

Introduction to the Study of Complex Systems

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Abstract

The structure of scientific inquiry is being transformed by broad relevance of the strategies and methods of complex systems science for understanding physical, biological and social systems. Disciplinary and cross-disciplinary interactions are giving way to trans-disciplinary and unified efforts to address the relevance of large amounts of information to description, understanding and control of complex systems. From the study of biomolecular interactions to the workings of the mind to global socioeconomic risks, pandemics and environmental disasters, complexity has arisen as a unifying feature of challenges to understanding and action. In this arena, information, structure, function and action are entangled. New approaches that recognize the importance of collective patterns of behavior, the multiscale space of possibilities, and evolutionary or adaptive processes that select systems or behaviors that can be effective are central to advancing our understanding and capabilities.

I. OVERVIEW

Complex systems analyses range from detailed studies of specific systems, to studies of the mechanisms by which patterns of collective behaviors arise, to general studies of the principles of description and representation of complex systems. These studies enable us to understand and modify complex systems, design new ones for new capabilities or create contexts in which they self-organize to serve our needs without direct design or specification. The need for applications to biological, cognitive, social, information and other systems is apparent.

For example, biology has followed the approach of accumulating large bodies of information about the parts of biological systems, and looking for interpretations of system behavior in terms of these parts. Yet, it has become increasingly clear that biological systems and their health and disease conditions are better understood as emergent collective behaviors of spatially structured networks, so that dependencies rather than components are the essential property to be understood. The role of information in biological action and the relationships of structure and function are only beginning to be probed by those who are interested in biological systems designed by nature for their functional capabilities. Underlying these systems are a wealth of design principles in areas that include the biochemical networks [1–5], immune systems [6–9] and neural systems [10–12], and animal behaviors such as the swimming mechanisms of fish [13] and the gaits of animals [14]. These systems and architectures point to patterns of function that have a much higher robustness to failure and error and a higher adaptability than conventional human engineered systems.

Computers have made a transition from systems with tightly controlled inputs and outputs to networks that respond on demand as interactive information systems [15]. This has changed radically the nature of their design. The collective behaviors of these networked computer systems, including the Internet, limit their effectiveness. Whether these have to do with the dynamics of packet loss in internet traffic [16], or cyberattacks [17–20] that, at times, have incapacitated a large fraction of the internet, these effects are not small. The solution to these problems is understanding collective behaviors and designing computer systems to be effective in environments with complex demands and to have a higher robustness to attack.

The human brain is often considered the paradigmatic complex system. The implications

of this recognition are that cognitive function is distributed within the brain and mechanisms may vary from individual to individual. Complete explanations of cognitive function must themselves be highly complex. Major advances in cognitive science are currently slowed by a combination of efforts to explain cognitive function directly from the behavior of individual molecular and cellular components, and on the other hand by aggregating or averaging the cognitive mechanisms of different human beings. Still, diverse advances that are being made are pointing the way to improvements in education [21], man-machine interfaces [22–24] and retention of capabilities during aging [25–28].

Recent global crises, including the global financial crisis, the global food crisis, social unrest including the Arab Spring, and the Ebola epidemic and other pandemics, have demonstrated that global connectivity leads to vulnerabilities due to the high rate of global travel, and the rapid propagation of economic and social influences [29–35]. Many of the key problems today have to do with “indirect effects” of human activities that may have substantial destructive effects on the human condition. These include global warming and ecological deterioration due to overexploitation of resources. Effective approaches to these problems will require an understanding of both the environmental and socioeconomic implications of both current actions, and of actions that are designed to alleviate these problems [36]. For example, the problem of global warming includes the effects of large scale human activity interacting with both the linear and potentially non-linear climactic responses. Despite the grave risks associated with global warming, a key factor impeding actions to alleviate it are fears of major impacts of such efforts on socioeconomic systems. Better understanding of the potential effects of such interventions should enable considered actions to be taken.

Other diverse social system problems may be linked to increasing societal complexity in healthcare, the education systems and governance more generally. Current approaches continue to be dominated by large scale strategies that are not effective in addressing complex problems. Even with the appearance of more holistic approaches to, e.g. third world development [37, 38], the basic concept of existing strategy remains weakly informed by complex systems insights. This gap is an opportunity for major contributions by the field of complex systems, both at the conceptual and technical levels. Further contributions can be made based upon research projects that emphasize the intrinsic complexity of these systems.

