



Complexity Theory



Systems + Complexity

An Overview

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Preface

This book is designed to be an overview to the core concepts within complexity theory, presented in an intuitive form that should be accessible to anyone with an interest in the subject. Complexity theory is an exciting new area that is offering us a fresh perspective on many important issues, such as understanding our financial system, ecosystems, and large social organizations. The aim of this book is to bring the often abstract and sophisticated concepts of this subject down to earth and understandable in an intuitive form. After starting with an overview to complex systems science and its context, we will focus on five of the core concepts within complexity theory.

Systems Theory: We will start with three sections on systems theory and systems thinking, thus introducing you to the bigger picture of why complex systems is seen as a new paradigm in science; what exactly this new paradigm is; why we need it, and lastly how it differs from our traditional methods of scientific inquiry.

Nonlinear Systems: The terms “nonlinear science” and “complex systems” are often used interchangeably showing how essential the concept of non-linearity is to this subject. In this chapter, we draw the distinction between linear and nonlinear systems and see why it matters. The second part of this section covers the subject of chaos theory and the dynamics of nonlinear systems.

Network Theory: Networks in general have arisen in almost all fields of inquiry in the past few decades, making it one of the most active and exciting areas of scientific study. In the two sections on network theory, we will explore many different types of networks, their properties and examples in the real world, from social networks to logistics networks. This section will conclude by looking at graph theory, the mathematical foundations that lie behind networks.

Complex Adaptive Systems: CAS is increasingly being used to model a wide variety of systems, from electrical power grids to economies and cultures, as it represents a powerful new way of seeing the world. This section will also cover CAS’s close relative cybernetics and the basic concepts of adaptation and evolution. Self-organization is another one of the foundational concepts within complex systems that is proving particularly relevant to the world of the 21st century as we see collaborative self-organizing groups, such as Wikipedia and the Linux foundation, emerge. But self-organization is more than just a social phenomenon. In these two sections, we will explore how it is in fact ubiquitous in our world from the formation of fish schools to magnetization and traffic jams.

The last five sections to the book are dedicated to the application of complexity theory to various domains of science. Complexity theory has been applied to many areas from business management and anthropology to engineering and the design of healthcare systems, with its number of applications continuing to grow yearly. Here, we will just give a quick outline to four different areas that it has been successfully applied to including the social sciences, economics, engineering, and earth science. Ok let's get started!



1. Complexity Theory

Every day, when we switch on the lights, connect to the Internet, or commute to work, we are forming part of what are called complex systems. However, in order to understand complex systems, we need to talk a bit more about systems in general first. A system is a type of model we use to understand the world around us. In its essence, it is a group of parts called elements and relations between these parts through which they can function together and form a whole that is called the system. This very simple and abstract model can be used to describe a wide variety of things.

Now, let's add complexity to this. Although there is no formal definition for it, we can understand complexity as a parameter, that is to say that it is a measurement of something. Firstly, it is a measurement of the number of elements within our system. A society is more complex than say a small group of friends, as it has many more sub-systems and elements interacting on various scales. Secondly, it measures the degree of connectivity within the system. In fact, when we have a low level of connections between elements within a system, we can explain it by simply describing the properties of the individual elements. But, as we increase the connectivity, we also increase the relations between elements that come to define the system. Thus,

complex systems are typically modeled as networks that can capture and quantify this information about the relations between elements.

Thirdly, we find adaptation, meaning when elements become capable of adapting their behavior over time can become increasingly complex. Thus, complex adaptive systems are often best modeled as the product of the evolutionary dynamics that have shaped them over time as opposed to the static analysis of their individual parts. The capacity of adaption also means that elements can self-organize, limiting the need for centralized control and allowing for the emergence of organization from the bottom up as individual elements can interact and synchronize to form patterns. Fourthly, complexity is also a measure of the degree of diversity between elements within a system. Again, the greater the diversity between the parts, the more complex and abstract our models will have to be to capture the underlining common features.

So now that we have an idea of what systems and complexity are, let's put them together starting with a system with a low level of complexity. An example of this might be a set of five billiard balls on a table. There are quite a few of them, they are all the same, they are all separate from each other and they are incapable of adapting.

If we input some energy into this system by pushing one of the balls, the outcome to this event is directly proportional to the input and is pre-determined by it. We can repeat the same action a million times and we will get the same exact result. We call this type of system a deterministic or linear-system because we can draw a direct line between cause and effect, that is to say the input and output to the system. Because linear systems are relatively easy to model and control much of our modern science, engineering and management practices rest upon this type of linear understanding to the world. Now, let's think about what happens when we turn the complexity up. Take as an example an ecosystem. Ecosystems typically have many elements or creatures. These creatures are diverse, interconnected and capable of adaptation.

If we add some input to this system, we build an industrial zone right next to it emitting pollution, given the ecosystems capacity for adaptation the result of this may well be negligible to us initially. So, we continue to expand our industrial area. At some point, the stress from this additional input will reach a critical tipping point with some small additional input being able to propagate through the system creating a phase transition as our ecosystem collapses.

Thus, complex systems can exhibit both extraordinary robustness and extraordinary fragility where some small-scale event can have a large systemic effect, known popularly as the butterfly effect. The point to take away from this illustration is that complex systems are what is called non-linear, meaning unlike our original example with the billiard balls, here, cause and effect are no longer directly related. This is due to the fact that complex systems are non-linear and largely defined by their

connections that make them un-amenable to our traditional scientific methods of analysis that often rely upon linear models and a component-based description of the world.

Thus, the area of complex systems has risen over the past few decades as an alternative paradigm within science to deal with these non-linear systems by placing a greater emphasis upon connectivity and the relations between elements. It currently represents a broad and diverse set of methods primary among which is the use of computational modeling, where elements are given a simple set of rules that govern their behavior and are left to interact and evolve over time to see what patterns emerge. As the world we live in becomes increasingly interconnected and interdependent, the need for a greater capacity to model, design, and manage complex systems is making this area particularly relevant to the challenges we face in the 21st Century.



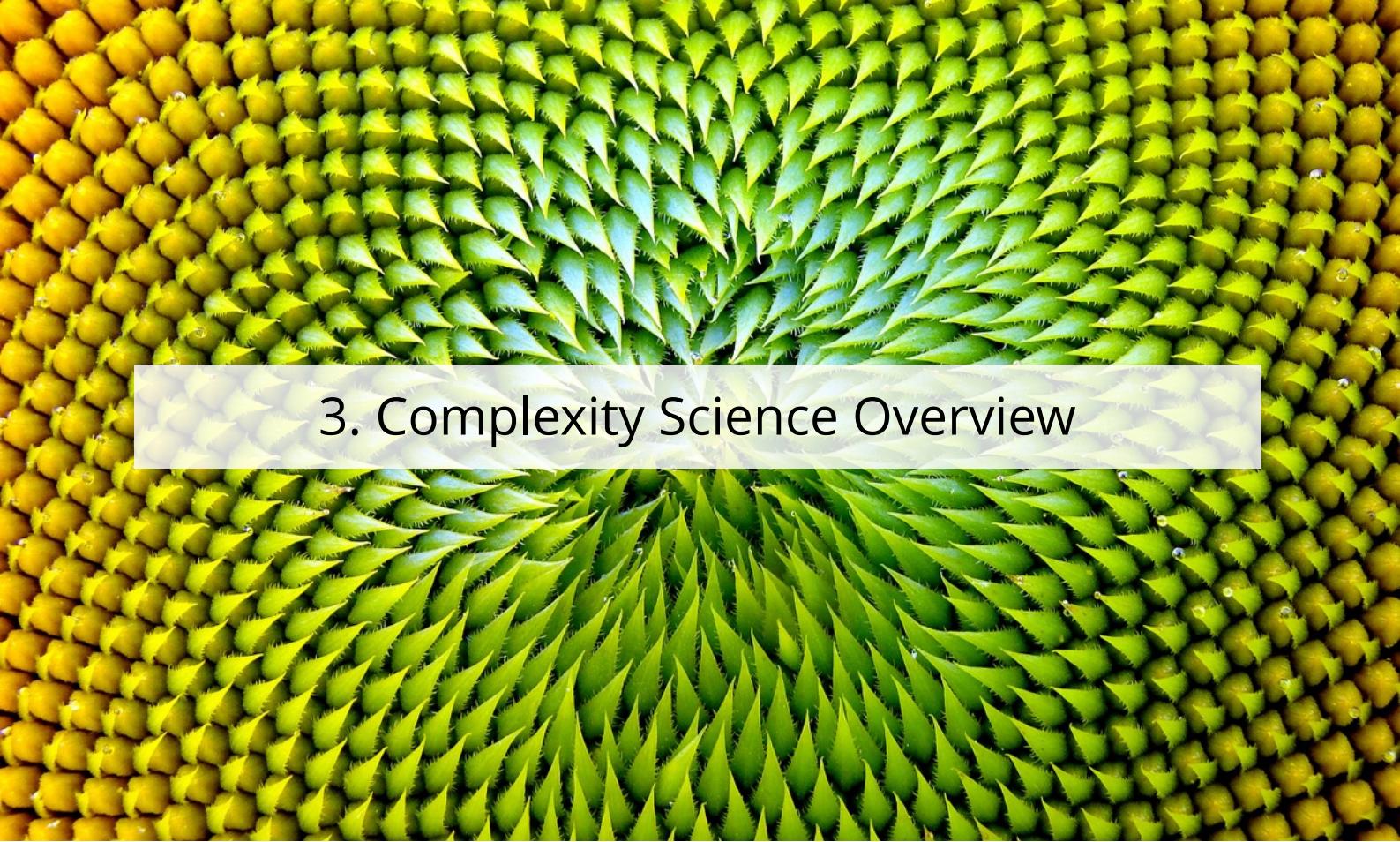
2. What Is A Complex System

At this stage, it might be helpful to offer a definition of what a complex system is exactly. Unfortunately, there is no agreed upon definition. Rather, there are many different opinions on the subject representing the different domains within which complexity theory has grown out of. But just to get us started, we will lay down a quick working definition that contains some of the most cited properties of complex systems. A complex system is a system composed of multiple diverse elements that are interconnected and give rise to some overall functionality.

A system is a set of parts called elements that perform some common function within a whole that is called the system. The human body is an example of a system. The human body is composed of many different parts that are all designed to function as an entirety. Earth's hydrological system is another example of a system. For example, the movement, storage, and exchange of water around the earth, at different stages in this process, exhibits different forms (cloud, ice, sea water etc.) but is part of an integrated whole, a system. Complexity is generally defined as something with many parts where those parts interact with each other in multiple ways. Thus, we can understand complexity as a measure of the number of elements within a system, their degree of diversity and degree of interconnectivity.

Some examples of complex systems that we might cite could include the internet, being composed of billions of web pages that are used for multiple different functions and are highly interconnected. We could also think of a city made up of multiple different sub-systems, transportation systems, telecommunication systems,

administration, businesses etc. all of which interact and are to some extent interdependent. Another example would be international political institutions, composed of representatives of multiple different nations with diverse interest all of which are interdependent in effecting some joint outcome. We could also think of a corporate information system as another example with multiple different software modules all interacting to create the state of the whole system. A national economy is another example, interactions between labor, financial capital markets, natural resources, government regulations etc. make economies a complex of interdependent parts.



