What Is a Complex System?

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Chapter 1

Introduction

Complexity science is relatively new but already indispensable. It is important to understand complex systems because they are everywhere. Your brain is a complex system and so is your immune system and every cell in your body. All living systems and all intelligent systems are complex systems. The climate of the Earth is a complex system, and even the universe itself exhibits some of the features of complex systems. Many of the most important problems in engineering, medicine and public policy are now addressed with the ideas and methods of complexity science – for example, questions about how epidemics develop and spread. Thousands of years of mathematical and scientific study have given us the technology to create new complex systems that rival those of the biosphere, such as cities, financial economies and the Internet of Things. Business leaders have started to think in terms of complexity science, using terms such as ‘robustness’, ‘redundancy’ and ‘modularity’ (Sargut and McGrath 2011; Sullivan 2011). State economic institutions such as the Bank of England (Haldane 2009) have also begun to use such terminology. This book is about how scientists think about complex systems and about what makes these systems special.

However, there is confusion in some of the discussions in the professional and scientific literature, and clarity is needed to facilitate the application of complexity science to problems in science and society. There is no agreement about the definition of ‘complexity’ or ‘complex system’, nor even about whether a definition is possible or needed. The conceptual foundations of complexity science are disputed, and there are many and diverging views among scientists about what complexity and complex systems are. Even the status of complexity as a discipline can be questioned given that it potentially covers almost everything.

Most sciences admit of informative definitions that are easy to state. For example, biology is the study of living systems, chemistry is the study of molecular structure and its transformations, economics is the study of the allocation of scarce resources that have different possible uses, and physics is the study of the most basic behaviour of matter and radiation. Complexity science is the study of complex systems, and, while it may be difficult exactly to define 'life', 'matter' and the other things just mentioned, to say what complex systems are is even harder. There is no agreement about what complexity is, whether it can be measured, and, if so, how, and there is no agreement about whether complex systems all have some common set of properties.

There are examples that everyone agrees are complex systems, but there are also many disputed cases. For example, some people regard a purely physical system like the solar system as a complex system (Simon 1976), while others think that complex systems must display adaptive behaviour (Holland 1992; Mitchell 2011), so only systems that have functions and goals can be complex.[1] The rest of this section states clearly what can be said about complexity science that is not contentious, beginning with the limitations of the rest of science that make it necessary.

Knowledge of physics and chemistry has enabled us to control many aspects of the world. The fundamental laws of mechanics and electromagnetism have a beautiful simplicity and incredible predictive accuracy. The atomic theory of matter, according to which all the material things we see around us are composed of elements like carbon and oxygen, can be used to understand the physical components of every chemical substance. However, many phenomena are very messy, and the behaviour of many systems, even relatively simple ones, is very hard to describe in detail. For example, the flow of turbulent water and the formation of a snow crystal are incredibly intricate phenomena involving a huge number of variables (a single snow crystal contains around 10^{18} molecules). Although fantastic progress has been made in computation and simulation, measuring and calculating the state of every molecule in a real snow storm is not remotely feasible.

Furthermore, the physics and chemistry of atoms and molecules cannot be used to predict individual people's actions, where the stock market will be tomorrow, or what the weather will be next week, because they cannot be directly applied to such problems at all. People, markets,,the atmosphere, and their properties are described by psychology, economics and climatology respectively. Even within physics there are many levels of description of entities and processes at very different length and time scales, from the

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[1] The term used in much of the literature is 'complex adaptive behaviour', but we drop the word 'complex' . A similar point was made by Murray Gell-Mann (1994, p. 27).

protons and electrons in the standard model of particles, to stars and galaxies in astrophysics. There is a lot of science that links the phenomena at different scales. For example, quantum chemistry links chemical reactions to the electromagnetic interactions between subatomic particles, and the kinetic theory of gases links the pressure and temperature of gases to the collisions and motions of their molecules. However, it is impossible to describe the solar system just using fundamental physics.

