COMPLEXITY THEORY

Complexity theory is a set of theoretical frameworks used for modeling and analyzing complex systems within a variety of domains. It can be understood as a composite of a number of major modeling frameworks that fall under its canopy including; systems theory; nonlinear systems; network theory; complex adaptive systems & self-organization theory. Complexity has proven to be a fundamental feature to our world that is not amenable to our traditional methods of modern science. And thus, as researchers have encountered it within many different areas from computer science to ecology to engineering, they have had to develop new sets of models and methods for approaching it. Out of these different frameworks has emerged a core set of commonalities that over the past few decades has come to be recognized as a generic framework for studying complex systems in the abstract. Complexity theory encompasses a very broad and very diverse set of models and methods. As yet, there is no proper formulation to structure and give definition to this framework. Thus, we will present it as a composite of four main areas that encompasses the different major perspective on complex systems and how to best interpret them.

Systems Theory

Systems theory is in many ways the mother of complexity theory. Before there was complexity theory, systems theory was dealing with the ideas of complexity, self-organization, adaptation and so on. Almost all interpretations to complexity depend on the concept of a system. Systems theory, though, is a very abstract and powerful formal language and it is typically too abstract for most people, and thus is understood and used relatively little. Cybernetics is another closely related area of systems theory. It was also part of forming the foundation to complexity theory. Cybernetics during the mid to late 20th century studied control systems and provided a lot of the theoretical background to modern computing, and thus we can see how the interplay between computing and complexity science goes all the way back to its origins as the two have developed hand-in-hand. A lot of systems theory is associated with and has come out of the whole area of computation. The areas of computer science and its counterpart information theory have continued to be one of the few major contributors to complexity theory in many different ways, though systems theory is about much more than just computers. It is a fully fledged formal language.

Nonlinear Systems and Chaos Theory

Nonlinearity is an inherent feature and major theme that crosses all areas of complex systems. A lot of nonlinear systems theory has its origins in quite dense and obscure mathematics and physics. Out of the study of certain types of equations, weather patterns, fluid dynamics and particularly, chemical reactions has emerged some very counter-intuitive phenomena in the form of the butterfly effect and
chaos. Chaos theory, which is the study of nonlinear dynamical systems, was one of the first major challenges to the Newtonian paradigm that was accepted into the mainstream body of scientific knowledge. Our modern scientific framework is based upon linear systems theory, and this places significant constraints upon it. Linear systems theory is dependent upon the concept of a system having an equilibrium. Although linear systems theory often works as an approximation, the fact is that many of the phenomena we are interested in describing are nonlinear. And processes of change, such as regime shifts within ecosystems and society, happen far-from-equilibrium. They are governed by the dynamics of feedback loops and not linear equations. Trying to model complex systems by using traditional linear systems theory is like trying to put a screw into a piece of wood with a hammer. We are simply using the wrong tool because it is the only one we have. Thus, the areas of nonlinear systems and their dynamics is another major part of the framework of complexity theory that has come largely from physics, mathematics and the study of far-from-equilibrium processes in chemistry.

**Network Theory**

Network theory is another major area of complexity theory, as almost all complex systems can be understood and modeled effectively as networks. Like systems theory, network theory is another formal language, but it is a much more practical tool for analysis and thus has found widespread application in many areas. The study of networks is probably the youngest and most active area of complexity science, again driven by the rise of computation and the fundamental role that networks are starting to play in our world with the advent of information technology. With the theory of networks and the availability of new sources of data, we are starting to get a real picture to what some of these complex systems that make up our world actually look like. We can start to see the connections within financial systems through which contagion spreads, the real-time movement of freight around the globe, or the socio-political networks that influence our lives. This is a new kind of science, driven less by models and equations but more by real-time dense data sets. This means we are no long left staring at models but now have accessible visualizations to give us a much richer, intuitive, and in many ways, more real sense of what exactly these complex systems are like. The main contributions to this area have come from the area of mathematics called graph theory, and again computer science.

**Complex Adaptive Systems & Self-Organization**

Complex adaptive systems are classical examples of complex systems, and people often use the two words somewhat interchangeably. They consist of many parts acting and reacting to each other's behavior, like a school of fish swimming together, nation states within the international politics environment, or businesses in a market. They are highly dynamic and develop through an evolutionary-like process. Self-organization theory tackles one of the main themes within complexity
theory, that is, how do things work together, how do differentiated components become integrated into a coherent functioning organization without centralized coordination. Here we are looking at how agents governed by simple rules synchronize their behavior with the result being a process of self-organization as patterns of organization emerge from the bottom-up. Researchers try to model complex adaptive systems by capturing these local rules and using computational tools like cellular automata and agent-based modeling to try and simulate how these systems are shaped by their interactions and evolutionary forces. This is an area that has grown out of cybernetics, computer science, and with major contributions also coming from ecology.

Application of Complexity Theory

Since its emergence during the seventies and eighties, complexity theory has gone on to be applied to many different areas where it is proving particularly relevant, given the rise of complexity brought about by globalization, IT and growing environmental awareness. Complexity science is the application of the models from complexity theory to various different domains of science. Complexity science is emerging as the most coherent post-Newtonian framework within contemporary science. Primary domains of interest within complexity science are complexity economics, social network analysis, earth systems science, political complexity, and systems engineering science, to name just a few.

The tools of complexity theory are beginning to be applied to the management of complex systems such as large corporations, IT systems, and economies. It is widely thought that complex systems are virtually impossible to control or predict with any great accuracy due to the number of their components, the degree of nonlinear interaction, and co-evolution that produces the emergence of unforeseen structures as the system evolves. Thus, as opposed to traditional methods of management that try to predict and control the outcomes through direct intervention, complexity management takes a more holistic approach, focusing more on creating the systemic conditions for success to emerge. Systems design is the application of systems theory and complexity theory to the design of technical systems. Systems design takes a holistic interdisciplinary approach to the development of complex projects to incorporate both social and technical factors whilst understanding product or technology within a whole life cycle perspective.

Significance

Lastly, it is worth noting the context and significance to the area of complexity theory as it plays a somewhat unique role within the framework of contemporary science. The website Scholarpedia describes complexity theory as an emerging post-Newtonian paradigm. There is a lot packed into this short statement so let's try and unravel and make sense of it. The Newtonian framework is based on linear systems theory. This has been a powerful tool for helping us understand the world. Through the contributions of millions of researchers over the course of centuries, we have built-up a large and
sophisticated body of scientific knowledge which is one of humanity's greatest achievements. Throughout the 20th century, though, the Newtonian paradigm and linear systems theory has become increasingly called into question as general relativity and then chaos theory proved some of its most basic assumptions to be in fact flawed. The fact is that much of the phenomena that we are really interested in are inherently nonlinear such as almost all social-political, ecological and economic phenomena. A core challenge of 21st-century science then is to extend this framework into the world of nonlinear systems, and this means going beyond the Newtonian framework, as Scholarpedia puts it, developing a post-Newtonian paradigm.