Chapter 1

Two's Company, Three is Complexity

1.1 A definition, of sorts

Take a look in many dictionaries, and you will find Complexity defined along the lines of "The behavior shown by a Complex System". Then look up "Complex System", and you will probably see "A system whose behavior exhibits Complexity". So what's going on? Well, unfortunately, Complexity is not easy to define. Worse still, it can mean different things to different people. Even among scientists, there is no unique definition of Complexity. Instead, the scientific notion of Complexity – and hence of a Complex System – has traditionally been conveyed using particular examples of real-world systems which scientists believe to be complex.

This book will take the "complex" out of Complexity, by going to the heart of what connects together all real-world Complex Systems. We will uncover the magic ingredients which make something complex as opposed to just being complicated, and show how Complexity is deeply engrained in our own everyday lives. We will also see why Complexity is set to revolutionize our understanding of science, and help resolve some of the most challenging problems facing society as a whole.

Complexity can be summed up by the phrase "Two's company, three is a crowd". In other words, Complexity Science can be seen as the *study of the phenomena which emerge from a collection of*

interacting objects – and a crowd is a perfect example of such an *emergent phenomenon*, since it is a phenomenon which emerges from a collection of interacting people. We only have to look at world history to realize that it is riddled with major events which have been driven by human crowd behavior. Everyday examples of crowds include collections of commuters, financial market traders, human cells, or insurgents – and the associated crowd-like phenomena which emerge are traffic jams, market crashes, cancer tumors, and guerilla wars. Even extreme weather conditions such as floods, heatwaves, hurricanes, and droughts can be seen as a sort of crowd effect, since they emerge from the collective behavior of "packets" of water and air in the form of oceans, clouds, winds and air moisture. And if we add to this the collective actions of humans – in particular, the environmental changes caused by human activity – we conjure up the controversial emergent phenomenon known as "global warming".

1.2 Complexity in action

At the heart of most real-world examples of Complexity, is the situation in which a collection of objects are competing for some kind of limited resource – for example, food, space, energy, power, or wealth. In such situations, the emergence of a crowd can have very important practical consequences. For example, in a financial market, or the housing market, the spontaneous formation of a crowd of people who wish to sell – and hence are effectively competing for buyers – can lead to a market crash in which the price falls dramatically in a short time. A related crowd phenomenon occurs among commuters who are competing for space on a particular road at the same time. This leads to a traffic jam, which is the traffic equivalent of a market crash. Other examples include Internet overloads and power blackouts, in which subscribers simultaneously decide to access and hence exhaust the available resources of a particular computer system or power network. Even wars and terrorism can be viewed as the collective, violent actions of different groups of people who are fighting for control of the same resources, e.g. land or political power.

The Holy Grail of Complexity Science is to understand, predict and control such emergent phenomena – in particular, potentially catastrophic crowd-like effects such as market crashes, traffic jams, epidemics, illnesses such as cancer, human conflicts, and environmental change. Are they predictable in any way, or do they just appear out of nowhere without warning? Can they be controlled, manipulated or even avoided?

What is remarkable about such emergent phenomena, is that they can arise in the absence of any central controller or coordinator. Just think about the level of coordination and communication which some central controller would actually require in order to be able to recreate a particular traffic jam. In other words, imagine the number of cell-phone calls he would have to make to ensure that all the drivers were on the same road at the same time, and in one particular pattern. It simply couldn't be done in a reliable way. This represents a universal feature of Complex Systems: emergent phenomena can arise without the need for an "invisible hand". Instead, the collection of objects is able to self-organize itself in such a way that the phenomenon appears all by itself – as if by magic.

The sheer power and momentum of these emergent phenomena can also be quite remarkable. We all know how easy it is to be swept up in the ebbs and flows of mob mentality – whether intentionally or unintentionally. Recent decades such as the 1970s delivered cultural tsunamis in terms of fashions and hairstyles: just think flared trousers and platform shoes. In the 1990s, we had the infamous dot-com boom with company employees agreeing to be paid in stock options rather than hard cash – only to find themselves penniless when the bubble burst around April 2000. And who hasn't had the experience of wandering along a busy street in the middle of a crowd of people, only to find yourself separated from your companions and going in a direction you don't actually want to go? We each seem to have an innate urge to join in with a crowd – but it may not be the best decision from our individual perspective. Just think of selling or buying a house or car. You will get a far better price if you sell when everybody else is buying, and vice versa.