3. Complexity Science Overview

Complexity science is a new approach, or method, to science that has arisen over the past few decades to present an alternative paradigm to our standard method of scientific enquiry. To give it context, let's start by talking a bit about our traditional approach to scientific research. We can loosely define science as a type of enquiry into the world around us, as opposed to other areas such as art or religion that are based upon aesthetics or revelation, the scientific method of enquiry claims to be based upon empirical data, otherwise known as facts.

The beginning of the modern era, circa 500 hundred years ago, saw the development of a systematic and coherent framework for conducting this scientific process. This framework became most clearly formulated with the work of Sir Isaac Newton, and thus Newtonian physics became an example or paradigm of how modern science should be conducted. The Newtonian paradigm is a whole way of seeing the world that describes phenomena as the product of linear cause and effect interactions between isolated objects that are determined by mathematical laws. This vision of things results in a very mechanistic view of the world, sometimes called the Clock world universe.

This new paradigm went hand-in-hand with a new method of enquiry called reductionism. Reductionism is the process of breaking down complex phenomena into simple components that can be described with reference to their properties and linear interactions. By reassembling these individual components, we can understand the whole system as simply the sum of its individual parts.

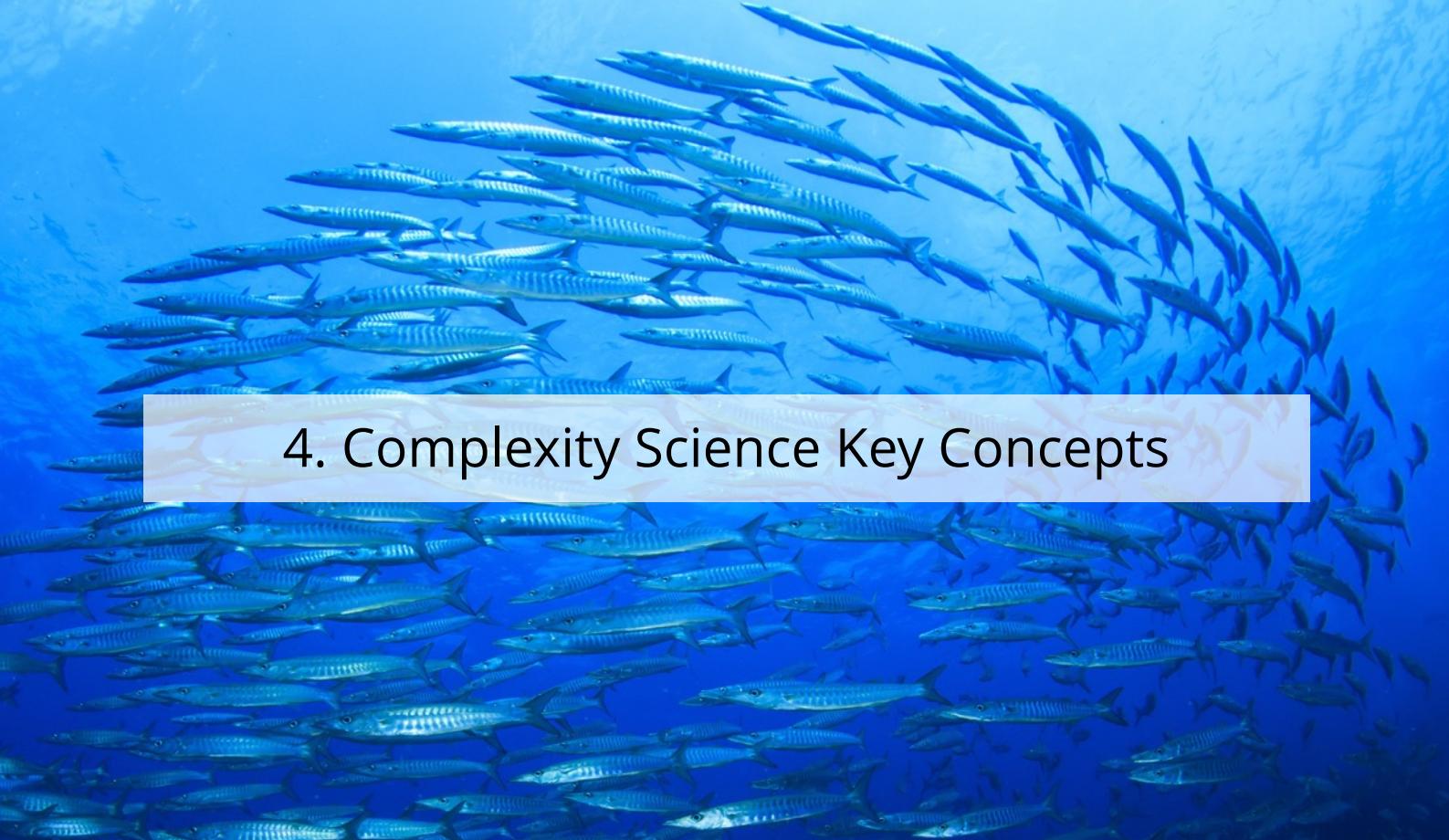
Having been phenomenally successful within physics, this framework for modern science has gone on over the centuries to be applied to almost all areas of enquiry from biology to engineering and business management, placing it at the heart of our modern understanding of the world. It is only during the later half of the 20th century that this approach to science began to be called into question, as the revolutions of quantum physics and relativity showed some of its most basic assumptions about time, space and causality to be flawed. Whilst later in the century chaos theory began to open up a new world of non-linear systems.

Outside of science, the world has also become very different from the one Newton lived in as globalization, information technology, and sustainability present us with the new challenges of understanding, designing, and managing systems that are highly interconnect, interdependent and non-linear, that we can now call complex systems. This is where complexity science comes in to provide us with an alternative scientific method better suited to researching these complex systems, supported by a paradigm that sees the world as a set of interconnected elements whose interaction give rise to the patterns and phenomena that we observe in the world around us.

As opposed to traditional science, which tries to eliminate complexity by studying the individual components of a system within an isolated environment, complexity science places a greater emphasis upon open systems, which means understanding a system within its environment and the complex of relations that give it context. Whereas traditional reductionist science primarily uses linear mathematical models and equations as its theoretical foundation, complexity science uses the concepts of complexity theory, such as self-organization, network theory, adaptive and evolution.

This new theoretical framework is combined with new methods, such as agent-based modeling. As opposed to describing the phenomena we observe in terms of "laws of nature" encoded in equations, agent-based modeling takes a more bottom-up approach describing them as the emergent phenomena of local level interactions between agents governed by simple rules. Complexity science studies the complex systems in our world that have previously fallen between the gaps of modern science, such as financial networks, cities, ecosystems and social networks, studying these large complex systems typically requires significant amounts of data.

Thus, what the microscope, telescope, and laboratory were for modern science, computation and data are to complexity science, which relies heavily on computer simulations and analysis of the mass of rich and diverse data that information technology, has provided us with. In a time when science has become highly specialized and focused upon extreme scales from the big bang to little strings, complexity science is providing a fresh perspective for refocusing on the everyday world in front of us and helping to bridge the traditional divides between sciences.



4. Complexity Science Key Concepts

"Isolated systems tend to evolve towards equilibrium, a special state that has been the focus of many-body research for centuries. Yet much of the richness of the world around us arises from conditions far-from-equilibrium. Phenomena such as turbulence, earthquakes, fracture, and life itself occur only far-from-equilibrium... While much is understood about systems at or near equilibrium, we are just beginning to uncover the basic principles governing systems far-from-equilibrium." - Far-From-Equilibrium Physics: An Overview

The First Law of Thermodynamics, what is called the conservation of energy law-states that; within a closed system neither energy nor matter can be created or destroyed but simply transformed from one state to another. It is this description of the world as a closed system and its emphasis upon empirical data that in many ways defines modern science as distinct from other enterprises such as art or spirituality, that see the world as an open system allowing for the creation of something from nothing in the form of divine intervention or revelation. Thus, science has been the development of a description of the world in terms of these closed systems wherein energy and/or matter are transformed from one state to another.

Archimedes displacement law is an early example of this, which states that, "Any floating object displaces its own weight of fluid". In other words, for a floating object on a liquid, the weight of the displaced liquid equals the weight of the object. Archimedes has here defined the components of an isolated system and identified the

transformation of matter and energy from one state -the floating object, to another, the displaced water- whilst both are conserved.

With the development of the modern science of classical physics came a much more systematic set of tools for iterating this process. On the empirical level, technologies such as the telescope, microscope and the laboratory were employed for isolating, analyzing and accurately measuring the inputs and outputs of energy and matter to these isolated systems. On the theoretical level, the development of modern algebra, calculus and the modern concept of a function equipped scientist with the tools to describe, in mathematical equations the relationship between the energy or matter inputted and its transformation within the system.

The archetype of this modern method is of course Newton's laws of motion and in particular his great equation, $f=ma$ that describes how in an isolated systems there is a direct linear relationship that converts the energy of a force inputted to the system to the output of the acceleration of matter. From Maxwell's laws of electromagnetism to the famous $E=mc^2$ equation the paradigm of modern science has been to capture within equations the linear transformation of energy and matter (electricity, acceleration, gravity etc.) within an isolated system.

Due to its phenomenal success within classical physics and the natural sciences in general, this method has been extended to many other areas such as biology, engineering and management to name but a few. In this way we have built a large and sophisticated edifice of methods where the aim has been to find these points of equilibrium and encode them in equations as laws. The unfortunate fact is that many of the types of systems we would like to understand are inherently complex meaning that they consist of multiple, diverse, interconnected elements often capable of adaptation, examples being economies, the Internet, international politics. It is due to these properties that complex systems are difficult or almost impossible to isolate, decompose and analyze using the traditional methods of modern science.

Complex systems are largely defined by their connections both in time, as they are dynamically evolving -meaning their present state is contingent on their history- and in space as they are by definition the product of multiple interacting elements. To study these systems requires a paradigm shift from a component based set of methods to a relational or process based set of methods. Thus, we can understand complexity science as the analysis of the world based upon this new paradigm from which follows a set of new tools many of which have only been developed over the past few decades.

Although pure science may be a somewhat timeless enterprise, much of science is inherently applied and has to in some way response to the world of its time. The world we live in is a very different one to the world of Newton and Coulomb, it is more

socially and technologically interconnected, one where we face systemic challenges such as growing demographics, sustainability and managing a global economy. Complexity science with its set of theoretical and technical methods is uniquely positioned to help us understand the social and technical complex systems that we are a part of today. Providing us with better insight as to what the critical nodes and relations are within these systems and thus help us in designing and managing them more effectively.

5. Complexity Science Tools

Complexity science is a science built on computation and it employs a number of new computation techniques primary among which are; agent-based modeling, cellular automaton; network analysis software; statistical analysis. Firstly agent-based modeling, the three ideas central to agent-based models are agents as objects, emergence, and complexity. An agent-based model (ABM) is a class of computational models for simulating the actions and interactions of autonomous agents (both individual and collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole. Examples might be traders within the financial market set to buy or sell at a certain price or it might be a bird within a flock given a set of rules that adjust its flight pattern according to the location of its neighbors. Most computational modeling research describes systems in equilibrium or as moving between equilibrium. Agent-based modeling, however, using simple rules, can simulate complex out of equilibrium behavior.

Agents (that may be any system with the capacity for autonomous action, such as market traders, governments, plants or fish) are endowed with simple rules that govern their behavior and interactions with other agents. The simulation is left to run for a given period of time so as to allow for a sufficient degree of interaction between agents thus revealing long-term stable patterns.