In general, collections of things can have different kinds of properties to their parts. For example, properties like pressure do not pertain to individual molecules but to gases. In a macroscopic sample of a gas, there are billions upon billions of molecules and many collisions and motions. If the gas is in a sealed container, then all these processes automatically make the gas approximately obey three laws. One of them is Boyle's law, stating that the pressure is inversely proportional to the volume at a fixed temperature. These 'ideal' gas laws relate the properties of pressure, volume and temperature independently of the kind of gas and regardless of the exact and incredibly complicated behaviour of the particles, all of which are extremely fast and short-lived compared to the time scale of the behaviour of the whole gas. (They are called 'ideal' because real gases do not obey them exactly.) Sometimes systems obey laws that are general and allow us to neglect almost all the details, and in this way simplicity can come from something very complicated.

There is no need to believe that some mysterious new ingredient has to be added to molecules to make gases. Gases and their properties are the result of the relations and interactions among the parts of the gas. If the sum of the parts is taken to be just the collection of the parts as if they were in isolation from each other, then the whole is more than the sum of the parts. However, the interactions of the parts are all it takes to make the whole exist. One of the most fundamental ideas in complexity science is that the interactions of large numbers of entities may give rise to qualitatively new kinds of behaviour different from that displayed by small numbers of them, as Philip Anderson says in his hugely influential paper, 'more is different' (1972).

When whole systems spontaneously display behaviour that their parts do not, this is called 'emergence'. Even relatively simple physical systems, such as isolated samples of gases, liquids and solids, display emergent phenomena in the minimal sense that they have properties that none of their individual molecules have singly or in small numbers. However, there are many different kinds of emergence that are much more intricate – for example, when systems undergo 'phase transitions', such as turning from liquid to solid or from insulator to superconductor. Phase transitions and associated 'critical phenomena' are examples of spontaneous self-organisation, in which physical systems are driven from the outside and there is emergent order to their behaviour. Systems can be driven by heat, for example, and also by a flow of matter. The famous Belousov-Zhabotinsky reaction produces patterns of different coloured chemicals that oscillate as long as more reagents are added. Such examples show that there are many rich forms of emergent behaviour in nonliving systems and that *nonliving systems can generate order*.[2] (These examples and those of some living systems mentioned below are explained in Chapter 2.)

Biological systems display many further examples of emergence, including metabolism and the coding for proteins in DNA, the representation of the state of the environment by perceptual systems, and adaptive behaviour like foraging and the rearing of offspring. Emergence in collectives of organisms includes the social behaviour found, for example, in beehives and ant colonies, which are in some ways like a single meta-organism, and elephant herds and primate groups, whose societies can be very sophisticated. There are cases of collective motion being directed by a privileged individual, such as a herd of horses following the leading mare. However, a flock of birds moves as a whole without a special individual leading it. Similarly, when social insects make decisions, such as bees collectively flying off to a new nest, they do so without one individual playing any special role in the group. Instead, their collective behaviour arises just as a result of their interactions and the feedback between their responses to each other's behaviour. A central idea in complexity science is that complex systems are spontaneous products of their parts and the interactions among them. Individual ants and small numbers of them just wander around aimlessly, but in large numbers they build bridges, maintain their nests and even grow fungi in them. This is another of the lessons of complexity science. *Coordinated behaviour does not require an overall controller*.

There is sometimes an underlying simplicity to the production of coordination and order that can be put in mathematical terms. It is surprising that the collective motion of a flock of birds, a shoal of fish, or a swarm of insects can be produced by a collection of robots programmed to obey just a couple of simple rules (Hamann 2018). Each individual must stay close to a handful of neighbours and must not bump into another individual. It regularly checks how close it is to others as it moves and adjusts its trajectory accordingly. As a result, a group moving together spontaneously forms. The adaptive behaviour of the collective arises from the repeated interactions, each of which on its own is relatively simple. This is another conclusion of complexity

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[2] For a discussion of emergence in physics see Butterfield (2011a,b).

science: *complexity can come from simplicity*.[3]