It is not just collections of people that show emergent phenomena. The animal, insect and fish kingdoms are awash with

examples of self-organization: from ant-trails and wasp swarms through to bird flocks and fish schools. In fact, biology is sitting on a treasure-chest of such collective phenomena – from the immune system's collective response to invading viruses through to intercellular communication and signalling which drives many important biological processes. The fact that all these effects represent emergent phenomena explains why so many different disciplines are getting interested in Complexity.

Closer to everyone's personal concerns – and indeed, worries – is the area of human health and medicine. This is a prime example of Complexity in action. Our immune system consists of a collection of defense mechanisms for dealing with invading viruses. However just like the traffic, the stock market and the Internet, the system can go wrong all by itself – for example, when the collective response of the immune system ends up attacking healthy tissue. Hence understanding the extent to which we can predict, manage and even control a Complex System has particular importance from the perspective of human health. Indeed it may even lead to new forms of treatment whereby the collective responses of the body are harnessed to deal with a specific problem in a particular organ, rather than relying on one particular targeted therapy. A cancer tumor is a particularly horrific example of a crowd effect gone wrong. Instead of staying in check, cells begin to multiply uncontrollably – and just as with other Complex System phenomena such as traffic jams, it becomes very hard to know what to do to reduce the size of the tumor without causing some even more damaging secondary effects. For example, any treatment which involves damaging the tumor may indirectly lead to the survival of the fittest, most malignant cells.

Interest in Complexity is not confined to natural objects such as people, animals or cells. The ability of a collection of objects to produce emergent phenomena without the need for some central controller, has attracted the attention of researchers at NASA. In particular, Kagan Tumer and David Wolpert have been leading a research team at Ames Research Laboratory in Mountain View, California which is looking at emergent phenomena in collections of machines. The machines in question could be robots, satellites, or even micro-spacecraft. For example, NASA are investigating the possibility that a collection of relatively simple robots can be used to explore the surface of a planet in a fast and efficient manner – as opposed to using one large and far more complicated machine. They have a good reason for doing this. If one robot in this collection were to malfunction, there would still be plenty more available. By contrast, a single malfunction in the large machine could lead to the immediate termination of a very costly mission. This also explains NASA's interest in exploring the properties of collections of simple satellites, as opposed to one large sophisticated one – and also collections of micro-spacecraft as opposed to one much larger one.

But there is another, far more intriguing reason that NASA is interested in such research. Most NASA missions are likely to involve sending machines to distant planets – and it is hard to maintain reliable communication channels over such distances. It would therefore be wonderful if NASA engineers could just sit back, relax and let the machines on the planet sort it out for themselves. This would of course land the machines with the same difficulty as we have when trying to arrange a lunch-date by phone with a group of friends. Judging from what typically happens with the lunch-date problem, you might think that one of the machines would simply end up acting as the local coordinator, checking one-by-one the position and availability of each machine and then coordinating their actions. This sounds like it should work fine – however, the collection of machines would then be reduced to having the same vulnerability as a single sophisticated machine. If the local coordinator malfunctions, the mission is once again over. Instead, the "killer application" aspect of such a collection of machines, and hence the interest in such Complex Systems within NASA, is that it is not necessary for the machines to have local coordination in order for them to do a good job. It turns out that a suitably chosen collection of such objects can work *better* as a group if they are not being coordinated by some single controller, but are instead competing for some limited resource – which is actually NASA's case, since there will typically be relatively few loose rocks available for picking up within a given area of a planet's surface.

A busy shopping mall provides a nice everyday example of why such a collection of selfish machines could be so useful.

Imagine that you have dropped a one-hundred dollar bill. You organize a search-team, stating that they will all share the money when it is found. If the search-team is a large one, you will have great difficulty in coordinating everybody's actions – hence you might never find the money. By contrast, if you tell everyone that the money is theirs if they find it, their individual selfish drive will likely be so strong that the money is found very quickly. In the sense that dropped bills are like available rocks, we can see that the collective action of selfish machines could be used to solve quite a complicated search problem.