The process is one of emergence where interaction from the lower (micro) level to the system gives rise to a higher (macro) level structure. As such, a key notion is that simple behavioral rules can generate complex behavior. Netlogo is the most popular open source software used for agent-based modeling.

A cellular automaton is another computation method. A cellular automaton is a computer program representing a collection of "colored" cells on a grid of specified shape that evolves through a number of discrete time steps according to a set of rules based on the states of neighboring cells. The rules are then applied iteratively for as many time steps as desired. Through this process of interaction between cells the system evolves over time to produce self-organized structures that are the product of simple rules. From these simple rules a vast amount of different structures can be produced (in fact it has been proven that they are capable of universal computation). Cellular automaton have been used to model real world self-organizing phenomena such as neighborhood racial segregation, the synchronization of flashing lights amongst fireflies and the patterns on seashells can all be generated by cellular automata programs. Cellular automaton (similar to agent-based modeling) mirrors the bottom up approach to self-organization.

Another central method of complexity science is the one of network analysis, which is the application of network theory to the analysis of empirical data. It is a key tool used by researchers in the analysis of complex systems. Massive amounts of data sets are now freely available on The Internet from trade relations, to social networks, to the flow of information. These data sets are brought into network analysis software to be visualized and to reveal patterns such as centrality, connectivity, robustness etc. which we will be discussing in a later section on network theory. Network analysis software allows us to convert (often times dense impenetrable) data sets into a visual language that makes it quick and easy to get an overview to the key structural dynamics underlining the system's functioning. Gephi is a popular open source network analyses package widely used by researchers.

Statistical analysis on data sets is another method used for measuring complexity. Complexity is here defined in terms of the amount of information needed to describe some phenomena. This is an approach more often used within physics deriving from statistical mechanics. It is based upon information theory/probability theory and closely aligned with the practice of data mining and computer analytic



6. Systems Thinking

System thinking is a way of describing the world in a more holistic manner based upon the model of a system. Let's start from the beginning. We can understand the world as things, that is to say parts or components and their relations, that is how they are connected or fit together. So take a car for example. A car is made up of parts, such as engine, wheels, and so on and these parts are put together or organized in a specific way so as to make them function as a vehicle of transportation.

Now, we call a group of things that are not organized in this way a set. So we would call a group of cups on a table a set of cups because unlike the parts to our car they have not been designed to serve some collective function. Because the group of cups is simple the sum of its parts we would describe them by describing the individual properties of each cup and this would tell us everything we needed to know about them. This approach to describing thing is called analysis or reductionism, reductionism is the traditional approach taken within modern science that tries to describe complex phenomena in terms of their individual parts.

Let's the human body that is highly organized through a complex set of relations between its parts. Out of the arrangement of these parts in a specific way we get the overall functioning of a living organism. Because the parts are so strongly defined by their connections and function within the body as an entirety, to properly describe the parts we need to first understand the functioning of the whole body. This approach to describing things that is that we can best describe things by understanding their place within the function of the whole that they are a part of is called synthesis and

synthesis is the foundations of systems thinking. Thus we have two different approaches to describing thing, analysis that is interested in describing the individual components and syntheses that talk about the relationship between these components and their functioning as a whole.

Ok so now that we know a bit about systems thinking let's put our new found knowledge to use, say a car manufacturing company has employed us to design their next great model. Now we could take two different approaches to this problem, applying analytical thinking or our friend systems thinking. If we approached the problem from a traditional perspective we would start by analyzing the car and looking for ways to optimize it, we might come up with a design that minimizes the car's drag by reducing its height by a few centimeters to increase its fuel efficiency. Now if we applied systems thinking to this problem, we would start by identifying the cars function, which is personal transportation and the system it is a part of, the transportation system. From this perspective we might not even need to design a new car. But end up designing some service that connects preexisting resources to provide the same desired functionality.

From this example we can see how systems thinking is often employed when the current paradigm or way of doing things has reached its limit and gives us a fresh perspective on things. Systems thinking is the beginning of another closely related area called systems theory that goes on to give us a whole suit of tools for analysis and modeling systems, their interaction and dynamics as they evolve over time. So we can wrap-up by saying that systems thinking is an emerging paradigm within many areas from science to engineering and business management, that presents an alternative to our traditional modern analytical methods of enquiry by emphasizing the need for a more holistic and contextualized understanding of the world.



7. Systems Thinking Key Ideas

"The beauty of a living thing is not the atoms that go into it, but the way those atoms are put together." — Carl Sagan, Cosmos

Systems thinking is a set of theoretical constructs for reasoning about the world that represents an alternative to our traditional methods of analysis, as such it is less a theory and more a paradigm. A dictionary definition of a paradigm would read something like this; a world view underlying the theories and methodology of a particular scientific subject. Thus, we can understand a paradigm to be the foundations that shape our way of seeing the world, it is the assumptions and methods out of which we build our theories.

There are two fundamentally different paradigms within science: one is called analysis and the other synthesis. Analysis is based upon the premise that our basic unit of analysis should be the individual objects, that is to say the parts of a system. From this follows the idea that we can describe a system as simply a composite of its individual parts. The analytical method thus proceeds to understand the world by breaking large complex phenomena down into these simple parts that can be modeled and then recombines them to give a description of the whole. This method is called reductionism as it functions by reducing things to their most basic elements. The method of reductionism is the de facto way of proceeding for most areas of science,

especially physics that has been highly successful in reducing the vast array of physical phenomena we see (from lightning flashes to the origins of the universe) down to just four fundamental forces and a handful of fundamental particles. Many systems, especially those that are isolated, linear, deterministic and static best lend themselves to this type of analytical method of enquiry and thus reductionism has been highly successful within the natural sciences in general.

However, many of the systems we are interest in describing are the opposite from this, that is to say they are interconnected, non-linear, non-deterministic and dynamic leaving them un-amenable to or traditional methods of analysis. Thus, a suite of concepts and methods have collected under that name of systems science, systems theory or just systems thinking that are in many ways the opposite from our traditional method of analysis. Core to the systems paradigm is the method of synthesis.

Synthesis means the combination of components or elements to form a connected whole, it is a process of reasoning that describes an entity through its context or function within a whole. As oppose to analysis that breaks things down to understand them, synthesis does the reverse building them up so as to gain an understanding of the whole systems and then defines an individual entity in terms of its function or place within this whole. Thus synthesis and systems thinking are called holistic in that their primary point of reference is the entire system, or whole.

As opposed to our traditional methods of analysis that removes the observer from the equation and assumes a single objective perspective, systems thinking allows for multiple perspectives and thus it is less about gaining insight through breaking the whole down into individual parts as it is about gaining insight from the synthesis of multiple different perspectives upon the whole, and thus it is inherently interdisciplinary by nature.

These two methods for reasoning about the world both have relevance depending upon the type or properties of the system we are interested in. Is it primarily a component-based system or does it serve some common function that integrates the various elements? Is it isolated or connected? Is it a linear deterministic system or a non-linear indeterminate system? Is it static or dynamic? These are some of the key considerations.

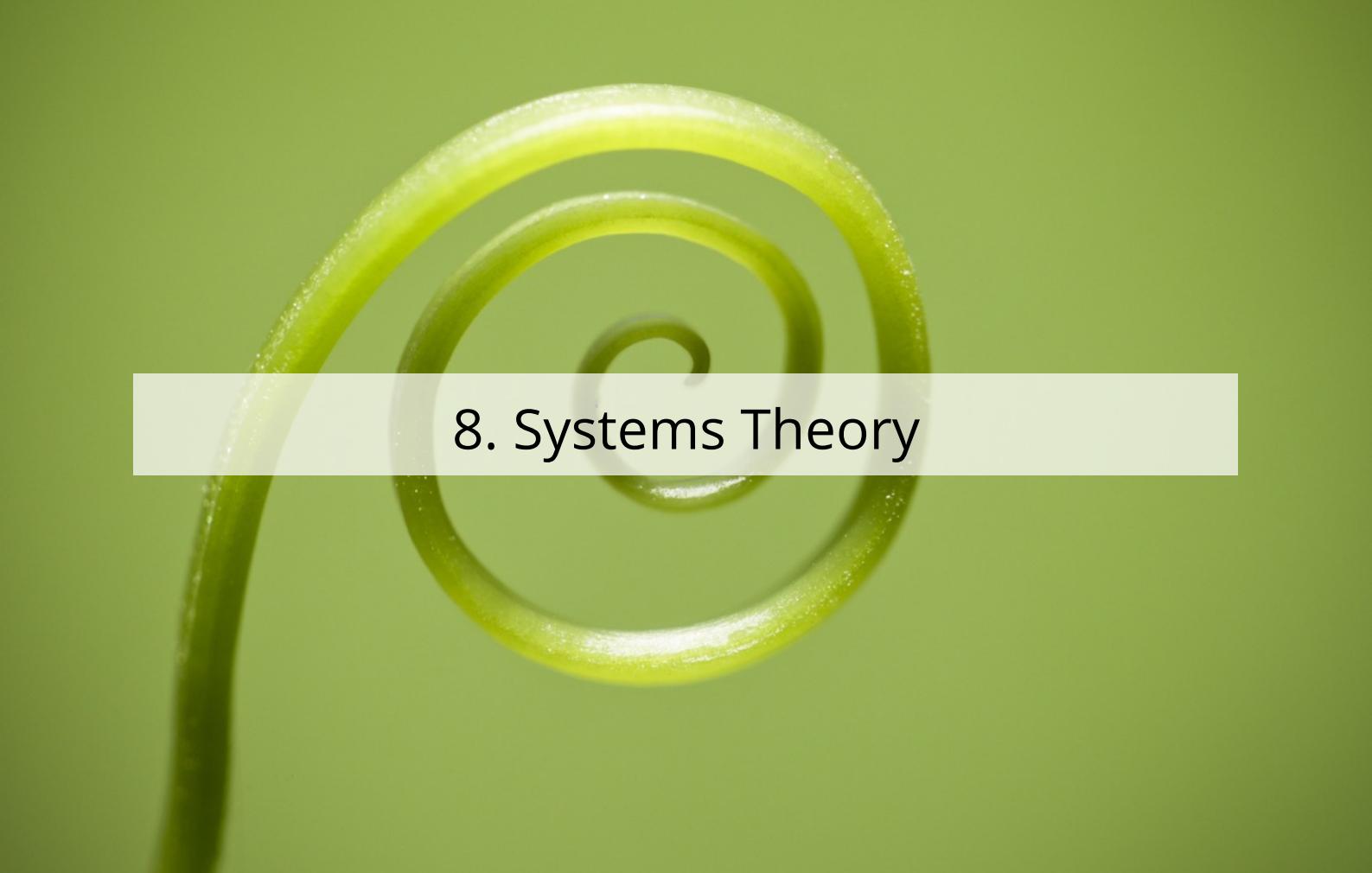
Key differences between analytical and systems thinking include; analysis focuses on sets of things where as systems thinking focuses on whole systems; analysis is focused on components where as synthesis is focused on relations; analysis looks for linear cause and effect relations where as systems thinking looks more at non-linear feedback relations; analysis is often more static in nature while systems thinking looks more at processes and dynamics.

Sets vs. Functions: When we wish to talk about a composite entity, that is to say a group of things, we can describe it as either a set of objects or a system, the difference here being that a set is a group of objects that share no common function, thus we call a group of chairs in a room a set of chairs as they exist independently from each other. In contrast if we take a business organization, again it is a composite entity, but this time the elements have been designed to serve some common function and thus we can call it a system.

