Coming to grips with complexity

The word *complex* is ubiquitous in today's world, which seems to be full of complex systems, complex relationships, and, of course, complex problems. But what does *complex* really mean? *Complicated* as a potential synonym comes immediately to mind. Yet there is a difference. Calling a situation c*omplicated* conveys an impression of tediousness and boredom. By contrast a complex situation promises to be intriguing, even fascinating, when studied closely.

But why are we so intrigued by complexity? Are the difficulties encountered in complex systems somehow special? Threading a small needle, for example may be difficult, but it would rarely be called complex, whereas understanding the functioning of an ant colony is certainly a complex task. What is clear in the case of the needle is that we understand the problem and know how to solve it: by trying. Repeatedly. In the case of the anthill, the right approach to the problem is in itself uncertain. At first glance we only see a mass of moving bodies which follow apparently random trajectories. Each individual ant seems unpredictable in its wanderings. So therefore how can we ever hope to understand the movements of the whole colony? But once we start asking the right questions, patterns appear. We may note that the ants follow different movement patterns dependent on the task they are performing. For instance, when travelling to known food sources, ants follow paths, marked according to an intriguing set of rules. While the movement of an individual ant may be unpredictable, we can understand, describe, and predict the movement of ants as a dynamic network of distinct paths which change according to a set of well-defined rules.

Comparing the two examples, points to an analogy between complex systems research and art. In the case of the needle, the result is all that matters and this result is obtained by following an obvious, albeit difficult, procedure. In the case of the anthill, determining a promising approach is in itself a central step in the solution. For complex systems, defining the approach to the problem typically requires defining good concepts, such as the concept of distinct paths. Finding concepts that *work* is the creative part of research. Once defined, they offer us an alternative language for describing and understanding the system, and often lead to a whole new way of thinking that sometimes opens up perspectives far beyond the immediate system under consideration. In other words, the next needle will always be as difficult to thread as the previous, whereas the next anthill not only becomes much easier to study once the concepts are clear. The same concepts that have proved advantageous for the ants may well hold the key to a large class of similar systems.

The observation that complex systems appear complicated at first glance, but may be found to follow simple principles if regarded from the right angle, may explain our fascination with complexity. As in any good puzzle, understanding a complex system presents us with a challenge, but as soon as we start putting the pieces together a picture appears that is more easily comprehended than the colours we see on the individual pieces.

"Appearing complicated, but being simple" is sometimes quoted as a definition of complexity. But many other (and perhaps better) definitions exist. In science, the probably most widely accepted definition of complex systems is "systems showing emergent phenomena". Here, "emergent" describes any type of non-obvious behaviour that is not inherent in the constituents of the system, but rather "emerges" as we put the parts together. In other words, the emergent property of our puzzle is the picture that is not recognizable on any individual piece, but appears when the pieces are fitted together.

Our usage of emergence as a defining property for complex systems implies that only systems consisting of many parts can be complex. However, this is hardly a constraint, as all material systems consist of many individual particles and even immaterial systems, for instance languages, can almost always be broken down into distinct entities and their interrelations. We can thus distinguish between the “microscopic level” at which the individual parts of the system (the ants or puzzle pieces) are discernible and the “macroscopic level” at which the emergent behaviour (columns of ants or the picture in the puzzle) is visible.

Our mental capabilities limit the number of distinct objects that we can consider and understand simultaneously. Therefore it is natural that complex systems appear to be complicated and confusing if regarded on the microscopic level. Just as in the case of the anthill, attempting to do so will only reveal a mass of moving bodies. However progress can be made in two ways: Either we cut the system into smaller and smaller pieces, for example by removing one ant from the anthill and studying its behaviour in isolation or – alternatively – we try to describe the system directly on the macroscopic level – by focusing on the paths rather than the ants.

Cutting the system into pieces is often the easier way to go, which explains in part the tremendous success of physics in the 19th and 20th centuries. A central focus of physics research was the understanding of matter on a more fundamental (meaning smaller) level. Thus it was discovered that matter consists of individual atoms which contain the nuclear core and a cloud of electrons. The core itself consists of several nucleons which in turn comprise three quarks. As research focused on ever smaller scales the objects under consideration became harder to handle in experiments, but their theoretical treatment remained relatively simple because all complexities that arise from the interactions of the particles are stripped away when particles are studied in isolation.

Because of the success of the approach described above, the physics of isolated atoms is well-understood, whereas the physics of systems much closer to everyday experience, such as a handful of soil, poses many open questions. – But how is this possible? After all, soil consists of nothing but atoms. Of course, in reducing the system to its parts, some properties are lost, namely those that arise from the interactions between the parts. In order to understand the emergent properties which have been identified as the defining characteristic of complexity, we have to put the pieces of the puzzle back together. Although we may say that the behaviour of a single atom is well-understood, the statement cannot be made with the same confidence for two or three atoms. And determining the precise behaviour of some hundreds of atoms is challenging even for modern computers. To understand systems consisting of 10^{24} atoms (i.e., a million of billions of billions), such as the handful of soil, we need to follow the second approach mentioned above. We zoom out and consider the system on a macroscopic level.