II. THE METHOD OF MULTISCALE ANALYSIS

The traditional approach of science to take things apart and assign the properties of the system to its parts has been quite successful, but the limits of this approach have become apparent in recent years. When properties of a system result from dependencies and relationships, but we assign them to their parts, major obstacles to understanding, design, regulation and control arise. Once the error of assignment is recognized, some of the obstacles can be overcome quickly, while others require rigorous inquiry. While many scientists think that the parts are universal but the way parts work together is specific to each system, 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, including physical systems like the weather, as well as biological, social and engineered systems.

One of the central insights about complex systems is that the effect of dependencies among components cannot be fully represented by traditional mathematical and conceptual approaches based in calculus and statistics. A key to their limitation is that they are applicable only to systems in which there is a separation of behavior between the micro and macro scales. Microscale behaviors are averaged using statistics, and macroscale behaviors are treated mechanistically. Interactions among the parts that cause behaviors across scales violate this separation.

But many systems are not well described by separate micro and macro scales. Consider a flock of birds. If all of the birds flew independently in different directions, we would need to describe each one separately. If they instead all went in the same direction, we could describe their average motion. However, if we are interested in their movement as a flock, describing each bird's motion would be too much information and describing the average would be too little information. Understanding complex behavior that is neither independent nor coherent behavior is best described across multiple scales. This requires knowing which information can be observed at a scale of interest.

Multiscale analysis [39–41] can be used to identify the complex relationships between the behavior of parts and the whole, across scales. In multiscale analysis we represent the behavior of a system completely at a consistent scale, and are able to vary that scale. Quantifying this strategy has been done through a variety of mathematical techniques, but the most widely applicable approach is that of renormalization group and its generalization

to multiscale information theory [39]. The overall complexity of a system, or the amount of information required to describe a system, can be analyzed as a function of scale. If the parts of a system are independent, then the whole system exhibits fine scale random behavior. If the parts are highly correlated, the system has large scale coherent behavior. In a case where there are fully dependent components in groups, the number of elements of the group is the scale and the behavior of that group occurs at that scale. More generally, if the parts are interdependent, the system can perform complex behaviors that can be characterized to identify key properties as a function of the scale they occur at. Many of the real world systems we are interested in are interdependent and the analysis of the scale dependent behavior is a technical challenge that requires analysis of how the aggregation of components gives rise to the behavior at larger scales, and the independence of those components gives rise to behavior at finer scales.

While the mathematical implementation can be challenging, multiscale analysis is ultimately essential to the study of biological and social systems because it is impossible to represent all of the information about a system, and such a representation would not be useful as each instantiation of a system is different at the microscopic scale. Without the ability to generalize, we cannot anticipate the behavior of systems that we have not fully characterized (an impossible task), inform decisions about how to respond to new circumstances that arise in the world (i.e. disease conditions or global crises), or design a system that we rely upon for such responses. Thus, characterizing the important information about a system is critical for both scientific knowledge that can be generalized across systems, and our ability to respond to real world circumstances. Case studies have been made but widespread application of this approach is necessary.

Additional background on the methodological approach and a set of diverse examples are provided elsewhere including application to evolutionary biology with relevance to ecology, biodiversity, pandemics, and lifespan, and in the context of social systems with relevance to ethnic violence, global food prices, and stock market panic [39].

As one example, consider the application of multiscale analysis to the vulnerability of species to ecological catastrophes. . If we consider just the biodiversity itself and not the importance of scale we can arrive at an incorrect conclusion. When considering the loss of biodiversity to a catastrophic event, extinctions are unlikely because they require the complete loss of all closely related types. A quantitative analysis implies that extinction of

95% of species would only eliminate 20% total diversity of the tree of life [42]. The reason is that random losses, even when high, are unlikely to remove all individuals belonging to a deep branch of the species tree even when it forms a small proportion of the population, thus preserving most of the diversity. However, to analyze the full effect we should consider not just the diversity, but the number of repetitions of specific genomes or of members of the same species, i.e. the multiplicity scale [43]. In contrast to the analysis of biodiversity, an analysis of multiplicity [44] suggests that the small immediate loss of species is followed by a much greater loss over time due to the vulnerability of small residual populations to extinction. The loss of a large fraction of a group of closely related species (or of closely related organisms) leaves the remainder of the group highly vulnerable to extinction. Other examples show how the role of both scale and complexity are important for biological and social dynamics. The selection of biological traits, such as altruism, is strongly affected by the role of interactions in space that lead to collective behaviors manifest as patches of genetic and behavioral types. In social systems, ethnic violence is linked to the geographical size of ethnic groups as they are embedded / surrounded by other groups, market prices behavior can be better understood by modeling the collective effects of trend following by traders, and market panic can be understood by considering the co-movement of prices. In each case, characterizing the scale of behaviors provides insight into the essential dynamical properties of interest.