Components vs. Relations: Analysis starts from a component based view of the world and builds a description based upon the properties of these components. Synthesis focuses upon the relationships between parts, thus from a systems thinking perspective we are often interested in connectivity i.e. answering the question what is connected to what.

Linear causality vs. Nonlinear feedback: Analytical thinking searches for a direct line in the relation between the cause of an event and its effect, thus we call this linear thinking. Systems thinking is more inclined to see events as the product of a complex of interacting parts where relations are often cyclical with feedback loops.

Static structure vs. Dynamic processes: Analytical thinking often results in a description of entities in terms of static structures with limited reference to their development over time. Systems thinking takes a more dynamic view of things often contextualizing entities in terms of the evolutionary forces that have shaped them and thus seeing the process of development as an important phenomena through which to view the world.



8. Systems Theory

Systems theory is a set of theoretical concepts used to describe a wide variety of things in terms of a model called a system. To give it context let's talk a bit about its origins. Of course people have been coming up with abstract theories about how the world works for a long time. Some ancient Greeks thought everything was made of earth, water, fire and air, whilst others came to the conclusion that it was the expression of perfect geometric forms.

Over the years, our theoretical systems have grown into large and sophisticated bodies of knowledge such as philosophy, mathematics and the many areas of theoretical science, although these theoretical frameworks are often limited to relatively specific areas of interest. During the 20th Century systems theory emerged as a new theory that draws upon many core concepts within these pre-existing methods to develop a more abstract framework that is designed to be universally applicable to all domains.

In order to achieve such a general relevance, systems theory starts with the abstract concept of a system and then applies this to modeling various different phenomena from biological to social and technical systems. The model of a system can be loosely defined as a set of parts often called elements that form a whole, which is referred to as the system. A system exists within an environment and has a boundary that differentiates the system's exterior from its interior. An example of this might be a

country, interior to which are all the people, institutions and other elements that constitute the nation as an entire system. Whilst exterior to its boundary is the international political environment. A system can be either open or closed. Isolated systems do not interact with their environment, but most systems are open meaning there is an exchange of energy and resources between the system and its environment. The passing of energy or resources from the exterior of the system's boundary to the interior is termed an input whilst the reverse is termed an output.

Systems develop or function through the input of energy or resources from their environment, they process this energy by transforming it to create an output, if this output is of some value to its environment it can be termed energy. If, on the other hand, it is of negative value it may be termed entropy, a scientific term for lack of order, disarrangement or in more familiar terms we might call it waste. An early use of this type of model was during the development of the steam engine where scientist and engineers were thinking about the amount of fuel inputted to the engine relative to the power output and heat energy wasted. By using this model they could create a quantifiable ration between them that we would now term the efficiency of the system.

Of course this same reasoning can be applied to a wide variety of phenomena from the processing of energy within a plant cell to the efficiency of a business organization. We can model systems on various scales, thus elements can form part of systems that themselves form part of larger systems and so on, this is termed nesting or encapsulation and helps us to analyze a system on various levels whilst hiding away the underlining complexity. Systems theory explores many other areas such as emergence that raises key question about the relationship between the parts within a system and the whole, which is how elements can function together or self-organize to create some new and emergent structure as an entirety.

Or other areas such as Cybernetics that deals with a systems control mechanism, that allow it adapt and respond to changes within its environment through positive and negative feed back loops. Systems theory has found application within a wide variety of areas forming the foundation for many new subjects such as systems psychology, systems engineering and systems ecology to name but a few. All of which place an emphasis upon a more holistic and contextualization approach to understanding the world around us.



9. Nonlinear Systems

Have you ever wondered why when we look around us in the natural world we see very few straight lines but the straight line is ubiquitous in the systems we engineer from buildings to circuit boards it appears to be the default position?

One way to understand this is that the systems we engineer are based upon our scientific and mathematical understanding of the world, which has inevitably started by describing the simplest and most orderly type of systems that is to say those composed of linear forms and relations. From Euclid to Newton and on science has been focused upon the orderly systems of perfect squares, triangles and linear relations of cause and effect that can be encoded into beautifully compact equations and thus we describe the real world as a kind approximation to these perfect linear models. But let's take a look at some of the basic principal underlining the theory of linear systems.

Linear is basically a fancy word for line and a line is often understood as the shortest or most direct path from one point to another. To say there is a linear relationship between two things is to say there is a direct relationship of cause and effect between them.

Let's take an example of this, say I am playing baseball and I hit a ball with a bat, if we make a model of this system, we see the energy inputted by my swinging the bat will be directly proportional to the output of the ball's momentum as it travels off in the opposite direction. This is a simplified model but it illustrates the direct or linear relationship between cause and effect, my swinging the bat and the ball's motion in response.

There are of course many more examples of linear systems particularly in physics. But we can capture the underlining logic of linear systems in general with a model that has only two simple rules called the superposition principle. This states firstly that the output to the system will always be directly proportion to the input, so if there is a linear relationship between the amount of fuel I put in my car and how far it will go, well then if I put twice as much fuel in it will go twice as far. Secondly, if we add the inputs from two or more different systems together, then the output to this combined system will simply be the sum of the two outputs of the original systems. So say we have two tractor factories each producing a million tractors a year, well if we merge them then we will get a factory that will produce 2 million tractors a year.

Linear systems are deterministic, meaning that if we know their present state we can fully determine their past and future states, this can be seen by plotting a linear system on a graph were it will always be depicted as a strait line. Although linear systems modeling has proven highly successful in may areas and is often a very good approximation, the reality is that we live in a world with ecosystems, economies, societies and many physical phenomena that are not governed by the superposition principle and thus are what we call nonlinear. An example of nonlinearity might be listening to two of your favorite pieces of music at the same time, because there is a relationship of interference between them, the result of this experience will not be a simple equation of adding the enjoyment from listening to each independently.

This illustrates how nonlinearity arises whenever there is some relationship between elements within the system that can be either synergistic, making the output to the system greater than the sum of its parts or one of interference making the output less than the sum of it individual components. To illustrate this further let's take an example of four workers producing clothing, in isolation each seamstress can sew a given amount of clothes within a day. Now if we put them together we might get one of three results, firstly they might not interact with each other very much meaning we would simply have a linear system where the whole would be the sum of its parts. But equally likely they might form some cooperative relationship that lets them each specialize in a particular function making them more efficient as a whole and thus the output to the system would be greater than the sum of its parts due to these synergistic relations.

Or inversely they might start all talking with each other getting let little work done and thus the total output would be less than the sum of the individual outputs due to these relations of interference.

Nonlinearity can also arise from feedback loops where by the same process is iterated with the output fed back as the input to the next cycle. A classical example is compound interest where at the end of each period the balance plus interest is fed back into a formula to compute the next cycle of interest accumulation. Iterative functions are an important concept within nonlinear science and have been used to create a whole new type of geometry called fractal geometry. Where by iterating a simple function generates irregular organic looking patterns that can model many of geometric forms we see in nature from the structure of sea shells to the rugged formation of mountains.

In these nonlinear systems superposition fails meaning, one cannot break the system down into small sub-problems and add their solutions, we must consider a nonlinear problem in total. It is this need to approach nonlinear systems as a whole that is giving rise to new more holistic approaches to science that are developing under the canopy of complex systems. Non-linearity in all its shapes and forms is at the heart of many of the 21st Century's major challenges within science, as we try to extend the scientific framework beyond its dependency upon linear systems theory to finding new ways to embrace the complex world we live in on its own irregular and imperfect terms.



10. Chaos Theory

As we saw in the previous section nonlinear systems are those whose output is non proportional to their input. Chaos theory in the area of mathematics that studies the dynamics of these nonlinear systems, that is to say how they change over time both qualitatively and quantitatively. For thousands of years, spiritual leaders, philosophers and artist have wondered about the nature of chaos in our universe, whilst scientist and mathematicians have shunned it in search of ordered patterns. It is only in the latter part of the 20th Century that some mathematicians and scientist begun to approach the subject of chaos and find methods to bring a certain kind of chaotic behavior into the modern scientific framework under the name of chaos theory.

Chaos theory deals with a certain type of chaos called deterministic chaos, a deterministic system is a system whose behavior is fully understood and thus it is possible to predict or determine all of its past and future states. Chaos theory is then interested in the dynamics of these systems and the patterns of order and chaos that emerge out of this.

So the question is how can some thing that if fully understood and determined produce what appears to be chaotic or random behavior. Modern science and in particular classical physics has from its beginning sought to find the basic laws of nature, breaking down complex phenomena in to simple deterministic parts that can be modeled and proven mathematically, this method has been the gold standard of

modern science. It is then assumed that the product of recombining these parts will result in nothing more than the sum of their parts in isolation. Thus, by understanding these fundamental laws we could fully understand the universe, it was just a matter of filling in the details and doing all the calculations.

It was not until the advent of powerful computers towards the end of the 20th Century that this assumption was proved to be incorrect, at least in some circumstances. Most notable among these was a computer simulation of weather patterns done by a scientist called Edward Lorenz in which he found that very small changes to the values he inputted into the computer resulted in a hugely disproportionate change in outcome. This large difference in ratio between the input to a system and its output due to the complex nonlinear interaction of its parts and feedback over time has since become popularly known as the butterfly effect and has been identified in everything from international politics to traffic congestion and financial crisis.