The ideal gas laws mentioned above as a very simple example of emergent behaviour are of limited application because they do not apply to real gases under many circumstances (for example, at very low temperatures or very high density or if a gas is compressed very quickly, heated very rapidly, or suddenly allowed to expand). Similarly, all sciences involve ways of approximating, idealising and neglecting details. For example, the law of the pendulum, which says that the time period of oscillation depends on the length of the string but not on the mass of the bob, applies only when the line connecting the bob to the pivot can be treated as being massless because it is so small compared to the mass of the bob. Similarly, Newton was able to work out the inverse square law of gravitation only because there is negligible friction to affect the motion of the planets, and their attraction for each other is negligible compared to the attraction of the sun. Even in such ideal circumstances, the equations describing how more than two bodies behave in general cannot be solved exactly and numerical methods must be used, or a restricted class of systems must be studied (Goldstein 1950).

Knowing how to model any complex system requires knowing what idealisations and approximations to make. Complexity science involves distinctive kinds of approximation and idealisation. For example, the Schelling model of segregation treats a population and its residences as a lattice of squares, each of which can be populated or not by one of two types of individuals (Schelling 1969). The system evolves according to the rule that individuals move on a given turn if and only if they are surrounded by fewer individuals of the same type than some specified number. The stable states of such systems are highly segregated, and in them most individuals are surrounded by others of the same type. These models show that segregation can arise even when individuals have a relatively mild preference for being near others they perceive to be in some way similar to themselves. This model can be applied not just to residence, but also to the formation of social networks (Henry et al. 2011).

Sometimes multiple approximations can be made, and different models of the same system often suit different purposes. For example, the nucleus of an atom can be modelled as a liquid drop, for the purpose of studying its overall dynamics, or with its component particles occupying shells analogous to those used to describe the atomic orbitals of electrons, for studying how it interacts with radiation. Similarly, there are very diverse models in complexity science. For example, economic agents can be modelled as computational agents whose states are updated according to rules describing flows of infor-

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[3] Strevens (2016) discusses the relationship between complexity and simplicity.

mation or as nodes in a network that are connected if two agents trade with each other. *Complex systems are often modelled as networks or information-processing systems.*

Complex networks can represent vastly different types of systems and the connections in a network may represent interactions of various kinds. For example, both the human body and a city can be modelled as a network with links representing the flow of energy, food and waste between many sites. However, networks do not represent only the flow of matter or energy, but also of information, causal influence, communication, services, or activation (among other things). In network models, the exact nature of the interactions may even be ignored when the properties of the system that are directly studied are the connections and interactions among the parts considered abstractly (Easley and Kleinberg 2010). In the biological and behavioural sciences models can be highly abstract – for example, graphs that only show ancestry relations – and highly idealised – for example, models of markets that treat agents as having perfect information.

While the interactions between the components in a network have some particular nature and are governed by the corresponding laws, often we can ignore the details about them, because the complex behaviour depends only on more abstract features of the interactions, such as how often they happen and between which parts. For example, in an economy, agents interact either face to face, or by post, or electronically, but how they interact is irrelevant beyond the implications for the timing and reliability of the exchange of information and resources. Similarly, each bird in a flock is an individual organism with a heart, a skin, eyes; it has an age, a certain size, and the need for food for survival and for procreation and many other things. But when scientists are studying collective motion, all that needs to be modelled is that the individuals in the group have a way of telling how close they are to each other. It is not important whether they do so by sight, like birds, or echolocation, like bats. The effect is the same, as long as they get the information somehow. Bees communicate by dancing when choosing where to make a new nest, but that is not important to the model of how the decision making occurs. Amazingly, the way your brain makes simple decisions is very similar, with neurons being analogous to bees. Such similarity is often captured by a common mathematical description of the different systems in question (more of this in Chapter 2 and Chapter 4). This is another important lesson of complexity science: *There are various kinds of universality and forms of universal behaviour in complex systems*.

