction by anyone. The global economy is far more robust, responsive and adaptive to changes in the environment. As a whole, it can overcome perturbations and failures in its sub-components. These differences have to do with the way components interact with each other at any particular moment in time, and over time.

Throughout our society, as well as the natural world, one can see many other systems with characteristics similar to the global economy we just discussed: communication networks, cities, organisms, ecosystems, etc. While the traditional engineering approach to systems does include relationships between parts, these relationships are carefully bounded and do not effectively describe systems that are truly complex. Thus, if we are to develop an understanding of biological and social systems, we must develop new tools that provide insight into the distinct way such systems work. This will become increasingly important as the line between engineered and natural systems blurs. The Internet is a great example of this phenomenon. While it is based on an engineered substrate, it becomes an organically growing system through its interactions. [3] The power of complex systems studies is that it enables us to understand social networks such as this, and perhaps even design them.

While developing a mathematical framework for studying complex systems has opened many doors, there are also a few basic concepts that are central to considering these systems either from a qualitative or from a quantitative perspective. Among these concepts are interdependence, scale, and emergence. [4] First let's look at interdependence. While it's true that the components of a microprocessor are "interdependent", the dependencies have been carefully controlled to enable the behavior of the system in relation to its parts to be transparent. In natural systems components are typically interdependent in ways that are not readily obvious. This makes reductionist approaches much less effective at addressing them. We say that pushing on a complex system "here" often has effects "over there." This has become more and more apparent in our efforts to solve large-scale societal problems caused by our own actions.

It is helpful to characterize how a system is interdependent. 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 large. Consider three examples: a piece of metal, a plant, and an animal. For the metal, removing a piece does not change the internal properties of the material, even though it will change its shape. If we look inside the piece that has been removed, the properties remain unaffected, and the same is true for the rest of the material. For the plant, if you take a part away, like a branch or some roots, typically the rest of 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. Generally, it will die unless it is placed in special conditions. Now, compare this with an animal. Removing any part of the animal will have devastating effects both on the part and the rest of the organism. Unless measures are taken to keep it alive, the animal will die. These examples demonstrate very different degrees of interdependence. Recognizing that these different behaviors exist is an important part of characterizing systems such as social networks. Consider the family or organization of which you are a part. How strong are the dependencies between the parts? What would happen if a part were taken away? Does it matter which part?

One reoccurring conceptual problem that has arisen when addressing complex systems is that people consider the complexity of a system to be subjective. However, accommodating for subjectivity is an established part of science. For example, the movement of an object depends on the observer's movement. This is a well-known part of the formulation of Newtonian as well as Relativistic Physics. In terms of complex systems, the most important aspect of observation is the scale of detail to which the observer is sensitive. We can also think about this as "the observer's distance from the system." [1,2,4-6] Depending on how close or far removed the observer is, a system may have differing levels of complexity. Consider our planet. At one scale of observation it is a simple dot—a planet moving predictably along its orbit. Yet, observed at greater detail (a smaller scale) its complexity increases dramatically: the movement of the atmosphere and the oceans, plants and wildlife, cities, human beings, etc. Note that in this comparison we continue to consider the entire earth, not just a piece of it, even as we move to smaller and smaller scales. Thus, complexity cannot be recorded as a single quantity or quality. Since it is not a unique number, some consider complexity to have little use. However, it is not the number itself, but the variation of complexity as scale varies that can reveal important properties of a system.

We at NECSI have developed a technique called multiscale analysis, [7-9] which helps us to arrive at these insights. Multiscale analysis simultaneously examines a system across multiple scales, determining the complexity at each and therefore the relationship between system components and behaviors across its scales. This technique is particularly helpful when describing emergence, or distinct patterns that arise from the collective interaction of a system's parts. For instance, the emergent behaviors of a forest would be its cycles of fire and regrowth. Such behaviors would be apparent at a large scale, even though details of the system behavior would be lost.

The dependence of complexity on scale can be discussed for many different kinds of systems. Yet, rather than thinking about the systems that are often studied in science, it is especially interesting to think about systems that conventional science doesn't have many tools to consider. Let's see what we can say about some of the most complex systems we know about: modern society and the organizations that comprise it. As we mentioned at the beginning of this essay, the world has become much more interdependent in recent years. Actions in one place in the world can, and often do, affect things happening in another place or places. To think back to earlier examples, we are becoming more like an animal than a piece of metal, or even a plant. If one part is removed, the effect on the remaining pieces is quite strong.

To consider how this increasing interdependence has arisen, we must consider the ways in which people influence one another. We think of influence between people as control— not necessarily coercive control, but control nevertheless. In traditional organizations control is exercised through a hierarchy. For about 3000 years, hierarchies have been the generic form of human organizations. Clearly, it would be helpful for us to understand how a hierarchy works, and how this affects the complexity of a social system.

