Simply Complexity

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Preface

It is 2050, and you are watching *Who Wants to be a Billionaire?* The contestant is one question away from the jackpot. Up comes his question: "What is the name of the theory that scientists started developing at the beginning of the twenty-first century, and which helped the world overcome traffic congestion, financial market crashes, terrorist attacks, pandemic viruses, and cancer?" The contestant cannot believe his luck. What an easy question! But he is so nervous that his mind temporarily goes blank. He starts to consider option A: "They are all still unsolved problems" – but then quickly realizes that this is a dumb answer. Instead, he uses his last lifeline to ask the audience. The audience responds unanimously and instantaneously with option B: "The Theory of Complexity". Without hesitation, he goes with option B. The host hands him the cheque, and the world has yet another billionaire.

Pure fantasy? Maybe not.

In this book, we will go on a journey to the heart of Complexity, an emerging science which looks set to trigger the next great wave of advances in everything from medicine and biology through to economics and sociology. Complexity Science also comes with the prospect of solving a wide range of important problems which face us as individuals and as a Society. Consequently, it is set to permeate through every aspect of our lives.

There is, however, one problem. We don't yet have a fully-fledged "theory" of Complexity. Instead, I will use this book to assemble all the likely ingredients of such a theory within a common framework, and then analyze a wide range of real-world applications within this same common framework. It will then require someone from the future – perhaps one of the younger readers of this book – to finally put all these pieces into place.

Complexity Science is a double-edged sword in the best possible sense. It is truly "big science" in that it embodies some of the hardest, most fundamental and most challenging open problems in academia. Yet it also manages to encapsulate the major practical issues which face us every day from our personal lives and health, through to global security. Making a pizza is complicated, but not complex. The same holds for filling out your tax return, or mending a bicycle puncture. Just follow the instructions step by step, and you will eventually be able to go from start to finish without too much trouble. But imagine trying to do all three at the same time. Worse still, suppose that the sequence of steps that you follow in one task actually depends on how things are progressing with the other two. Difficult? Well, you now have an indication of what Complexity is all about. With that in mind, now substitute those three interconnected tasks for a situation in which three interconnected people each try to follow their own instincts and strategies while reacting to the actions of the others. This then gives an idea of just how Complexity might arise all around us in our daily lives.

While I was writing this book, I had the following "wish-list" in my head concerning its goals:

1. To provide a book which a wide cross-section of people would want to read and would enjoy reading – regardless of age, background or level of scientific knowledge.
2. To introduce readers to the exciting range of real-world scenarios in which Complexity Science can prove its worth.
3. To provide the book on Complexity that "I never had but always

needed". In other words, to provide an easily readable yet thorough guide to this important scientific revolution.

4. To provide a book that my kids could read – or rather, a book that they would actually *choose* to read all by themselves. This is a very important goal, since Complexity will likely become *the* science of interest for future generations.
5. To provide a book which is just as readable on a plane or bus as in a library. As such, it should also make sense when read in short chunks.
6. To provide a book which provides professional scientists, economists, and policy-makers with a new perspective on open problems in their field, and to help stimulate new Complexity-based interdisciplinary research projects.

However, as I finish the book and offer it up to potential readers, I realize that the above wish-list can essentially be reduced to just one item: I would wish that you enjoy reading this book, and that it might provide you with fresh thoughts and insights for dealing with the complex world in which we live, and which our children will inherit.

There are some practicalities concerning the book's content and layout which I would like to explain. The language, examples and analogies are kept simple since the focus of the book is to explain *what* Complexity Science is all about, and *why* it is so important for us all. I therefore avoid delving into too much detail in the main text. Instead, the Appendix describes how to access the technical research papers upon which the discussions in the book are based, and gives a list of Internet websites containing additional information about Complexity research around the world. Having said this, I won't pull any punches in the sense that I tackle all the topics which I believe to be relevant. Part 1 of the book takes us through the theoretical underpinnings of Complexity, while Part 2 delves into its real-world applications. Some of the territory is only just beginning to be explored, with very few answers available for the questions being posed. From the perspective of other scientific revolutions throughout history this might seem to be par for the course. However we are not talking about history here – instead, we are looking at work which is emerging at the forefront of a new discipline. For this reason we will be highlighting where such research is heading, rather than where it has been.

But why should you believe what I write about Complexity? This is a crucially important question given that Complexity Science is still being developed and its potential applications explored. Unfortunately many accounts of Complexity in the popular press are second-hand, i.e. they are typically written by people who have done little, if any, research on Complexity themselves and are instead reporting on their interpretation of other people's work. Given the relatively immature nature of the field, I believe that such indirect interpretations are potentially dangerous. For this reason, I will base the book's content around my own research group's experience in Complexity. This has various advantages: (i) it reflects my own understanding of the Complexity field; (ii) it represents what I believe to be the most relevant and important topics; (iii) it will hopefully give the reader a sense of what it is like to be at the "pit-face" in such a challenging area of research; and (iv) it ensures that any reader can challenge me directly on any claims that I make, and can demand an informed answer. To facilitate this process of public scrutiny, a complete list of the relevant scientific research reports is presented in the latter part of the Appendix. I also encourage any readers who wish to email me with questions, to do so at n.johnson@physics.ox.ac.uk