There are even research groups investigating how such a collection of machines might design itself, by allowing the individual machines to adapt and evolve of their own accord. This research borrows ideas from real-world situations involving collections of humans. After all, humans acting in the setting of a financial market are doing nothing other than competing for a limited resource in a selfish way – exactly like the machines. The same applies for drivers in traffic: it is because of their competition for space on a road that we typically see arrangements of cars which are spread out in some reasonably regular pattern.

Now, if you are reading this book on a plane, you might want to take a deep breath. The increasingly high-tech nature of on-board computer systems means that each next-generation aircraft will itself be a Complex System – a Complex System which needs to be managed and controlled. But as well as creating a challenge in itself, ideas from Complexity are being harnessed to develop novel designs for such aircraft. For example, Ilan Kroo and co-workers at Stanford University have been looking at lining the back of conventional aircraft wings with a collection of robotic microflaps. The design is such that the flaps compete to be orientated in the right direction at the right time, according to the plane's planned trajectory – just like our selfish shoppers would compete to be in the right place at the right time in order to pick up the lost money. A central controller, which in this context is an aircraft pilot, would therefore no longer be needed. Now, the possibility of pilot-less planes might sound scary, but apparently many people would indeed be willing to fly in such an aircraft as long as it is cheap – and as long as their bags turn up on time.

And while we are in the air, what about those air conditions? More generally, what about the effects of our own collective actions on our environment and weather? Global competition for increasingly scarce natural resources is leading to increased levels of pollution and deforestation, and these may in turn affect our climate. The weather results from a complicated ongoing interaction between the atmosphere and oceans, connected as they are by currents of water, winds and air moisture. Floods, hurricanes, and droughts represent extreme phenomena which emerge from this collective behavior. Although scientists know the mathematics which describes individual air and water molecules, building up a picture of what billions of them will do when mixed together around the globe is extremely complicated. Now add on top of this the collective actions of human beings, and you come up against the emergent monster of global warming – and in particular, the complex question of evaluating how the Earth's climate is affected by the collective actions of its inhabitants, and what can then be done about it.

So that is Complexity in action – from technology, to health, to everyday life. But does it play any role in fundamental science, and in particular fundamental Physics? Well, it turns out that it does – and in a very big way. When you get down to the level of atoms, the range of emergent phenomena is simply breathtaking. Electrons are negatively charged particles which typically orbit the nucleus in an atom. However if you put together a large collection of such electrons, you will uncover a wealth of exotic crowd effects: from superconductivity through to effects such as the so-called Fractional Quantum Hall Effect and Quantum Phase Transitions.

It doesn't stop there. If we take just two particles such as electrons, they can show a particular type of "quantum crowd effect" called entanglement. This is an emergent phenomenon which is so bizarre that it kept Einstein baffled for the whole of his life. Indeed the information processing power underlying such a quantum crowd is so powerful that it has led to proposals for a quantum computer, which is a fundamentally new type of computer that is light years ahead of any conventional PC; quantum cryptography, which can yield completely secure secret codes; and quantum

teleportation. There is even the possibility that such effects are already being exploited by Mother Nature herself – but more of that in chapter 11.

Even the fundamental physics of Einstein's space–time and Black Holes doesn't escape the hidden clutches of Complexity. At the very heart of Einstein's theories of relativity was the idea that space and time are coupled together. Another way of saying the same thing is that two pieces of space and time can interact with each other by means of light passing between the two. Hence the entire fabric of space–time is a complicated network of interconnected pieces. In chapter 5 we will look more closely at networks in general – suffice to say that they are just another way of representing a set of objects that are interacting, i.e. they are just another way of representing a Complex System.