Understanding complex systems does not mean that we can predict their behavior exactly. It is not just about massive databases or massive simulations, even though these are important tools of research in complex systems. The main role of research in the study of complex systems is recognizing what we can and cannot say about complex systems given a certain level (or scale) of description, and how we can generalize across diverse types of complex systems. It is just as important to know what we can know, as to know. Thus the concept of deterministic chaos appears to be a contradiction in terms: how can a deterministic system also be chaotic? It is possible because there is a rate at which the system behavior becomes dependent on finer and finer details [45–49]. Thus, how well we know a system at a particular time determines how well we can predict its behavior over time. Understanding complexity is neither about prediction or lack of predictability, but rather a quantitative knowledge of how well we can predict and, only within this constraint, what the prediction is.

III. MAJOR DIRECTIONS OF INQUIRY IN COMPLEX SYSTEMS

Complex systems science combines approaches that recognize the importance of patterns of behavior, the multiscale space of possibilities, and evolutionary or adaptive processes that select systems or behaviors that can be effective in a complex world [50]. Each of these is informed by multiscale analysis and its ability to describe behaviors at the largest scales.

A. Self-organization, pattern formation, and design of systems

Self-organization is the process by which elements interact to create spatio-temporal patterns of behavior that are not directly imposed by external forces. To be concrete, consider the patterns on animal skins, spontaneous traffic jams and heart beats. The robustness of self-organized systems is also a desired, and difficult to obtain, quality in conventional engineered systems. For biomedical applications, the promise is to understand processes like the development of the fertilized egg into a complex physiological organism, like a human being. In the context of the formation of complex systems through development or through evolution, elementary patterns are the building blocks of complex systems. This is diametrically opposed to considering parts as the building blocks of such systems.

Spontaneous (self-organizing) patterns arise through symmetry breaking in a system when there are multiple inequivalent static or dynamic attractors. In general, in such systems, a particular element of a system is affected by forces from more than one other element and this gives rise to “frustration” as elements respond to aggregate forces that are not the same as each force separately. Frustration contributes to the existence of multiple attractors and therefore of pattern formation.

Pattern formation can be understood using simple rules of local interaction, and there are identifiable classes of rules (universality) that give rise to classes of patterns. These models can be refined for more detailed studies. A useful illustrative example of pattern forming processes is local-activation long-range inhibition models. Local activation leads to similar behavior among nearby elements, while long range inhibition leads to breakpoints so that patches of a certain size arise. There can be many reasons for the local activation and long range inhibition. In chemical systems the local activation can arise from slowly diffusing species that engage in self-reinforcing chemical reactions, while the long range inhibition

arises from more rapidly diffusing species that are produced by the reaction but inhibit it and have their effect in a larger area around locations where the reaction takes place due to their rapid diffusion. Social system patterns can arise from within group mimicry. These models may be used to describe the complex patterns of animal skins, magnets, dynamics of air flows in clouds, wind driven ocean waves, and swarm behaviors of insects and animals. Studies of spontaneous and persistent spatial pattern formation were initiated by Turing [51] and the wide applicability of patterns has gained increasing interest in recent years [50, 52–56].

The use of multiscale analysis to characterize patterns that self-organize involves understanding the universality of these patterns in their macroscopic description, including how this description changes or responds in the presence of external forces, perturbations or changes in initial conditions [50].

B. Description and representation

The study of how we describe complex systems is itself an essential part of the study of such systems. A description is a map of the “actual” system onto a mathematical, graphical or linguistic object. Shannon’s information theory [57] has taught us that the notion of description is linked to the space of possibilities. Thus, while description appears to be very concrete, any description must reflect not only what is observed but also an understanding of what might be possible. The “space of possibilities” is an essential and deep concept about the behavior of complex systems. The space of possibilities is captured in the representation we use the parameters and variables of its mathematical description.

Among the essential concepts relevant to the study of description is the role of universality and non-universality [58] as a key to the classification of systems and of their possible representations. In this context, rather than studying a single model of a system, effective studies are those that identify the class of models that can capture properties of a system or a group of systems. Related to this issue is the problem of testability of representations through the validation of the mapping of the system to the representation. An important practical objective is to capture information and create representations that allow human or computer based inquiry into the properties of a system. The construction of human-usable representations must grapple with the finite complexity of a human being, and other human

factors due to properties of our sensory and information processing systems.