Finally I would like to thank most warmly the following highly talented scientists with whom I am fortunate to enjoy ongoing interactions on Complexity: Pak Ming Hui, Luis Quiroga, Ferney Rodriguez, Mike Spagat, Jorge Restrepo, Elvira Maria Restrepo, Roberto Zarama, Derek Abbott, Chiu Fan Lee, Tim Jarrett, Alexandra Olaya Castro, David Smith, Sean Gourley, Sehyo Charley Choe, Douglas Ashton, Mark McDonald, Omer Suleman, Nachi Gupta, Nick Jones, Ben Burnett, Alex Dixon, Tom Cox, Juan Pablo Calderon, Juan Camilo Bohorquez, Dan Reinstein, Mark Rondeau, Paul Summers, Stacy Williams, Dan Fenn, Richard Ecob, Adrian Flitney, Matt Berryman, Mark Fricker, Philip Maini, Sam Howison, Tim Halpin-Healy, David Wolpert and Kagan Tumer. In particular, I would like to specifically mention Felix Reed-Tsochas and Janet Efsthatiou, who are also my fellow co-directors in Oxford University's inter-departmental complex systems research group. Many of the above-named scientists have played a fundamental role in the research discussed in this book – I have indicated their contributions explicitly where appropriate. I am also very grateful to Marsha Filion at Oneworld Publications, for her constructive comments on how to finalize the manuscript – and to my mother and father for gently encouraging me to get a move on and finally finish it.

I would like to express my deepest gratitude to Elvira Maria, Daniela, Nicholas and Dylan. Thank you for putting up with a very complex husband/father while this book was being prepared, and thank you for putting last Christmas on hold.

Oxford, U.K.
2007

PART 1

What exactly *is* Complexity Science?

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 oneby-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 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 supplylines 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.

Chapter 2

Disorder rules, OK?

One of the tell-tale characteristics that a particular system, such as traffic or a financial market, is complex is that it exhibits emergent phenomena which are surprising, extreme and self-generated – just think of a traffic jam or a financial market crash. Although it is certainly true that some traffic jams and market crashes are triggered by a particular outside event (for example, a road accident or the announcement of a particular company going bankrupt), more often than not there is no obvious reason either for their appearance or disappearance. In particular, they are not being engineered or controlled by some mysterious "invisible hand" operating in the background. So what makes them appear and disappear of their own accord?

We've all had the experience of driving happily along an apparently clear highway, only to suddenly find ourselves in a traffic jam for no apparent reason. And then, just as mysteriously, the jam disappears. We drive on, looking for an obvious cause for the jam such as an accident – but there is none. The same happens in financial markets, where it is actually quite rare that the cause of a given market crash can be assigned to a particular event or set of events. Indeed, for every financial expert who says that the cause of a given crash was X, you can find one who says it was Y. For example, the dot-com bubble which burst around April 2000 was supposedly "bound to happen". But why did it happen at that fashion, suddenly becomes filled with people who have all decided to sell at the same time. What's more, such effects can then disappear just as suddenly. So what is going on?

Complex Systems are able to move spontaneously back and forth between ordered behavior such as a traffic jam or a market crash, and the disorder typical of everyday operation, *without any external help*. In other words, a Complex System can move freely between disorder and order, and back again, and can therefore be said to exhibit "pockets of order". The emergence of such pockets of order has very important implications in terms of being able to predict and control the system. Their appearance is also quite mysterious – after all, if a bag of unsorted socks were a Complex System (which it isn't) it should therefore be capable of organizing itself into an ordered pile of pairs, ready for placing in the clothes cupboard. A wonderful idea but as we all know it doesn't happen in something as simple as a collection of socks. So there must be something more complicated going on at the heart of a Complex System which we need to understand. But the good news in practical terms is that pockets of order *can* indeed arise in a Complex System and this gives us hope that there might be a way of partially predicting the future evolution of such a system, and even being able to manage or control it.

These pockets of order can arise in both time and space. For example, traffic jams arise at a particular time and place, and then later disappear. Market crashes also arise at a particular time and in a particular world market, and then later disappear. The challenge in this chapter is to understand *why* such pockets of order arise. But to do this, we need to go on a journey from order to disorder – and where better to begin than a typical day at the office.

2.1 Another day at the office

hour. But since the exact number of arrangements is actually 3,628,800, it will take you approximately 10,000 hours to search all of them – and 10,000 hours means that it will take you more than one year even if you don't stop to sleep, eat or go to the bathroom. So unless you have a very patient boss, you will likely be out of a job before you find the correct arrangement.

2.2 If things can get worse, they probably will

In the above story, we imagined that your intern accidentally pushed the whole pile over and hence instantly took the pile from maximum order to maximum disorder. In many other situations, things will move between order and disorder in a more gentle way. Imagine that instead of the whole pile being knocked over all in one go, your intern just randomly changed the position of one file each day. Going back to our picture with only three files, you can see that even after only a couple of days the new pile is likely to be quite different from the original one. Admittedly, the more files there are in the pile, the longer this process of order-to-disorder will take – but in the end, disorder rules.