Switching between different levels of description requires moving to a different system of concepts—a different language. By zooming out from the level of a single atom to systems of many atoms we leave the terrain of physics and enter the world of chemistry. In the language of chemistry the behaviour of the system can once again be described by sets of simple rules. Unlike physics, the laws of chemistry do not explain the behaviour of every electron at a given point in time. They do reveal, however, which atoms can bind to form molecules. For describing systems that contain thousands of different molecules that have to come together to form a living cell requires an even more macroscopic level of description: the language of biology. Beyond the three sciences already mentioned, essentially all sciences – including social sciences (like psychology or sociology) – describe complex systems on different levels, using different frameworks of fundamental concepts.

But how is it possible that, for instance, the behaviour of a certain number of atoms may appear simple, if seen within the framework of chemistry, but complicated if seen within the framework of physics? Clearly, the answer lies in the transition between the different levels of description. When zooming in to smaller and smaller scales we cut out the complexity of the interactions. But when moving to larger and larger scales, we neglect the internal workings of the parts. Indeed, the precise position of atoms which is central to physics is often irrelevant in chemistry. Likewise, the state of the inner electrons and the atomic core is not important for conventional chemical reactions. For the chemist, therefore, only the outer electrons of the atoms are relevant because only they take part in interactions.

When zooming out, the nature of the individual parts of the system become less and less important whereas their interactions become more and more important. This observation was summarised by P. W. Anderson in the statement "more is different", which has become a paradigm of complexity. To make this clear, let us consider for example a chicken. A biologist may characterise what a chicken is by its genetic code. On this level for instance the laws of inheritance can be formulated as simple rules. We may also try to characterise the chicken in the language of physics, which would perhaps result in a long list of different atoms and their position. The laws of inheritance, if they could be formulated on this level, would be much too complicated to comprehend. More importantly, the positions of the atoms would change even when the chicken flaps its wings. The position of any individual atom is therefore hardly a characteristic of the chicken. But, if we ignore the positions, we are just left with a list of atoms: a lot of carbon and hydrogen, some oxygen, nitrogen, and phosphorus and tiny amounts of all the other stable elements. A very similar list of ingredients would also be found in a dog or even in a can of chicken soup. What defines "chicken" is not the molecules but their interactions: how parts come together to form cells, tissues and organs. The chicken is therefore more than a bunch of atoms because *more is different*, and what makes it different are the interactions between the parts.

The chicken in our example is certainly a complex system. It consists of many parts which interact in a complex way on the microscopic level. We can argue that what defines "a chicken" is how these parts come together, so "being a chicken" is an emergent property. In fact, the chicken is so complex that emergent properties exist on various levels. We can talk about the genetics of the chicken and also the physiology of the chicken, perhaps even the psychology of the chicken.

The example of the chicken reveals a shortcoming of the puzzle as a metaphor for complexity. In contrast to the chicken the puzzle is designed to fit together in a specific way, i.e. their interactions are simple, not complex. The picture that appears is thus a built-in property and not truly emergent. On a deeper level we can still argue that a puzzle is a system of many atoms and that "being a puzzle" is an emergent property that appears because of the arrangement of atoms fitting into pieces. But even then the puzzle lacks all the additional layers of complexity that we can find in the chicken. There are no genetics, no physiology or psychology that can be applied to puzzles.

In almost all systems in which many individual parts come together to interact in a non-simple way, emergent phenomena can be observed. The synchronous flashing of fireflies, earthquakes, panic in crowds, the flocking of birds, and the cascading failure of electrical systems are just some examples of the large variety of emergent phenomena. Typically these phenomena can be described by (relatively) simple laws once a good framework of concepts has been found.

Why and how simple relations emerge from complexity is still an active question of research. In its purest form this question is perhaps investigated in statistical physics. By going downwards through the different scales, physics has identified many examples of systems where both the macroscopic and the microscopic behaviour is known. Perhaps the oldest example is that of thermodynamics, where emergent phenomena such as temperature emerge from the collective dynamics of atoms. By studying such examples, physicists have not only discovered physical laws but have also developed methods for studying how the macroscopic behaviour emerges from microscopic interactions.

Making progress in research requires reducing complexity. However, to understand emergence, we can neither neglect the macroscopic nor the microscopic level entirely. We need to cut in yet another way. In physics, this is done by studying simple, abstract models of the system under consideration, which neglect details on both the microscopic and the macroscopic level retaining just the bare necessities for describing a certain phenomenon. In order to understand why ants form distinct paths, it is irrelevant to know that they have six legs, how they reproduce and even that they need food to survive. By ignoring these details we obtain a model that provides a poor description of ants as such but is geared towards the specific question of path formation and therefore is simple enough to be analysed in detail.

The simple models of physics provide a detailed account of neither the parts nor the bigger picture, but focus on how parts interact and thereby create the bigger picture. In general this pattern of interactions is not unique to a specific system. Therefore investigating abstract models of the interactions found in one system may reveal insights that are also relevant for a large class of systems, comprising, for example, cars or packets of internet data instead of ants.

As the examples of traffic and internet communication show, an area where complexity is of immediate importance is human behaviour. Today we live in a world that is fast becoming increasingly more connected, globalised, and interlinked, introducing new levels of collective emergent phenomena. Returning to our initial observation, not only the word *complex* is ubiquitous in today’s world, but the world itself is a complex place and becoming more complex by the hour. In the future, coming to grips with this complexity will be a central challenge for humanity as whole, and for each person individually. On the larger level this challenge is addressed by science where, for instance, physics and sociology are presently joining forces, and the new discipline of “network science” is emerging. On the level where the individual person is concerned, the same challenge may be more properly addressed by art, which can provide a different form of abstraction, define concepts, outline a new way of thinking and help us coming to grips with complexity.