In an idealized hierarchy, the only way people talk to one another is vertically, up or down the structure of command. If you want to coordinate your activities with a person in the office next door you talk to your boss, and your boss tells the person in the office next door what to do. If you wan to coordinate with someone who is down the hall and is not supervised by your boss, then you have to talk to your boss, who talks to your boss' boss, who talks to the boss of the person down the hall, who finally talks to the person down the hall telling him or her what to do. Of course, the bosses don't need to wait for someone in the ranks to suggest something; they might just tell the people who report to them what to do. Another way to think about communication through the hierarchy is that it is filtered *up* the hierarchy reducing the amount of information to the information the bosses need, while communication *down* the hierarchy provides details that are needed for the workers' actions.

Consider simple examples of how hierarchies work in military force and industrial production. For the case of a military force, take as examples the ancient armies that conquered much of the known world, specifically Alexander the Great's phalanxes or the Roman legions. Their behavior is characterized by long marches with many individuals performing a single task in unison, and repeating it many times. The behavior of each individual is of a low complexity and demonstrates an important trade-off between complexity and scale. For action to happen on a large scale, complexity at smaller scales must be reduced. The large scale of action also enables a large scale of impact, as evident in the large size of the empires that were created by these military organizations. Indeed, the scale of impact of phalanxes and Roman legions was remarkable, even by today's standards. Furthermore, for this organization to operate, many individuals respond to the instructions of a single commander. The leader at the top determines where to march, when to fight, etc.

For our industrial example, take a Model-T Ford factory. Before Ford, a single car was made by a craftsman, who took about a year to put it all together. Ford's basic idea was to simplify what each individual had to do, and have the low-complexity task repeated over and over. As with the Roman Legion, each individual in the factory performed a repetitive task. In this case, however, not everyone did the same thing. Different people performed distinct tasks, the tasks then needed to be coordinated to produce a single product. In the end, the product could be quite complex, like a car. Yet the most notable achievement of this system was that a huge number of cars could be produced (i.e., a large-scale impact). Again we see that lowering complexity can increase scale. But in addition to the trade-off between scale and complexity, we can also see the role played by the control hierarchy. The hierarchy coordinates the tasks of different individuals to ensure that the overall behavior is as desired. Because individuals are performing different tasks, the control hierarchy has to give many more instructions than in the case of our military example. Intuitively, the hierarchy's need to communicate information to its component parts rapidly increases.

This brings us to an important observation. Since large-scale behaviors must be communicated through a single leader, there is a limit to how complex these behaviors can be. The large-scale behaviors controlled by that individual cannot be more complex than he or she is. Though the complexity of a human being can be quite large, it is not infinite. In this context, the relevant complexity bound is the complexity of a human being at the scale of observation by others (i.e., the amount of information a human being can communicate in a specified period of time). So, while a hierarchy is good at amplifying individual actions (increasing the scale of behavior), it is unable to create a system with larger complexity in its collective behavior than in its component parts. Conversely, this limitation does not exist in a network, such as the brain, or a market-based economy. A network can function in a more complex way than any of its single components.

The current breakdown of hierarchical organizations implies that the complexity of action required of our social organizations has exceeded that of individual people. The reason for this is quite clear to individuals who live and work in these organizations. In order to be effective in our complex, fast-paced world, organizations must be designed to transfer information laterally (rather than up and down).That is to say, networks of interaction must replace hierarchical control. While this is already apparent to those involved, it is significant that scientific studies can establish a mathematical basis for understanding this phenomenon. Only by doing this can we understand more specific contexts, the problems they entail, and the appropriate solutions.

To turn to a particular application, we will consider the recent developments in the US healthcare system. The difficulties faced by this system are common to other countries around the world. Additionally, the application to healthcare illustrates how the mathematical framework of multiscale analysis can be applied to improve essential aspects of the society around us. Currently, the healthcare system is experiencing many failures. Medical errors are rampant, measures of quality are low and costs are high [10,11]. The inability of the system to perform its task effectively, and specifically the existence of widespread mistakes that appear entirely avoidable, is symptomatic of a system that is not well structured for its task.

To understand the origins of these difficulties, we performed an analysis of the behavior of the system in terms of scale and complexity [12]. The key outcome of this analysis is the distinction of the traits of two aspects of the system. On one hand, the task of medical care of individual patients is highly complex, requiring physicians to respond in many different possible ways to individual conditions. As a result, physicians must be highly trained to identify which of the many responses are necessary. On the other hand, the large financial flows associated with insurance occur without direct correspondence to the medical care that is needed. These financial flows are large scale rather than complex. Because of the high costs of medical care, there is an effort to control the costs by setting the amount of the financial flows. This in turn must be translated into controls over the medical care provided to individuals. This dichotomy of large-scale flows controlling highly complex behaviors is already a prescription for severe problems.

One way to consider these problems is in the language of fluid flow. Turbulence occurs when a simple, coherent flow is broken up into many smaller flows. It can be observed in the swirls and eddies in a fast-flowing river, or in the way the column of smoke rises from a campfire. Although one can identify situations where turbulence will occur, it is very difficult to predict the resulting motions, which are irregular and change rapidly.