So, our office filing story tells us that it is quite easy to disorder something which is ordered, while it requires a long time and a *lot* of care to reorder something that is disordered. Exactly how long either of these takes will depend on what is doing the disordering or reordering. But one thing is for sure: *there is a natural tendency for something that is ordered to become disordered as time goes by. In contrast, something that is disordered is highly unlikely to order itself without any additional help*. And herein lies our interest in order and disorder. We have already established that a Complex System such as the traffic or a financial market, can spontaneously move from order to disorder and back again. At the same time, we know that a Complex System contains a collection of objects in a similar way to you are one of the unlucky ones who has to put up with complicated office dynamics, this effect sounds pretty close to home. But it also turns out to be quite a general emergent phenomena in real-world Complex Systems – in particular, the ones which involve collections of objects competing for some kind of limited resource.

To help understand how frustration can arise in a Complex System, we go back to our files. Suppose that for some reason there is a rule that says that file A must not be placed next to C. This may sound unusual for an office but it often arises in a social setting. For example, teachers know that they cannot sit certain kids together because it will cause trouble – and the same can be true at dinner parties. The arrangement of the shelves themselves then becomes crucial. If they are in a line, the problem can be solved as shown in the top of figure 2.4. But if they are in a circle, then it is impossible. In other words the arrangement is always frustrated as shown in the bottom of figure 2.4.

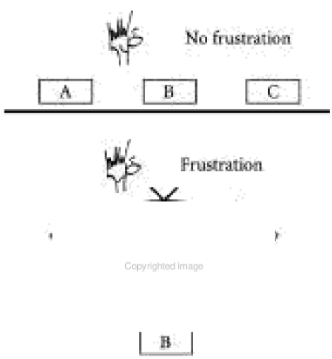

Figure 2.4 The dinner-party dilemma involving three people A, B and C, in which A and C do not want to sit together. Top: a rectangular table allows for a non-frustrated, relatively happy outcome. Bottom: a circular table always leads to frustration.

In addition to unhappy offices and dinner parties, frustration is upper ones, in order to save reaching up or having to stand on something. Likewise the amount of energy available to a physical system such as a collection of molecules, is restricted by its temperature. Continuing with the filing analogy, an outside observer who is checking the office's filing arrangement night after night would be left with the impression that the filing system was reasonably well ordered, since the arrangements he observed would tend to be those shown in the middle and left-hand side of figure 2.2. Within the context of physics, the temperature controls the amount of energy available for arranging objects, and this in turn biases the arrangements. As the temperature increases, the amount of available energy increases, and so the biasing becomes less apparent. For the filing analogy, our office observer would then get the impression that the filing system was becoming less ordered since a wider range of arrangements would be observed over time. Eventually, at very high temperatures, the amount of energy available is huge – which is analogous to saying that the secretary has so much energy that she doesn't bias the distribution of files among the shelves in any way. Since the filing process is now unbiased, our outside observer would conclude that the disorder is large since he would observe all possible arrangements of files among shelves with equal frequency.

Hence increasing the temperature in a physical system such as a collection of molecules, generally takes the system from an ordered to a disordered state. The way in which water passes from ice at low temperatures to steam at high temperatures is a great example of this effect. Ice is a solid containing an ordered array of water molecules, while steam is a completely disordered gas. Physicists call the transitions between these different states of water, phase transitions – and the particular mathematical formula that they use to describe how the temperature biases arrangements of molecules is called an exponential or Boltzmann weighting factor. It seems that the popular press on Complexity likes to borrow this type of physics terminology related to phase transitions. However such literal translations of models and ideas from physics should be handled with care, since the biasing in arrangements caused by temperature is only strictly valid for systems such as a collection of molecules which sit in a particular type of laboratory environment. In short, physics has a remarkably large number of answers for certain types of systems – but it is still a long way from having all the answers for general Complex Systems.

Chapter 3

Chaos and all that jazz

3.1 Dealing with office dynamics

In the popular science literature, one often sees the term Complexity bundled together with another "C" word, Chaos. This might suggest that Complexity and Chaos are essentially the same thing. But they are not.

A Complex System tends to move between different types of arrangements in such a way that pockets of order are created – for example, the appearance and subsequent disappearance of a market crash. But we haven't yet said anything about *when* such transitions might occur. In short, we are missing a discussion about time, or what is technically called the dynamics of the system. Given that a Complex System comprises a collection of interacting objects (for example, traders in a financial market), it is likely to exhibit quite complicated dynamics. In other words, the output of the Complex System as seen from the outside by any one of us will appear quite complicated. This word "output" just means any kind of observable number that is produced by the collection of objects. For example, the output of a financial market at any given moment is the price, e.g. $2.50 for a given stock. The fact that the output of a financial market (i.e. price) changes in time in such a complicated way is the reason that we, as outside observers, always see such complicated price-charts appearing in the news