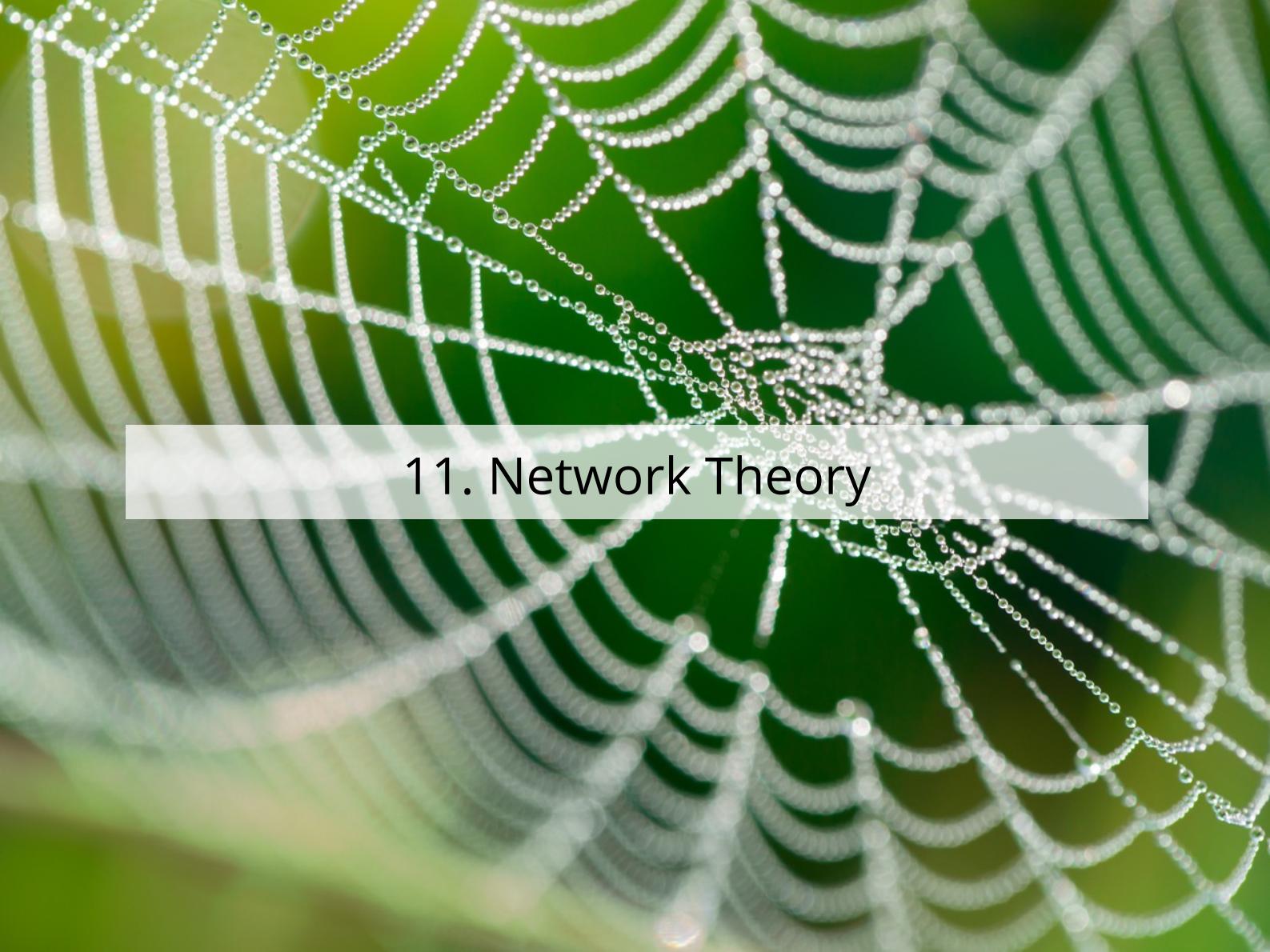
The butterfly effect is due to the fact that we can never know the absolute values to the initial input to a system. This small uncertainty in the initial input to the system over time can through feedback loops compound some small event into a large effect. This results in the development of a large space of possible outcomes contingent on very small differences in the input value, the difference in input value is so small that we can't know them and thus the outcome becomes chaotic and unpredictable.

The butterfly effect is challenging because we understand, engineer and manage our world by creating closed systems that can be understood and controlled, this is only possible by excluding all of the weaker connections and focusing on the most influential ones, but the butterfly effect essentially states that anyone of these weaker connections could become a strong influence. Added to this linear systems of equations normally have only a single solution. Non-linear systems, on the other hand, have typically several solutions. This means that there is a range of stable configurations in which the system may settle and thus there is no one right answer or equilibrium point.

Chaos research, tracks the transformation of dynamical systems from one behavioral regime (attractor state) to another. From orderly states of equilibrium, to simple periodic oscillations to complex periodic oscillation, through to chaotic and random behavior. The periods of change as the system goes from one qualitatively different regime to another are called bifurcations. A bifurcation occurs when a small smooth change made to the parameter values (the bifurcation parameters) of a system causes a sudden 'qualitative' or topological change in its behavior, characterized by a branching or splitting off.

These patterns of order are found in what are called state space modeling, where the state of a system as described by a number of parameters is plotted within a graph. From this visual patterns in the state of the system can emerge as it evolves over time. An attractor is a set of physical properties toward which a system tends to evolve, regardless of the starting conditions of the system. An attractor represents a system's long-term mode of behavior or points of equilibrium. If we disturb the system it will return to this attractor.

Chaos theory has established itself as a quantitative science, but with its evocative name it has reinvigorating fundamental question about the processes of change that give rise to patterns of order and chaos both within science and society.



11. Network Theory

Network theory is a way of describing the world in terms of a model called a network that allows us to capture the information about the relationship between things. But let's first think about why we might be interested in this at all. We often describe the world in terms of objects or things and their properties, we talk about countries and their GDP, people and their age or the color of a car, this type of component based analysis works well when the system we are interested in is relatively isolated. But when we turn up the interactions and connectivity between elements within a system it is increasingly the connections that come to shape the elements and define the system as a whole and thus we need a model that captures this information about the relationships and allows us to reason about it, this is where network theory comes in.

Network theory starts with a very simple view of the world as made up of nodes which are things or objects, like people, cities, computers etc. and the relationships between these things, called edges, such as friendships, trading partners, cables and so on. This abstract representation of the world, can be used to model a wide variety of things, thus we can have social networks, biological networks consisting of interacting creatures within an ecosystem or logistic networks composed of interacting suppliers

and consumers. Network theory gives us a set of tools for analyzing the individual elements and relations within these networks, the structure of the network and the properties that these different networks structures give rise to. The first set of question we might like to ask about a particular network relate to its degree of connectivity, that is how connected an individual element or the whole network is, this will tell us many things about it such as how quickly a new event could spread or propagate through the system.

The average degree of connectivity will give us a quick answer to this; this is calculated by taking the total number of edges and dividing it by the total number of nodes within the network. We also need to take into account how large the network is, that is to say how far it is on average from one point to another. This is called the average path length and we can calculate it by taking the average of all the path lengths between all the nodes. Because networks are all about connectivity we often ascribe value to individual nodes based upon their degree of connectivity, there are various methods for calculating this but a popular one is called eigenvector centrality, which measures both how many edges a node has and how connected the nodes it joins to are also. Popular web search engines use variants of this eigenvector centrality measure to rank webpages by calculating both the number of links into a webpage and the degree of connectivity of the pages that link into them thus gaining an idea of the relative importance of the website.

Next, we are also interested in talking about the overall structure to the network this will be largely determined by how the relationship between the nodes was formed. If the relations between elements was generated randomly we would expect a relatively even distribution of edges across the network, this type of structure or topology is called a random graph or distributed network as the relative importance of any node is distributed across the entire network. A second type of network structure we can get is called decentralized or small world, this is generated by having local clusters of connections, but also having some random distant connections. An example of this might be a group of friends, with some of the friends having distant relatives in other parts of the world. By using these local connections within the group and distant connections research has shown that it is possible to connect two random people within an average of just six steps and thus it is termed a small world network.

Lastly we have more centralized networks called scale-free networks, this is where many nodes have chosen to connect to the same node giving it a degree of connectivity that greatly exceeds the average whilst leaving many with a very low level of connectivity. Many real networks are thought to be scale-free, including social, biological and technological systems such as World Wide Web, where very few sites like Wikipedia have a very large amount of links into them, whilst the vast majority of websites have very few.

These various types of network structures give rise to different properties, a key question we are interested in asking here is how robust or fragile is a particular type of network as this will not only help us understand networks better, but will also be of great significance in how we design and manage them. For example, think about a country with many small to medium size cities supplying the population with various public services, if we were to remove one of the cities it would have a limited effect on the overall system, because the network has a distributed structure making it robust to failure of this kind. On the contrary, if we take a country with one dominant capital city with the rest of the urban network dependent upon it for core services, this centralized network may be more efficient but it is also in what is called a more critical state as effecting this single primary node would have a large systemic effect.

As we transition from an industrial to information societies, networks are emerging as a new paradigm in how we structure our systems of organization both social and technological. Network theory is a young and rapidly growing area that provides us with a set of tools for designing and managing these new types of organization and more generally understanding the world around us from a different perspective, in terms of connectivity.

12. Networks Key Concepts

In systems with a low level of connectivity, we can best describe the over all state of the system as simple a product of the properties of its individual components. But as the elements within a system become more interconnected and interdependent it is increasingly the structure and type of relations between elements that comes to define them. For example when we have a group of nations with little affiliation we can analyze them by talking about their individual capabilities. However, when we have a group of nations that are highly interrelated through a set of treaties and international agreements it is these networks of relations that we need to analyze if we are to understand how the system will behave given the occurrence of some event.

Networks provide a mechanism for defining the relations between elements. Without being constrained by some formal method for categorizing elements. Networks are used to model or structure what are called loosely coupled systems where the elements are only loosely associated with a high degree of individual autonomy. This is one reason why networks are often contrasted with the formal structure of hierarchies.

Graph theory is the area of mathematics that studies the properties of graphs which are mathematical structures used to model pairwise relations between objects, a graph is just a more formal mathematical term for a network. For us to be able to use

graph theory we must first be able to contextualize or translate the system we are interested in analyzing into the language of graph theory, that means firstly identifying what are the nodes and what are the relations. Some systems lend themselves naturally to this analysis, for example transportation systems and social groups. Others it is less straight forward for example in modeling an ecology or city. Once we have been able to identify nodes and edges we need to identify what are the types of nodes and relations, for example with an ecosystem we might make a distinction between nodes that represent plants and animals and edges that represent synergistic relation (mutually beneficial) and predator-prey relations.

To gain a quantitative understanding of the graph we can ascribe values to the nodes and edges, this might be the size of a population or amount of resource exchange within the ecosystem. Edges can also be directed, meaning that a resource flows in one particular direction. This much information should give us a clear understanding of the topology of the network that is the overall structure to the system derived from the way in which its constituent parts are interrelated or arranged.

Connectivity is one of the basic concepts of graph theory. It asks for the minimum number of elements (nodes or edges) that need to be removed to disconnect the remaining nodes from each other. The connectivity of a graph is an important measure of its robustness. Networks are classified in four different categories of connectedness:

Clique/Complete Graph: A completely connected network, where all nodes are connected to every other node. These networks are symmetric in that all nodes have in-links and out-links from all others.

Giant Component: A single connected component which contains most of the nodes in the network.

Weakly Connected Component: A collection of nodes in which there exists a path from any node to any other, ignoring directionality of the edges.

Strongly Connected Component: A collection of nodes in which there exists a directed path from any node to any other.

Clustering is one of the most important topological features that will be found in many networks as in most kinds of networks there are at least a few different types of nodes, and the probabilities of there being a connection between nodes often depends on their type. In social networks this kind of selective linking is called homophily, homophily gives us the famous saying "Birds of a feather flock together". Clustering is computed in terms of the mean probability that two nodes that are

network neighbors of the same other node will themselves be neighbors. Clustering is asking how many of your friends know each other, if they all know each other then this is a cluster.

The density of a network is defined as a ratio of the number of edges to the total number of possible edges. Node centrality can be viewed as a measure of influence or importance in a network model. There is a number of main measures of centrality that are studied in network science.

Closeness Centrality: represents the average distance that the node is from all other nodes in the network

Betweenness Centrality: Is the number of shortest paths in a network that traverse through that node.

Degree Centrality: Is the amount links that a particular node possesses in a network. In a directed network, one must differentiate between in-links and out-links by calculating in-degree and out-degree. The analogue to degree in a weighted network, strength is the sum of a node's edge weights. In-strength and out-strength are analogously defined for directed networks.

Prestige Centrality: Finally prestige centrality is another measure, asking how well connected are the nodes that a given node is connected to.

Network dynamics is a relatively new area that studies how graphs evolve over time, with vertices or edges appearing or disappearing, there value changing and the overall network topology morphing into new forms. Network dynamics helps us to try and understand important questions about how networks are formed and dissolved over time. From the internet to neural pathways to the increasingly networked structure of our economy, complex networks have become an integral part of our everyday lives and it is quite surprising that it is only in the past few decades that we have really started to take notices of them.