In all of these examples, the precise nature of the crowd-like phenomena which emerge will depend on how the individual objects interact and how interconnected they are. It is extremely difficult, if not impossible, to deduce the nature of these emergent phenomena based solely on the properties of an individual object. For this reason, it is pretty much true that every new crowd effect which is found involving fundamental quantum particles such as electrons, leads to a Nobel Prize in Physics. Even though we understand the properties of a single electron, for example, the corresponding emergent phenomena from a collection of them tend to be so surprising that each one represents a remarkable new discovery by itself. On an everyday level, we know that market crashes and traffic jams can also be surprising – both in their form and in terms of when they occur and how long they last. Given this difficulty in predicting what crowd effects will arise, under what conditions and when, we can begin to see how Complexity Science might also be referred to as the science behind surprise.

So it seems like Complexity has many possible applications across the sciences, medicine and in our everyday world. Whether you are interested in fundamental physics, biology, human health, or you just want to avoid traffic jams on your way home from work, Complexity is key.

1.3 Why is my own life so complex?

It is 6 p.m. You are leaving work – and the only thing on your mind is to get home quickly. But which route should you take? It turns out you have a choice. But so does everybody else. And this is the point: the best route is the one which is the least crowded – but it is the collective decisions of everyone else which determine which of the possible routes this turns out to be. In effect you are not deciding between routes home – you are instead trying to out-guess everyone else. In other words, you are trying to out-guess the crowd in the competition for space on the road. Of course, everyone else is trying to do the same. Thinking back to our earlier discussion, this everyday situation represents an ideal candidate Complex System since it comprises a collection of objects (drivers) competing for a limited resource (road space).

But your complex life doesn't stop there. You get home, eventually, and decide you would like to go out to relax. You want to go to a particular bar – but let's assume that this bar has a limited capacity and so not everyone who turns up may actually get in. You yet again find yourself having to decide which choice to make: do you make the effort to get ready, get to the bar and run the risk that you won't get in? Or do you stay at home and run the risk that you are missing a great night out? Since the bar has a limited capacity, and yet is so popular that there are lots of potential attendees, you are again trying to out-guess the crowd. In particular, you are trying to predict whether the bar will be over-capacity or not, and hence what your action should be. Everyone else is trying to do the same. So this is again an ideal candidate Complex System since it comprises a collection of objects (bar-goers) competing for a limited resource (a place in the bar).

Say you decide not to go. Instead you will cook a nice meal at home. But you need to buy food. Where should you go? There are two supermarkets, one called "zero" and the other called "one", on opposite sides of the town. Which will be least crowded? It is again the same situation of competition for a limited resource – in this case, space in the market.

Things don't get better when, following the meal, you decide to go online and review the stock that you bought a year ago. You

get the price chart up on your screen. The stock's price has gone up and down – but what is that telling you? Should you buy more stock, or sell the stock you already have? Suppose you decide to sell. If everyone else also decides to sell, there will be a sudden oversupply of these shares. Nobody would then pay you very much for them. On the other hand if you manage to sell at a moment when there are lots of buyers, you will be laughing. The same holds for selling things on any other market, from housing through to eBay. Even though you may be buying or selling based on some long-term preference or need, the decision of exactly when to buy or sell is a strategic one – and is dominated by the need to predict what everyone else will do. In other words, you must once again try to out-guess the crowd. Everybody else is again trying to do the same, and obviously not everybody can win. As a result, we once more have an ideal candidate system for Complexity since we have a collection of objects (investors) competing for a limited resource (a favorable price).

When you start to think about it, there are loads of examples from our everyday lives where, in one form or another, we are indirectly trying to out-guess what everyone else will do. And unfortunately for all of us, the correct action in such situations is determined by what everybody else actually does. What is worse is that such everyday problems are repeated over and over again, as each day goes past. This then tempts us to try to learn from the past and hence adapt our strategies to try to improve our chances of coming out on top. In other words, our daily life becomes a sequence of ongoing games – a sort of multiple "rat race".

This common everyday situation in which a collection of objects (people) repeatedly compete for some kind of limited resource, illustrates the complexities of everyday life extremely well – a fact that was first pointed out by Brian Arthur and later by John Casti, both of the Santa Fe Institute in New Mexico. But even more remarkable is the fact that it also provides us with a generic Complex System which can be adapted to describe a wide range of scientific, medical, and technological scenarios. We have already discussed various applications in section 1.2 in connection with the design of collections of machines – and as we move further through the book, we will see this same generic set-up reappearing in various guises.