Some complex systems involve billions upon billions of interactions between vast numbers of individuals. The complexity that can emerge is astonishing. Even the dynamics of the interactions of a thousand birds in a flock following two simple rules are beyond what a human being can calculate. Successful scientific modelling of the structure that can arise from repeated interaction requires computers. Without very powerful computers, it is impossible, for example, to collate all the data to map the flow of gas, electricity, water, people, and information in a city. Only for a few decades have we had the necessary computational power to analyse complex behaviour, simulate complex systems, and test hypotheses about how simple interaction rules and feedback produce complex behaviour. Even with vast computational power many complex systems are so complicated that making precise predictions about exactly what a particular system will do is practically impossible. Hence, predictions of real world complex systems are always of a statistical nature. In general, *complexity science is computational and probabilistic*.

Complexity science is often contrasted with reductive science, where the latter is based on breaking wholes into parts. This is misleading, because, as the rest of this book shows, complexity science always involves describing a system by describing the interactions and relations among its parts. The parts of complex systems interact by various mechanisms studied by individual scientific disciplines. Furthermore, the remarkable properties of complex systems arise because of the effects of the laws that govern the parts and their interactions. However, when there are many parts and they interact a lot, studying them requires other methods as well as those of the more fundamental science or sciences that describe the parts and involves new concepts and theories to describe the novel properties that the parts on their own do not display. In most complex systems, the interactions between the parts are of more than one kind. For example, there are both chemical and electrical interactions in the brain and both electromagnetic and gravitational interactions in galaxies. Hence, for these reasons, in complexity science often no single theory encompasses the system of interest.

Clearly complexity science would not be possible without the rest of science, and it involves combining theories from different domains and synthesising tools from various sciences. Complexity science does not involve revisions to fundamental laws, but it does involve the discovery of completely new implications of these laws for the behaviour of aggregates of systems that obey them. This is one reason why *complexity science involves multiple disciplines*. Scientific theories that have been studied and applied autonomously are integrated in a single context. Complexity science is therefore essentially interdisciplinary in both method and subject matter. It uses established scientific theories from whatever domain is relevant to the system at hand and then uses whatever resources are needed to combine them. Particular sciences provide different aspects of the explanation of the overall behaviour of the system. The relevant theories and the relations between them provide the basis for a new (complexity) theory of the system and new ways of explaining and predicting its features.

Complexity science combines the science specific to the kind of system being studied with mathematical theories, models and techniques from computer science, dynamical systems theory, information theory, network analysis and statistical physics. Much has been learned in this way about complex systems in neuroscience, cell biology, economics, astrophysics and many other sciences, and the techniques of complexity science are now essential for much of engineering, medicine and technology.

Understanding the nature of complex systems is made more difficult by the fact that complexity science studies both systems that produce complex structures and those structures themselves. Nature is full of beautiful patterns and symmetries, such as those of honeycombs, shells and spiderwebs, which are made by living systems. Intricate structures are also found in the nonliving world – for example, in the rings of Saturn or geometrical rock formations on Earth. *There is a difference between the order that complex systems produce and the order of the complex systems themselves.*

The most astonishing example of novel properties arising in a biological system is the human brain. Our mental life and consciousness somehow emerge from the electrical and biochemical interactions among neurons. Human beings and culture are the most complex systems of which we know, and there are layers upon layers of complexity within them: for example, the many individual actions that give rise to the single event of an election or a stock market crash; the intricate feedback between humans and the climate and the environment; and the incredible complexity of a city where millions of people live and interact from moment to moment. There are many kinds of interactions, such as business transactions, bus journeys, crimes, school classes, car crashes, and chats between neighbours. Yet simple predictable social behaviour does sometimes arise. For example, many diverse properties of cities from patent production and personal income to pedestrians' walking speed are approximated by functions of population size (Bettencourt et al. 2007).

The next section introduces the main question of this book and how to answer it. First, we repeat the core claims above.