13. Complex Adaptive Systems

Complex adaptive systems are systems composed of multiple diverse elements that are capable of adaptation and thus can evolve over time to exhibit highly complex behavior. But let's start from the beginning by talking a bit about adaptation. Adaptation is a process or capability through which systems can change in response to some event within their environment. In order for this to happen there needs to be some control or regulatory mechanism within the system. Cybernetics is the area that deals with a system's regulatory mechanism through what are called feedback loops, whereby the actions of a system generates some change in its environment and that change in turn feeds back to effect the system itself.

A classical example given of this is a thermostat that regulates the temperature of a house. The system consists of a central controller where the desired temperature is set, a heater that creates an action that changes the state of the environment, and a sensor to feedback information about the environment to the controller. Wherever we have this basic degree of interaction and interdependence between elements, we can us the model of an adaptive system and feedback loops to describe its dynamics and thus we can model economies, society and ecosystems in this way.

The different ways in which the interactions between a system and its environment affect each other generates different types of feedback loops. Primary among these are what are called positive and negative feedback. Firstly, positive feedback is an action that produces more of the same. For example as global temperatures rise, Arctic sea ice melts, as this reflective sea ice disappears the now exposed dark ocean waters absorb more heat which in turn increases global temperature and so on.

In contrast negative feedback produces less of the same action. For example the more the price of apples goes up the less the demand from apple consumers, which in turn feeds back to reduce the price of apples again. These different feedback patterns in turn give rise to different systems properties, for example negative feedback is a form of self-regulation that typically generates very stable systems, whereas positive feedback loops often have destabilizing effects. An example of how this works may be seen in a grounded flock of birds, any of which is likely to fly away when it sees a neighboring bird fly off, every time another bird reacts and takes flight it increases the likely hood of more birds flying way. Thus the system can be said to be unstable due to these positive feedback loops that allow for some small event to propagate through the system. This same dynamic can be seen within many other domains such as in financial systems where loss of confidence can cascade through the system generating a bank run.

We have been talking about adaption and feedback loops, but to get complex adaptive systems requires multiple adaptive elements interacting, from this micro level interaction adaptive systems can self-organize allowing for the emergence of some macro level pattern. An example of this might be the formation of a culture, where individuals in close proximity develop standardized methods for interaction and coordination through a common set of greetings, language, and rituals. Over time these micro interactions will develop into a formal cultural system. These emergent self-organized macro structures, whether they are markets, social institutions or cities then in turn feedback to effect the actions of individuals within the system both constraining and enabling their future actions.

Given this emergence of new levels of order as the system evolves, the element's capacity for adaptation and the complex interactions within the system it is almost impossible to predict the future state of a complex adaptive system with any accuracy. The only viable method for modeling how these systems evolve over times is to simply let them develop and see what happens, fortunately we have computers that can simulate this process. This method of simulation is the agent-based modeling method we previously discussed, where an agent is given a simple set of rules that govern its behavior and left to interact to see what macro scale patterns emerge over time. This method has shown that even with very simple rules governing the agent's behavior complex and unpredictable phenomena can arise.

Complex adaptive systems, and its friend cybernetics, are more than just the study of how birds flock or thermostats work. They are a whole paradigm with which to understand and model the complex set of interconnected feedback loops that make up the natural, social and technological world we live in.

14. Adaptive Systems



Adaptive systems are those that are governed by some control or regulatory mechanism that allows them to change their state in response to changes within their environment. This regulatory mechanism is best understood in terms of information and communication, and has been primarily studied within the domain of cybernetics. The word cybernetics comes from the Greek word κυβερνητική meaning to govern, steer or navigate. Cybernetics is applicable when a system being analyzed is involved in a closed signaling loop; that is, where action by the system generates some change in its environment and that change is reflected through feedback that triggers a system change. Cybernetics is relevant to the study of mechanical, physical, biological, cognitive, and social systems.

These adaptive systems are interconnected and importantly interdependent, an example might be the energy infrastructure for a country, the different elements within the system interact through the market, are interdependent and adapting to each other. This constant interaction and adaptation creates what has been called a dancing landscape, that is to say the environment is continuously changing and the system must stay responding and exploring the changing playing field. An example might be a company that is developing a new service, they will have to respond and adapt their service to the changing landscape within which other operators are providing similar services. In this complex adaptive system all players are continuously shaping and reshaping the overall topology of the environment.

Game theory is the area of mathematics that tries to model these types of adaptive systems in economics, political science, and psychology and biology. It is "the study of conflict and cooperation between intelligent rational decision-makers." There are four essential elements required to model a "game" between adaptive agents, we need to know who are the players, what information do they have, what actions are available to them and what are the payoffs (what can they gain or win by playing the game) for each outcome to the game. Game theory uses matrixes to represent and quantify the different strategies an agent might take within a game plus the payoffs that they will receive for each different strategy. In this way these "games" (environments within which adaptive systems interact) can be brought within the quantifiable framework of mathematics. Different classes or types of games can then be identified and attempts made to find optimal solutions to a given class of game.

Emergence is a key concept in complex systems in general but particularly so with complex adaptive systems. It describes how global patterns (macro scale) can emerge out of local level interaction (micro scale) and most importantly how these emergent phenomena can be qualitatively different from any of the constituent parts of the system, resulting in novel and unpredictable phenomena emerging as the system evolves overtime. Due to the fact that complex adaptive systems are dynamic we can best understand them as the product of evolutionary force that has shaped them. For example many countries use different types of electrical sockets, if we were to analyze this system in static terms it would not make any sense for the system to have been designed in this way. But when we see the system as the product of evolutionary dynamics where each region developed their one standard locally before becoming part of a large system we can understand how the system is arranged in such a manner.

Agent-based modeling gives us a way of simulating this process of evolution. As opposed to many traditional forms of mathematical modeling that search for equilibrium points (that can be encoded as equation) within the system, such as where supply equals demand in an economy, agent-based modeling makes no such suppositions about there being an equilibrium within the system, agents are simply left to interact and evolve, this can result in a much more organic and granular model of the system. For example an agent-based model of the financial (stocks and shares) market was made (at Santa Fe Institute) that was able to create realistic models of the market as it went through periods of stability, bubbles and crashes, similar to a real economy.

Cybernetics represents a powerful way of modeling adaptive systems through a focus upon regulatory mechanisms and information. Whilst the area of complex adaptive systems is more focused on the overall dynamics and structures that emerge out of interactions and adaptation. They both place a strong emphasis upon a cyclical and iterative process of evolution through feedback and adaptation.



15. Self-Organization

If a system, such as a plant, a building or a car, shows organization we tend to assume that someone or something must have designed it in that particular order. Self-organization is the idea that this type of global coordination can instead be the product of local interactions. The theory of self-organization has grown out of many different areas from computer science to ecology and economics. Out of these different areas has emerged as core set of concepts that are designed to be applicable to all self-organizing systems from galaxies to living cells. But let's start by talking a bit about organization itself.

Organization is a highly abstract concept but we can loosely equate it to the idea of order with its opposite being what is called entropy or disorder. Order and entropy are typically measured by scientist in terms of information, that is to say the more information it takes to describe something the more disordered the system is said to be. An example of this might be a piece of metallic substance consisting of tiny magnets called spins, each spin has an particular magnetic orientation and in general they are randomly directed and thus cancel each other out. This disordered configuration is due to its heat energy causing the random movement of the molecules in the material.

When we cool the material down the spins will spontaneously align themselves so that they all point in the same direction. To describe the state of the spins in this ordered system would involve far less information relative to its original state that required unique values for each randomly directed spin. This process of

magnetization is often cited as an example of self-organization, that is to say the spontaneous appearance of order or global coordination out of local level interactions. But let's take a closer look at how this happens.

As we cooled the material down, there was some area that had by chance some spins pointing in the same direction, their alignment generated an increased magnetic force that was exerted upon its neighbors, creating what is called an attractor state, attracting other spins to this configuration. Each time another spin aligned itself with this particular attractor state it augmented the force it exerted upon other spins through what is called a positive feedback loop that would cascade through the system until all elements were aligned within this new regime.

Another example of self-organization through positive feedback is what is called the network effect, where the more people who use a product or service, the greater its value becomes, the telephone and Facebook are such examples becoming more useful as more users join, in this way local connections between individuals can rapidly form into global patterns. The network effect illustrates the positive relations or synergies between elements that can be created when they coordinate. It is due to the presence of these synergistic relations that the system as an entirety can become more than the sum of its parts, in a process called emergence. Ant colonies are a classical example given of emergence, ants governed by very simple rules and only local interactions, can through their combined activities generate colonies that exhibit complex structures and behavior that far exceed the intelligence or capability of any individual ant and thus it is said to have emergent properties.

Ant colonies also illustrate the decentralized structure to self-organizing systems. The queen does not tell the ants what to do. Instead, each ant reacts to stimuli in the form of chemical scent exchanged with other ants, in this way organization is distributed out over the whole system. All parts contribute evenly to the resulting arrangement. As opposed to centralized structures such as most social organizations that are often dependent upon a single coordinator, this decentralized structure that is inherent to self-organized systems often gives them resiliency and robustness, as any element that is damaged can be simply replaced by any other given them a high redundancy.

Whether the self-organizing system is a social institution, a technology or ecosystem for it to sustain itself over time it must be able to withstand change and interventions from its environment, requiring the system to be both robust to these perturbations and capable of adapting to changes. The generation of noise and variation within the system is a classical mechanism for achieving this. Without diversity a system can become rigid and develop into what is called a critical state. An example of this self-organized criticality, could be an economy whose many industries have developed a dependency upon petrochemical fuels. This lack of diversity of energy sources means

a small disruption in the supply of petroleum from the system's environment could have a large global consequence.

Inversely systems with a high degree of diversity between elements will be more robust as the variety between elements will make them more effective at absorbing change. Ecosystems are a classical example of this generating a large variety of species that make it capable of surviving significant changes within its environment. Thus we can see how evolution is a core concept in understanding the dynamics of self-organizing systems, whereby attractor states and feedback loops generate the system and periodic perturbations from its environment work to select the most adapted or fittest elements.

As information technology is enabling new forms of organization, people within many domains are faced with practical challenges of how to design and manage self-organizing systems, such as computer networks and new forms of social collaborative.



16. Self-Organization Digging Deeper

Self-organization can be defined as the spontaneous appearance of global coordination or order out of local level interactions of initially independent components. This collective order is organized towards its own maintenance, and thus tends to resist external perturbations. A classical example of self-organization would be the emergence of convection patterns in a liquid heated from below. Water heated from the bottom moving up, and cool water from the surface moving down, self-organize into a circular belt called convection cells. This is similar to the self-organization process that takes place as pedestrians cross the street. As people at the front first interact and create a path around each other this creates an attractor for those behind to follow. Out of this we get the emergence of a global pattern of distinct lanes of people going in each direction without anyone having coordinated or designed this emergent pattern.

As we previously touched upon when a system is synchronized it requires less information to describe it. This is equivalent to the increase of coherence, or decrease of statistical entropy that defines self-organization. The basic mechanism underlying this process of self-organization is the deterministic or stochastic variation that governs any dynamic system, exploring different regions in the state space until it happens to reach an attractor, i.e. a configuration that closes in on itself. This process can be accelerated and deepened by increasing variation, for example by adding, "noise" to the system. Entering the attractor precludes further variation outside the

attractor, and thus restricts the freedom of the system's components to behave independently as they become synchronized into a coherent pattern.