1.4 The key components of Complexity

There is no rigorous definition of Complexity. But that isn't so bad – after all, it is hard to define a word such as "happiness" and yet we all know what its characteristics are. We will characterize Complexity in a similar way by describing the features which a Complex System should have, and looking at the behaviors which it should then show. This might sound very abstract – but fortunately the everyday scenarios that we have discussed come straight to our rescue. Indeed it will turn out that these characteristics are the very same ones that make our own everyday lives so complex.

Most Complexity researchers would agree that any candidate Complex System should have most or all of the following ingredients:

The system contains a collection of many interacting objects or "agents". In the case of markets, these are traders or investors. In the case of traffic, these are drivers. Typically the scientific community refers to such objects as agents. Interactions between these agents may arise because the agents are physically close to each other, or because they are members of some sort of group, or because they share some common information. For example, the agents may be linked together by some public information that they share – like investors who are watching the same price chart for a given stock, or commuters who are listening to the same traffic report on the radio. On the other hand, some agents may be linked together by private information, like two investors who happen to be friends sharing private information over the phone. To the extent that the agents are linked together through their interactions, they can also be thought of as forming part of a network. For this reason, networks have become an integral part of Complexity Science, together with the study of collections of agents. Indeed for many scientists in the community, the study of Complexity is synonymous with the study of agents and networks together.

These objects' behavior is affected by memory or "feedback". This means that something from the past affects something in the present, or that something going on at one location affects what is happening at another – in other words, a sort of knock-on effect. For example, if you happened to have taken Route 0 home for the past few nights and it was always overcrowded, you may choose to flip to Route 1 tonight. Hence you have used information from the past to influence your decision in the present – in other words, the past has been fed back into your present decision. Of course the nature of this feedback can change with time. For example, you may care less about past outcomes if it is the start of the week as opposed to the end of it. The net result of everyone having such memory can be that the system as a whole also remembers. In other words, a particular global pattern or sequence appears in the traffic or in the stock market.

The objects can adapt their strategies according to their history. This simply means that an agent can adapt its behavior by itself, in the hope of improving its performance.

The system is typically "open". This means that the system can be influenced by its environment, just like a market might be affected by outside news about the earnings of a particular company – or the traffic is affected by the closure of a particular road. By contrast, a closed system means one which is not in contact with the outside world – sort of like an office on a desert island with no Internet. And just like it sounds, such truly closed systems are rare. Much more common are systems that in some way are in contact with the outside world. In fact, the only truly closed system is the Universe as a whole. The trouble is, as we will see in chapter 2, that most fundamental theories in Physics only apply to closed systems. This is one reason why Complex Systems are so interesting not just to engineers, biologists and social scientists, but also to theoretical physicists.

The resulting system – a Complex System – will then show the following behaviors, all of which are characteristic of Complexity:

The system appears to be "alive". The system evolves in a highly non-trivial and often complicated way, driven by an ecology of agents who interact and adapt under the influence of feedback. For example, financial analysts often talk as though the market were a living, breathing object, assigning it words such as pessimistic or bearish, and confident or bullish.

The system exhibits emergent phenomena which are generally surprising, and may be extreme. In scientific terminology, the system is far from equilibrium. This basically means that anything can happen – and if you wait long enough, it generally will. For example, all markets will eventually show some kind of crash, and all traffic systems will eventually have some kind of jam. Such phenomena are generally unexpected in terms of when they arise – hence one aspect of surprise. But the system will also tend to exhibit emergent phenomena which are themselves surprising in that they could not have been predicted based on a knowledge of the properties of the individual objects. For example, no amount of understanding of the properties of water molecules could have led to the prediction that an iceberg would form and sink the *Titanic* as it passed. In terms of emergent phenomena such as market crashes and traffic jams, an important question concerns whether these extreme events might result from a sort of comedy of errors, like one domino knocking over another. For example, in the animated movie "Robots!" one small domino falling over eventually leads to a tidal wave of dominos – a sort of domino tsunami – upon which Mr. Bigwell and the other robots ended up surfing.