The combination of multiscale analysis with the problem of description/representation gives rise to a theory of structure in which each piece of information is characterized as to its redundancy [59]. The amount of information as a function of scale is the “Complexity profile” [40, 41, 50] which is the amount of information necessary to specify the system as a function of the scale of description. The complexity profile has been used to study a variety of questions ranging from the mathematical behavior of coupled variables to the effectiveness of social organizations, including the healthcare, education and military systems [60]. In each case, the way a system is organized leads to the scale and complexity of its behaviors, which have to match the demands of its tasks in order for it to be effective. This is as true about military organizations as it is about healthcare and educational ones. For example, in health care, organizational structures that are effective for simple tasks such as providing flu shots and blood tests, are different from organizational structures that are effective at diagnosis and treatment of diverse medical conditions. Absent an understanding of this distinction, efforts to reduce medical costs may mistakenly apply approaches to improvement that are appropriate to industrial (large scale) processes to complex medical services instead of the ones that would benefit from them like flu shots and screening tests. Applications to education include recognizing the role of standardized testing as a large scale strategy for evaluation, and the contrast to the complexity of student abilities and their eventual professional diversity. Military applications include the distinction in scale and complexity between conventional conflicts as compared to insurgencies and combating terrorism.

C. Evolutionary dynamics

The formation of complex systems, and the structural/functional change of such systems, occurs through a process of adaptation, especially through evolution. Evolution [61] is the adaptation of populations through intergenerational changes in the composition of the population (the individuals of which it is formed). Learning is a similar process of adaptation of a system through changes in its internal patterns, including, but not exclusively, the changes in its component parts.

Characterizing the mechanism and process of adaptation, both evolution and learning, is a central part of complex systems research [62–66]. This research generalizes the problem

of biological evolution by recognizing the relevance of processes of incremental and competitive evaluation based change to the formation of all complex systems. It is diametrically opposed to the notion of creation in engineering which typically assumes that new systems are invented without precursor. The reality of incremental changes in processes of creativity and design reflect the general applicability of evolutionary concepts to all complex systems.

Multiscale analysis and the multiscale characterization of biological and social complex systems informs our understanding of how evolution is responsible for the creation of structure. Rather than understanding evolution as a generic process based upon energy flows that counter equilibration by entropy increase, we must understand evolution as a process that results in multiple scales of patterns of structure from the microscopic to the macroscopic.

D. Choices and anticipated effects: Games and agents

Game theory [67–70] explores the relationship between individual and collective action using models where there is a clear statement of consequences (individual payoffs), that depend on the actions of more than one individual. A paradigmatic game is the prisoners dilemma. Traditionally, game theory is based upon logical agents that make optimal decisions based upon full knowledge of the possible outcomes, though these assumptions can be usefully relaxed.

Underlying game theory is the study of the role of anticipated effects on actions and the paradoxes that arise because of contingent anticipation by multiple anticipating agents, leading to choices that are undetermined within the narrow definition of the game, and thus sensitive to additional properties of the system.

Game theory is relevant to fundamental studies of various aspects of collective behavior: altruism and selfishness, and cooperation and competition. It is relevant to our understanding of biological evolution, socio-economic systems and societies of electronic agents. At some point in increasing complexity of games and agents the models become agent based models directed at understanding specific systems.

Multiscale analyses of game theory provide new insights into the relevance of game theory to collective social processes [71].

E. Generic architectures

The concept of a network, describing the connectivity, accessibility or relatedness of components in a complex system, is widely recognized as important in understanding these systems. So much so, that many names of complex systems include the term “network.” Among the systems that have been identified thus are: artificial and natural transportation networks (roads, railroads, waterways, airways) [72–75], social networks [76], military forces [77–83], the Internet [84–86], the World Wide Web [87–89], biochemical networks [2–5], neural networks [10–12], and food webs [90]. Networks are anchored by topological information about nodes and links, with additional information that can include nodal locations and state variables, link distances, capacities and state variables, and possibly detailed local functional relationships involved in network behaviors.

Networks may be understood as universal properties in a multiscale analysis in which system properties require characterization of the network for description of its collective behavior [39].

IV. APPLICATIONS OF MULTISCALE ANALYSIS

The full richness of complex systems applications for multiscale analysis cannot be captured here. However, a few examples should provide a sense of the integral nature of complex systems science to advances in biomedicine, cognitive science, and social and global systems.