The transition from the large to the small scale in the context of healthcare results in organizational change as individuals and organizations try to direct the flow. The issue stems from the problem of controlling the flow of the system, specifically: Who controls the flow of money? The growth of managed care, physician cooperatives, reporting and billing systems, as well as hospital mergers are all part of the shifting interface between insurers and physicians. The use of turbulence as an analogy to what occurs in healthcare will not surprise those who work in it, people who have experienced its growing turmoil for the past 20 years.

Even when we don't consider organizational change, we can see why the transition between a large scale flow and a highly complex decision making process of individual physicians makes the system ineffective. The large-scale financial flows that drive the system eventually have to be allocated as payments to individual doctors treating individual patients for individual problems. Usually once a year government agencies and private insurers negotiate he overall rate of flow. In some way, based upon this decision, individual doctors have to change how they decide on the amount of care to provide individual patients, but the amount of time they can see them, the tests they can provide, and the treatments they can give. Clearly this is a very difficult task. Indeed, rather than having individual doctors make decisions, what happens is that there are overall restrictions placed on care by the insurance companies. This is called "managed care." Such centralized decision making could work for Roman legions and Model T factories. However, when such an approach is used to "manage" the delivery of care, we can state categorically that it won't work. The reason is that the task of care is not a large scale task, it is a highly complex task. Inevitably, the restrictions that are applied across different physicians treating the many different conditions they are faced with will inhibit their ability to act in accordance withy the needs of the individual patient. The result is a process that has been observed: a rise in cost accompanied by a decrease in the quality of care [13,14,15].

According to analysis using the complexity dependence on scale, the imposition of large-scale controls on a highly complex task inevitably result in ineffectiveness— even if the immediate connection between the imposition of the control and its outcome is not apparent. Generally the resulting difficulties manifest in indirect ways. Moreover, efforts to improve the system by changing the role of the insurers, for example, shifting from multiple payers to one payer, cannot resolve these problems because they do not significantly change the relationship between the large-scale flow and the highly complex care provided by physicians. Ultimately the key to addressing the problem is matching the complexity of the system to the complexity of the task.

Matching the complexity of the organization to the task requires each part of an organization to have the right complexity for the task it is performing. One aspect of the solution to healthcare's problem comes from recognizing that there *are* large-scale elements—the many tasks in repetitive and (relatively) simple actions, such as screening tests, inoculations, and treating certain common ailments. Such large-scale tasks *can* be met by efficient large-scale processes, thereby reducing expenses and improving the overall effectiveness of the system. Recognizing these tasks as large-scale, we can improve the matching of tasks and organizational processes.

This multiscale complex systems analysis of healthcare suggests that a key step will be the separation of responsibility for two distinct types of tasks: those of high complexity and those of large scale and low complexity. On the high-complexity end lies specialized medical care for individual patients. On the low-complexity end is preventive care and population health. By removing the simple repetitive tasks of prevention and population health from the traditional system to a system that is designed for them, physicians will be freed to concentrate on more unique problems.

We note that while some separation of tasks exists already in healthcare, particularly in hospitals, this is not the kind of distinction needed for this purpose. The most important step toward effectiveness at a large scale is designing a system specifically to deliver a particular service that is needed by many individuals. Once this is set up, for example, for flu shots, the delivery process is simple and streamlined and efficient. Physicians who are highly trained for decision making are generally not needed for providing such services, any more than they are needed for handling a hospital's laundry In spite of this, the current highly individualized system uses a one-patient/one-doctor model even for tasks that are needed on a population-wide scale. Individualized care should be entrusted to an individual-care system, while a distinct system should be created for large-scale, efficient prevention and public wellness programs. Trying to perform both tasks in the same organization creates a conflict between short-term responses to patients' immediate needs, and the longer-term benefits of prevention and public wellness projects.

Returning to the world of complex systems in general, these conclusions are supported by a number of examples in organizations,[4] both biological and social, which separate distinct tasks. Legs are great for getting around, but not as useful as arms and hands for complex manipulation of objects. The immune system is designed for complex, smaller-scale challenges than muscles are. By comparison with the immune system, even finger muscles are performing very large scale tasks. The military, to name a social organization, is partitioned into a variety of forces: tank divisions, infantry, marines, and Special Forces. Each is designed for different trade-offs in scale and complexity. [

Ultimately, we see that understanding the role of scale and complexity in structure and function enables us to think more clearly about the effective arrangement of social organizations. For more information on the mathematics behind multiscale analysis of these issues, consult the references. Scientific means can be used to identify how behavior at different scales of a system requires an organizational structure that is suited to performing necessary tasks. Sensitivity to scale and complexity is a requirement for solving our problems in this highly complex world. There are many other areas in which an understanding of scale and complexity would have clear benefits, such as international development, poverty and health problems in the Third World. In addition to the potential benefit to such national and global concerns, this understanding can be applied to human organizations and the specific tasks and problems they must confront. address their own needs. Only by matching correctly structured organizations to the tasks they must perform can we address systemic problems in our society.

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