The resulting organization is fully decentralized or distributed out over all the components in the system. As such it is typically very robust and able to survive and self-repair substantial damage or perturbations. This can be contrasted with systems that are centrally designed and controlled which often results in some hierarchy. Within centralized structures elements can specialize in specific functions which may make the system more efficient but also more vulnerable to strategic attack as critical control mechanisms are concentrated within a few elements, which if damaged would leave the whole system vulnerable.

To adapt to a changing environment the system needs a sufficiently large variety of possible stable states to cope with likely perturbations. This variety, however, must not be so large as to make its evolution uncontrollably chaotic. Given this variety, the most adequate configurations are selected according to their fitness. Either by the environment, or indirectly by subsystems that have already adapted to the environment and become more advanced. Thus, the system can adjust its internal configuration to external perturbations, while minimizing the changes to its overall structure and functionality. But there is tension within these systems between the need for variation (to be able to adapt and respond to the changes within their environment) and a need for homogeneity with which to maintain a coherent structure. This dynamic is captured in the catchy term "edge of chaos" that describes how many self-organizing and complex adaptive systems exist far from stable equilibrium, where they are capable of maintaining the dynamic state needed to evolve over time.

On the contrary, our traditional vision of the world often assumes the need for centralized coordination and control in order to create some ordered system. Self-organization theory represents a whole new paradigm that see things as the product of the emergence of order from the bottom up, through the interactions of element governed by simple rule as they evolve over time.



17. Applications

In these final four sections to the book, we will be taking a brief overview to some of the applications of systems theory and complexity theory to various domains of science. Complexity theory is one of the fastest growing and most exciting areas of science today sitting at the cutting-edge of research as it is applied to an ever expanding set of areas. Just to name a few we could site: complexity management that applies the ideas of self-organization, resiliency and systems thinking to the management of public and private organizations.

Systems engineering is another area, systems engineering can be understood as the application of systems theory to the design, coordination and management of large complex industrial projects that require a holistic approach in order to integrate the many different specialized engineering domains into the overall project. Another area is systems ecology, the application of systems theory to the modeling and analysis of ecosystems, understanding them in terms of emergence, self-organization, hierarchy and resiliency.

The four areas we have chosen here are: Social network analysis: The use of network theory to understanding social organizations. Complexity economics: A new paradigm within economic theory based on complexity theory. Socio-technical systems: An approach to understanding coupled technology systems that involve the interaction between people and technology. Earth systems science: Finally we will look at the application of systems theory to the earth sciences what is called earth systems science.



18. Social Network Science

Social network analysis is the application of network theory to the modeling and analysis of social systems. It combines both tools for analyzing social relations and theory for explaining the structures that emerge from these social interactions. Of course the idea of studying societies as networks is not a new one but with the rise in computation and the emergence of a mass of new data sources, social network analysis is beginning to be applied to all type and scales of social systems from, international politics to local communities and everything in between.

Traditionally when studying societies we think of them as composed of various types of individuals and organizations. We then proceed to analyze the properties to these social entities such as their age, occupation or population, and they ascribe quantitative value to them. This allows social scientists to use the formal mathematical language of statistical analyst in order to compare the values of their properties and create categories such as "low income house holds" or "generation x". We then search for quasi-cause and effect relations that govern these values. This component-based analysis is a powerful method for describing social systems. Unfortunately, though it fails to capture the most important feature of social reality that is the relations between individuals, statistical analysis presents a picture of individuals and groups isolates from the nexus of social relations that give them context.

Thus we can only get so far by studying the individuals because when individuals interact and organize, the results can be greater than the simple sum of their parts. It is the relations between individuals that create the emergent property of social institutions and thus to understand these institutions we need to understand the networks of social relations that constitute them. Ever since the emergence of human beings we have been building social networks, we live our lives embed in networks of relations, the shape of these structures and where we lie in them all affect our identity and perception of the world.

A social network is a system made up of a set of social actors, such as individuals or organizations, and a set of ties between these actors that might be relations of friendship, work colleague or family. Social network science then analyzes empirical data and develops theories to explain the patterns observed in these networks. In so doing we can begin to ask questions about the degree of connectivity within a network, its overall structure, how fast something will diffuse or propagate through it or the influence of a given node within the network. So let's take some examples of this. Social network analysis has been used to study the structure of influence within corporations. Where traditionally we see organizations of this kind as hierarchies, by modeling the actual flow of information and communications as a network we get a very different picture, where seemingly irrelevant employees within the hierarchy can in fact have significant influence within the network. Researchers have also studied innovation as a process of diffusion of new ideas across social networks. Where the overall structure to the network, its degree of connectivity, centralization or decentralization are a defining feature in the way that innovation spreads or fails to spread.

Network dynamics, which is how networks evolve over time, is another important area of research. For example within Law enforcement agencies social network analysis is used to study the changing structure to terrorists networks, to identify changing relations through which they are created, strengthened and dissolved? Social network analysis has also been used to study patterns of segregation and clustering within international politics and culture, by mapping out the beliefs and values of countries and cultures as networks we can identify where opinions and beliefs overlap or conflict.

Social network analysis is a powerful new method we now have that allows us to convert often large and dense data sets into engaging visualization, that can quickly and effectively communicate the underlining dynamics within the system. By combining new discoveries in the mathematics of network theory, with new data sources and our sociological understanding, social network analysis is offering huge potential for a deeper, richer and more accurate understanding, of the complex social systems that make up our world.

19. Complexity Economics



Complexity economics is a new paradigm within economic theory that sees the economy as complex adaptive systems, composed of multiple diverse agents interacting through networks and evolving over time. It is one of a number of alternative economic theories that have arisen over the past few decades, due to a growing awareness to the limitations of our existing economic theory. So let's first talk a bit about this standard approach to economic theory. The foundations to modern economics date back to the 18th century where it borrowed much of the formal apparatus of mathematics and the natural sciences, especially from physics with its classical mechanistic view of the world in terms of linear deterministic cause and effect.

Within this paradigm of classical economics individual human behavior is comparable to the physical laws of motion, it is regular, predictable and largely deterministic, meaning the standard tools of mathematics can be applied. Standard economics models the economy as a closed system, that is to say separate from social, environmental and cultural factors, which are not included in the models thus the social domain is constituted by sets of isolated individuals that are governed almost purely by economic self-interest. Similar to classical physics, equilibrium is a fundamental assumption of many economic models. According to the equilibrium paradigm, there are optimal states to the economy, to which the system will automatically and quickly evolve, driven by the market forces of supply and demand. This idea is enshrined in the metaphor of the "invisible hand."

Lastly standard economics inherits the reductionist view of classical physics implying that the behavior of a society and its institutions does not differ in kind from the sum of its individual agents. Thus the behavior of all the agents together can be treated as corresponding to that of an average individual.

By applying this assumption standard economics has converted what was once a branch of moral philosophy into a powerful framework based upon formal mathematics, which has proven to be a solid foundation in supporting the massive economic transformation that was the industrial revolution. But today major trends such as the rapid development of our global economy, the rise of financial capitalism, the huge growth in the services, knowledge and information economy and environmental awareness are all working to reveal the limitations in the foundational assumptions of classical economics.

In response to these changes a number of new economic theories have emerged under the heading of heterodox economics, that all emphasize a need for an expansion of our economic framework to incorporate new social, cultural and environmental parameters to give a more realistic vision of how economies functions in practice. Primary among these is behavioral economics that tries to go beyond the classical model of the individual motivated by rational self-interest to incorporate a richer set of cultural and social motives driving individuals' behavior. Or environmental economics is another area, which tries to address the failure of the current framework to incorporate the value accruing from natural resources and ecosystems services.

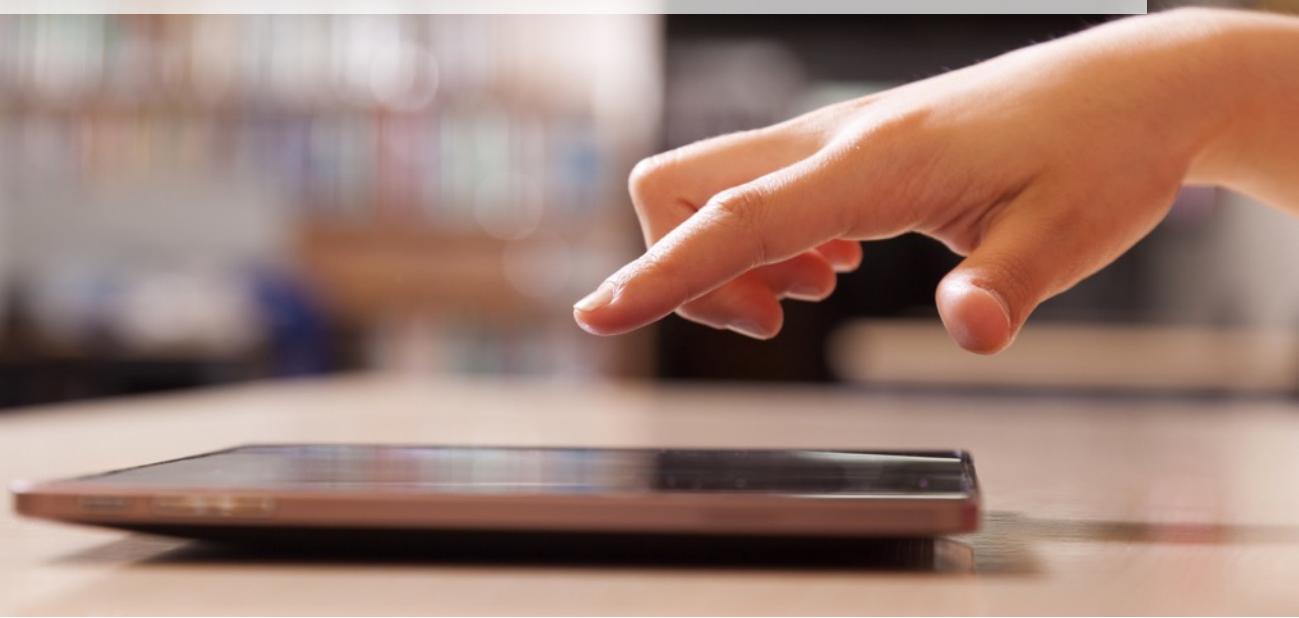
Complexity economics is part of this alternative theoretical framework. Representing a new paradigm that sees the economy as a complex adaptive system, composed of multiple agents with diverse motives, whose interaction within networks gives rise to emergent structures such as enterprises and markets. Instead of seeing the economy as the product of isolated individuals making rational choices with perfect information resulting in efficiency markets, complexity economics see the individual as embedded within social and cultural networks that influence their behavior and with limited information that often leads them to make apparently irrational actions, resulting in suboptimal markets.

As apposed to seeing the economy as the product of a static equilibrium, complexity economics is more focus upon the non-equilibrium processes that transform the economy from within, through continues adaptation and the emergence of new institutions and technologies as the economy evolves over time. Complexity economic applies this concept of evolution to understanding the dynamics of economic development. Which is understood as a process of differentiation, selection and amplification, acting on designs for technologies, social institutions and businesses that drive continuous internal change within the economy.

Complexity economics is beginning to employ the whole suit of tools from complexity theory such as agent-based modeling of economies, that gives us the possibility to run simulated experiments to understand the possible positive and negative consequences of an economic regulation or intervention. Network theory is another important tool, as economic and financial globalization have networked our world with a complex and often unknown set of interdependencies, network analysis of these linkages is becoming crucial to gaining an understanding of the over all system. Many other concepts from complexity theory are being applied to economics such as feedback loops to model the relations of interdependence between different parts of the economy that work to regulate it on the macro level. Or game theory and even chaos theory have been used for analyzing regularities within the fluctuation of stock market prices.