A. Biomedical systems

Applications of complex systems methods in biomedical systems include the study of biochemical networks (gene regulatory networks, metabolic networks, etc.) that reveal the functioning of cells and the possibilities of medical intervention [2–5], detailed studies of the mechanisms and function of specific biochemical systems [91], and high throughput data acquisition in genomics and proteomics [92]. The key to a broader perspective on such applications is recognizing that the large quantities of data that are currently being collected are being organized into databases that reflect the data acquisition process rather than the potential use of this information. The description of cellular and multicellular organisms must capture the spatiotemporal dynamics of the system as well as the biochemical

network and its dynamics. More significantly, the multiscale analysis of this data will enable characterizing the collective properties of the system, including health and disease.

The challenge is to develop comparative multiscale descriptions, including the variety across organisms (e.g. human beings) and the variety that exists across types of organisms. Ultimately, the purpose is to develop an understanding / description of the patterns of biological systems today as well as their evolution. The objective of understanding variety and evolution requires us to understand not just any particular biochemical system, but the space of possible systems, their general properties, their specific mechanisms, how these general properties carry across organisms and how they are modified for different contexts. Approaches that study large scale biological structure and function as well as information flow are necessary. For healthcare in particular, abstracting the large scale behavior from molecular interactions will lead to an effective knowledge resource about interventions.

B. Cognitive systems

The problem of understanding the brain and mind can be understood quite generally through the role of relationships between patterns in the world and patterns of neuronal activity and synaptic change. While the physical / biological structure of the system is the brain, the properties of the patterns identify the psycho-functioning of the mind. The relationship of external and internal patterns is further augmented by relationships between multiple patterns that are possible within the brain. This complex nonlinear dynamic system has a great richness of valid statements that can be made about it, but identifying an integrated understanding of the brain / mind system cannot be captured by perspectives focusing on particular representations. Indeed, the potential contributions of the diverse approaches to studies of brain and mind have been limited by the difficulty in relating them to each other.

A key way to make progress is the adoption of a multiscale analysis that identifies the universality of representations, i.e. relates different representations to each other as to what they actually represent. Since many different kinds of representations represent the same things, such an effort would unify or help to distinguish the unique contributions of different approaches to neuroscience.

The multiscale approach can further contribute principles that are necessary for the

understanding of practical issues in cognitive function, including teaching and learning, and the role of complexity in individual and societal function. An approach that recognizes the differences between individuals is needed.

C. Global systems

In our increasingly complex, interdependent world, it is important to recognize how changes in one part of the world can have important effects in another. Complex systems science, using multiscale analysis to identify the largest scale effects, has the ability to describe dependencies and infer their policy implications. National and international policies should be informed by complex systems science to evaluate global consequences. For example, these methods can be used to trace the cause of the Arab Spring to market policies in the U.S. The wave of social unrest known as the Arab Spring was preceded by food riots, the result of spiking global food prices. In turn, the cause of the fluctuations in the food markets can be traced to commodities deregulation in the U.S., which allowed for rampant speculation, as well as ethanol fuel mandates which promoted the inefficient conversion of food into fuel [29–31]. Similar policy decisions in the U.S. precipitated the 2008 economic crisis, as well as other market crashes [32, 33]. Global interconnectedness also plays a role in the incidence of ethnic violence [34]. Increasing long-distance travel is crucial for the modern global economy, but it also acts a vector for the transmission of pathogens [35] including a new strain of Ebola virus that spread internationally in 2014.

Among the key problems in studies of global systems is understanding the indirect effects of global human activity, which in many ways has reached the scale of the entire earth / biosphere. The possibility of human impact on global systems through overexploitation or other byproducts of industrial activity has become a growing socio-political concern. The cascading effects of societal problems are also a concern. Our effectiveness in addressing these questions will require a greater level of understanding and representations of indirect effects, effective interventions, and which aspects of a system can be understood or predicted based upon available information.

In general, the ability of humanity to address these global problems must rely upon the collective behavior of people around the world. Global action is now almost standard in responses to everything from local natural disasters to wars to environmental concerns, The

high complexity of these problems implies that many individuals, who are diverse and yet coordinated, must be involved in addressing these problems.

V. CONCLUSIONS

The excitement in the study of complex systems arises not from a complete set of answers but rather from the appearance of a new set of questions. These questions differ from the conventional approaches and provide an opportunity for advances in understanding and in applications. Human civilization, across multiple scales from biological molecules to international economic systems, and its environmental context, are all complex. The most reliable prediction possible is that this complexity will continue to increase. The increasing complexity suggests that there will be a growing need for understanding of complex systems as a counter point to the increasing specialization of professions and professional knowledge. The insights of complex systems research and its methodologies, including multiscale analysis, may become pervasive in guiding research and policy decisions, across disciplines as diverse as biomedical, information, cognitive, and global systems.

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