The emergent phenomena typically arise in the absence of any sort of "invisible hand" or central controller. In other words, a Complex System can evolve in a complicated way all by itself. For this reason, Complex Systems are often regarded as being more than the sum of their parts which is just another way of saying "Two's company, three is a crowd". Given that the Universe itself is a Complex System of sorts, this feature deals a damaging blow to proponents of so-called Intelligent Design.

The system shows a complicated mix of ordered and disordered behavior. For example, traffic jams arise at a particular point in time and at a particular place on a road network, and then later disappear. More generally, all Complex Systems seem to be able to move between order and disorder of their own accord. Put

another way, they seem to exhibit pockets of order. We return to this point later in the book.

1.5 Complexity: the Science of all Sciences

But what is the value added by Complexity? After all, Complexity Science is only really of value if it can add new insights or lead to new discoveries – for example, by uncovering connections between phenomena which were previously considered unrelated. There is no point inventing a new name if we are just repackaging things that we already know. You might, for example, think that all the things that scientists traditionally look at are already sufficiently complicated to qualify as Complexity Science. As we shall see in later chapters, it is certainly true that many of the systems which scientists already study could be labelled as complex according to our list. However, the *way* in which scientists have traditionally looked at these systems does not use any of the insight of Complexity Science. In particular, the connections between such systems have not been properly explored – particularly between systems taken from different disciplines such as biology and sociology. Indeed it is fascinating to see if any insight gained from having partially understood one system, say from biology, can help us in a completely different discipline, say economics. One particular example of this is the ongoing research of Mark Fricker, Janet Efstathiou and Felix Reed-Tsochas at Oxford University, in which they analyze the nutrient supply-lines in a fungus in order to see whether lessons can be learned for supply-chain design in the retail trade.

In an everyday context, the negative effect of overlooking similarities between supposedly unrelated systems, is akin to someone becoming an expert on the detailed cultural life of New York, Washington, and Boston – yet never realizing that these cities have a shared culture because of their location on the East Coast of the United States. Unfortunately such bridge-building is doubly difficult in a scientific context, because no individual scientist can possibly know the details of all the other research fields which might be relevant. This not only holds up the advance of Complexity

Science as a whole, but it also reduces the chances of new breakthroughs in our understanding of important real-world systems.

Much of traditional Physics has dealt with trying to understand the microscopic details within what we see. This has led to physicists smashing open atoms to look at the bits inside, and then smashing these bits open to see the bits inside the bits – eventually getting down to the level of quarks. It is certainly complicated – but this reductionist approach is in a sense the opposite of what Complexity is all about. Instead of smashing things apart to find out what the components are, Complexity focuses on what new phenomena can emerge from a collection of relatively simple components. In other words, Complexity looks at the complicated and surprising things which can emerge from the interaction of a collection of objects which themselves may be rather simple. Hence the philosophical questions driving Complexity Science are similar to those for the manufacturers of a toy like LEGO: starting with a set of quite simple objects, what can I make out of them, and what complicated and surprising things can I make them do? And what happens if I change one piece for another, does that change the types of things I can make? If I am missing a few pieces, or I add a few specialist pieces, how does that change the spectrum of possible things that can be built?

Going further, the underlying philosophy behind the search for a quantitative theory of Complexity is that we don't need a full understanding of the constituent objects in order to understand what a collection of them might do. Simple bits interacting in a simple way may lead to a rich variety of realistic outcomes – and that is the essence of Complexity.

Complexity therefore represents a slap in the face for traditional reductionist approaches to understanding the world. For example, even a detailed knowledge of the specifications of a car's engine, colour and shape, is useless when trying to predict where and when traffic jams will arise in a new road system. Likewise, understanding individuals' personalities in a crowded bar would give little indication as to what large-scale brawls might develop. Within medical science, it is likely that no amount of understanding of an individual brain cell is likely to help us understand how to prevent or cure Alzheimer's disease.

So what have we got so far? We have seen why Complexity is likely to be important not only for many areas of science, but also across many other disciplines and indeed everyday life. In particular, we have seen that its role in making connections between previously unrelated phenomena taken from distinct scientific disciplines is likely to be a very important one. For this reason, we can justifiably think of Complexity as a sort of umbrella science – or even, the Science of all Sciences.