Our global economy is a true complex system, with multiple highly interconnected and interdependent social and technical elements that co-evolve. Expanding our economic framework beyond equilibrium and linear systems theory is a core challenge that complexity science is helping us bridge.

20. Socio-Technical Systems



Socio-technical systems is an relatively new area which takes a more holistic approach to the development of engineering projects that involve that interaction between people and technology. But let's start by taking an example of how our traditional approach to the development of technology and social organizations works. Take Bob and Alice, for example. They are both web developers and they both work on the same website. But Bot is a backend web developer; he eats databases for breakfast and spends his days crunching code. Whilst Alice is a front-end web designer, she makes words sing and graphics come alive in simple and user-friendly interfaces that people love. Every few months the site needs updating and Bob works hard behind the scenes coding away, he then hands the project over for Alice to work her magic on. This works fine initially but as the site grows with more employees being taken on thing become a little less straight forward. We soon have multiple people working on increasingly specialized areas of the side with developers and designers often needing to interact and collaborate but finding themselves stuck in their separate departments.

Bod and Alice's site now requires a more holistic and non-linear approach to overcome this stumbling block as it has now become what we can call a complex socio-technical system. But what do we mean by this? Firstly it is complex in that it has multiple elements such as lines of code, databases, graphics and so on, with all of these different things needing to interact and being dependent on each others functioning.

And secondly it is socio-technical as a website represents an interaction between the technical domains of computer software and the human interface. For the site to function fully we need to design both areas to work together. When we look around us we can begin to see socio-technical systems everywhere. Let's take another example of a station for a subway in Hong Kong. This station represents a highly integrated set of diverse elements, from the residential area to the commercial center to the transport hub it was engineered and constructed by a single company. The designers of this system needed to think not only about how the physical technologies would interact and work together within a confined space but also about how the residence and commuters might wish to use the system for multiple different functions.

The website and the subway station are examples of systems on the small to media scale. But as we enter the 21st Century many of the challenges we face involve macro scale socio-technical systems. Such as growing demographics and urbanization. With urban infrastructure companies now offering solutions that integrate power grids, water supply, transportation and other utilities that must interface with thousands of people on a daily basis and have a strong influence on the social fabric. Or, with respect to the environment, where nations must balance social needs, technological requirements and environmental considerations to manage and grow efficient sustainable economies. This again involves the interaction of social and technical elements that need to work together for the entire economy to be fully productive.

We can think about socio technical systems then, as an approach to overcoming the problems of optimizing either the social or technical side to a project in isolation, and a more holistic method for developing synergistic relations between both areas that create optimal solutions for the system as a whole.



21. Earth Systems Science

Earth systems science is the interdisciplinary study of The Earth as a complex system. Composed of multiple physical and biological processes that interact within cycles or spheres to give rise to the overall state of the earth as entire systems. Of course people have been studying The Earth for a long time. Geologists study the formation of rocks, meteorologists are interested in the atmosphere and so on. With all of these different domains supported by the deep understanding of our physical environment that physics has built up over the past few centuries. But it is only more recently that satellites have started to allow us to see The Earth as an entirety and human activity has begun to have a significant enough effect to alter Earth's systems making it increasingly important for us to be able to model and manage them.

From space we can view the net results of Earth's complex interactions and with high-tech sensors on land and in the ocean, we are getting a clearer idea of its overall make up. From this researchers in different domains are discovering how their pieces of the puzzle are related to each other. Earth systems science then tries to develop models that give an integrated picture of how all these parts fit together. The first of these models is of earth as a system in space with inputs and outputs of energy or

radiation from the sun. With this energy being the primary factor in driving the dynamic processes within the system.

As opposed to focusing on the static properties of Earth's individual components. Earth systems science instead takes a more dynamic view of the world, studying the ways energy and materials cycle through the different subsystems or what are called "spheres". Earth's different sphere is largely defined by the different phases of matter they are composed of. Thus the atmosphere is composed of gasses, the hydrosphere of liquid water and the lithosphere solid minerals added to this is the biosphere, which is the sum of all biological material and processes.

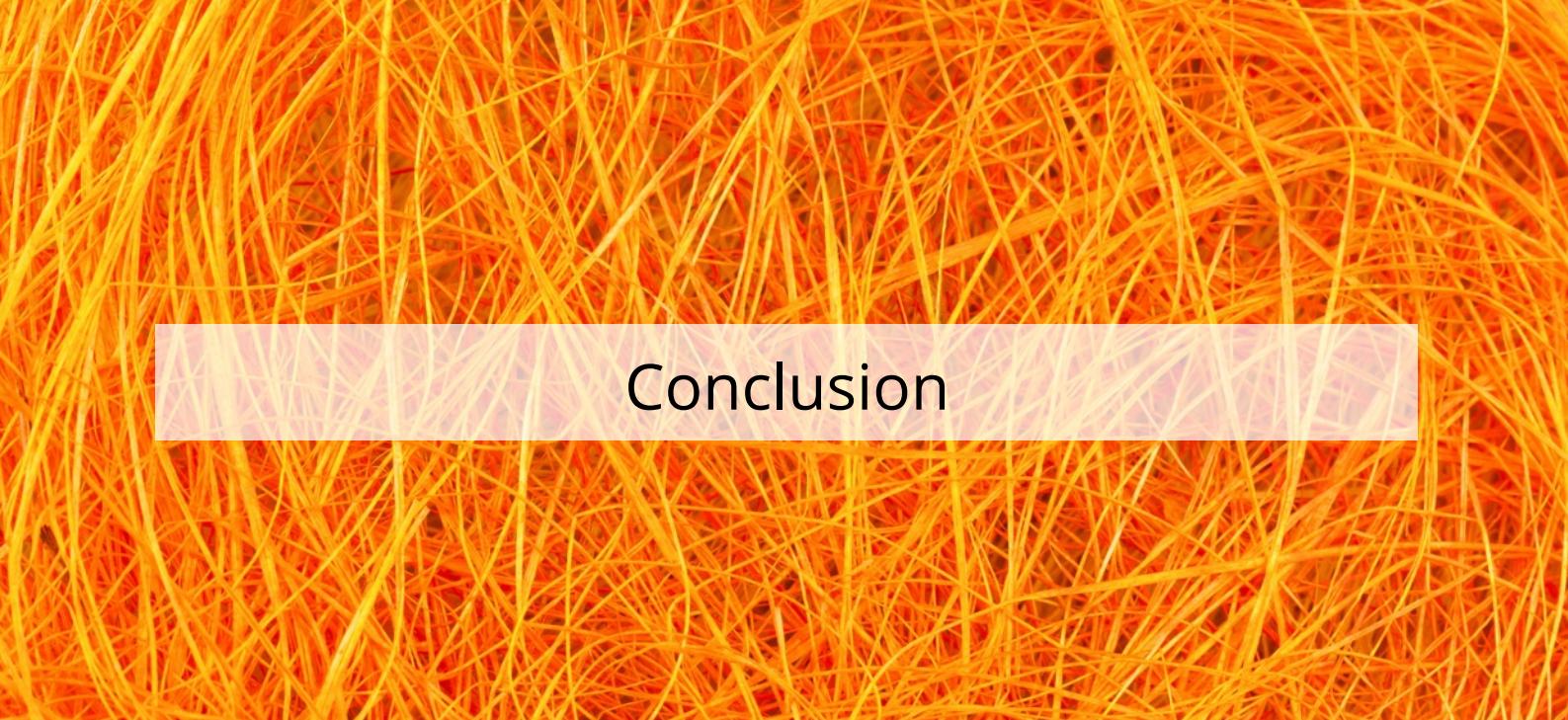
Within each sphere a process called a cycle takes place. For example in the lithosphere we have the rock cycle driven by the thermal energy within earth's interior that releases minerals through ocean ridges and volcanoes that are weathered as they cycle through Earth's crust and are eventually returning to their origin through subduction. The hydrologic cycle driven by the thermal energy of the sun, cycles water between the earths surface and atmosphere through the process of evaporation, condensation and precipitation, this process helps to distribute moisture and support ecosystems at a variety of locations. The atmosphere is a layer of gases surrounding the planet that is held in place by gravity. It is the primary vehicle of temperature and climate regulation through the cycle of carbon in and out of the atmosphere where it functions (through the greenhouse effect) to trap the sun's heat. The biosphere is the relatively thin layer of Earth's surface that supports all biological activity on earth. The biosphere is a system also characterized by the continuous cycling of matter and energy in the form of the flow of solar energy and nutrient mineral cycles.

Solar energy flows through the biosphere along a unidirectional path, as the sun's energy is inputted through plant photosynthesis and processed up through what are called trophic levels from primary producers to herbivores and on to predators and apex predators. Along side the flow of energy through food webs is the cycling of mineral nutrients. The core substances required for the construction of biological materials and processes, carbon, water, oxygen and nitrogen have all been continuously cycled through the biosphere from one generation to the next for billions of years. These different spheres interact to create a unique state or ecosystem. An ecosystem is the combination of a community of biological organisms and a particular physical environment with which they interact.

Thus we can understand an ecosystem as a certain combination or mix of our different spheres and the climate. For an ecosystem to develop over time it requires a relatively stable balance between its constituent elements. This balance is typically regulated through some form of feedback loop. Earth systems scientists are beginning to understand earth's regulatory mechanism's as a complex of feedback loops. These feedback loops can be either positive or negative. Positive feedback loop typically

have a destabilizing effect and can lead to rapid changes in weather such as a hurricane. Inversely negative feedback loops typically have a stabilizing effect on earth's systems, allowing for the maintenance of stable atmospheric gasses or temperature over prolonged periods.

Planet Earth is one of the true complex systems with multiple diverse elements on multiple scales that are highly interconnected, interacting and adapting as they co-evolve over time. Developing the models and amassing the data to get a coherent picture of the functioning of the earth system is one of the core challenges to contemporary science.



Conclusion

In this book, I have tried to present complexity theory from a systems perspective in order to make it intuitive and accessible. The hope is that you come away with a basic understand of the key concepts within this area. Such as what synthetic reasoning and systems thinking are and how they represent an alternative paradigm within science. The other big idea we introduced here was that of nonlinear systems, how nonlinearity is the product of the interaction between the parts in a system. Where when we put two or more things together we get a combined effect that is greater or less than the sum of their parts, what is called a synergy or interference. But also the idea of feedback loops is another central concept within nonlinear systems theory, where something can feedback on itself over time so as to become compound into a large effect and given enough time or rapid iteration, we can get the butterfly effect.

Hopefully at this stage you have some insight into network thinking and its relevance, the ideas of centrality, distributed and centralized networks can help us in understanding the workings to may different types of systems from the internet to the workings of economies and new IT enabled networked organizations.

Finally adaptation and self-organization were two of the other major concepts within complexity theory that we talked about. Where we looked at how agents governed by simple rules can interact locally, adapt to each other and out of this we get the emergence of global patterns of order. With this idea of emergence being other key concepts, where the whole system comes to have features and properties that none of its parts posses, such as life emerging out of nonliving matter or concise emerging out of the interaction between millions of neurons. Complexity theory and systems theory are very broad areas with lots to explore. We have only really scratch the surface here but hopefully this has been sufficed to stimulated your curiosity to stay exploring farther.