The Truisms of Complexity Science

Truisms state the obvious. The following statements will not be obvious to everyone, but they will be to those working in complexity science. However, these truisms have not yet been stated clearly and explicitly. They are the starting point for the analysis of this book because they state the basic facts about the subject while being compatible with the very wide range of views about the nature of complexity science and complex systems found in the literature.

1. More is different.
2. Nonliving systems can generate order.
3. Complexity can come from simplicity.
4. Coordinated behaviour does not require an overall controller.
5. Complex systems are often modelled as networks or information processing systems.
6. There are various kinds of invariance and forms of universal behaviour in complex systems
7. Complexity science is computational and probabilistic.
8. Complexity science involves multiple disciplines.
9. There is a difference between the order that complex systems produce and the order of the complex systems themselves.

The truisms are all independent of each other. Number 6 is an important discovery of complexity science. Note also that numbers 5, 7 and 8 are not about complex systems themselves but the science that studies them. Numbers 6 and 9 are the least obvious and most in need of the articulation and argument given for them in Chapters 3 and 4.

1.1 What Is a Complex System?

Despite the lack of consensus about how to define complex systems and complexity, there is a core set of complex systems that are widely discussed throughout the literature. Chapter 2 presents some of these canonical examples of complex systems and highlights some of their distinctive and interesting characteristics. Then Chapter 3 discusses the concepts which are ubiquitous in the scientific literature about complexity and complex systems. Ten features associated with complex systems are identified. A distinction is made between the first four, which are conditions for complexity to arise, and the rest, which are the results of these conditions and indicative of various kinds of complexity. The examples of Chapter 2 are considered in an analysis of which features are necessary and sufficient for which kinds of complexity and complex system. The features are as follows:

1. Numerosity: complex systems involve many interactions among many components.
2. Disorder and diversity: the interactions in a complex system are not coordinated or controlled centrally, and the components may differ.
3. Feedback: the interactions in complex systems are iterated so that there is feedback from previous interactions on a time scale relevant to the system's emergent dynamics.
4. Non-equilibrium: complex systems are open to the environment and are often driven by something external.
5. Spontaneous order and self-organisation: complex systems exhibit structure and order that arises out of the interactions among their parts.
6. Nonlinearity: complex systems exhibit nonlinear dependence on parameters or external drivers.
7. Robustness: the structure and function of complex systems is stable under relevant perturbations.
8. Nested structure and modularity: there may be multiple scales of structure, clustering and specialisation of function in complex systems.
9. History and memory: complex systems often require a very long history to exist and often store information about history.
10. Adaptive behaviour: complex systems are often able to modify their behaviour depending on the state of the environment and the predictions they make about it.

Some people argue that no scientific concept is useful unless it can be measured. Many putative 'measures of complexity' have been proposed in the literature, and we review some of the most prominent in Chapter 4 (the Appendix summarises some of the mathematics used in these measures). We argue that none of them measure complexity as such, but they do measure various features of complex systems. We give examples of measures of almost all of the features of complexity listed above.

Chapter 5 considers complexity science in a wider philosophical and social context, summarising what we have learned and reflecting on it. We say what we think complex systems are, argue for our view, and draw consequences from it. We argue that a system is complex if it has some or all of spontaneous order and self-organisation, nonlinear behaviour, robustness, history and memory, nested structure and modularity, and adaptive behaviour. These features arise from the combination of the properties of numerosity, disorder and diversity, feedback and non-equilibrium. We argue that there are different kinds of complex system, because some systems exhibit some but not all of the features.

We argue that our review of the scientific literature shows that the ideas of complexity and complex systems are useful in the sense of aiding successful science. We distill what it is about complex systems that makes them hard to put in the language of the traditional disciplines and what can be gained in developing a new language for them. This language allows descriptions and prediction of complex systems and their behaviour and features that would otherwise be impossible. The complex systems discussed in this book, such as beehives, brains and the climate can be remarkably resilient, but they can also be very sensitive to disruption. Understanding them is vital for our survival. The final section of this chapter briefly reviews the history of complexity science.