Agent Based Modelling for Social Research

Intro to modelling Part 2

Hello, in this part of the video, I'm going to talk about complexity, and in particular about chaos, criticality and emergence.

Modern in science has its roots, at least as far back as ancient Greece. However, it really only came into its own in the 18th and 19th century. In this time, spectacular advances were made in various different kinds of science, physics, chemistry, beginnings of biology and medicine and that led to a general feeling of optimism. So people thought that essentially the universe was a huge clockwork, with deterministic laws that people were supposed to be mostly known at that time. And since most systems were thought to be in equilibrium, people thought that sooner or later, everything would be possible to be calculated and predicted. And that extended not only to fundamental laws of nature, such as gravity and magnetism, but also to assemblies of many elements. So statistical mechanics, for example, was able to explain the behaviour of a gas based on the distribution of energy in its components, or in population dynamics Verhulst and Gompertz developed two different formulations for logistic growth that was able to more or less replicates natural population and not natural dynamics of populations that had been measured.

And that extended beyond these even to social sciences. So people thought that sooner or later, some kind of social physics could be developed that would be able to predict the development of societies. something along the lines of what Isaac Asimov developed by science fiction novel Foundation, where people predicted the development of society 1000s of years in advance.

So why does that not work? The first step in answering that question was made by Edward Lorenz in 1961. He was running a simple weather model, with 12 state variables representing for example, temperature and wind pressure, wind speed, and pressure. On one of the very slow and simple computers of the time. That computer printed out the state of the model on a sheet of paper. So when Lorenz wanted to rerun the model from an advanced state, he took the print out and typed in the values of the state variables into the computer, and then started the model from that point onwards. When he came back from fetching a cup of coffee a while later what he found was that the second run of the model had diverged from the first run significantly, and that only over two months of simulated time. The reason for that he found out later was that the printout only showed three significant digits, whereas the computer internally calculated with six significant digits. And that tiny difference was sufficient to produce entirely different dynamics in the rerun of the model.

This phenomenon we now call deterministic chaos. An easy way to understand the dynamics of this type of system is to look at the trajectory in time. So what we have here is a simplified version of Lorenz model developed by Lorenz himself with only three state variables.

Each state of the system is defined by three numbers, so one number for each state variable, that means we can display the current state of the system as a point in three dimensional space, as you can see here, if we then run the model, and let the state develop over time and continue plotting the state continuously, what we get is lines in three dimensional space that represent the development of the state of a time that's called a trajectory. If the trajectory of the state of the model stays within a bounded area, that's called an attractor, so that's part of the state space that the model will will develop to evolve towards in all cases. What we see in chaotic systems is that the attractor tends to have a more or less complicated shape with different areas that this trajectory can stay in. So in this case, what we can see is that there are two loops and the track, the state's state of the system can circle around each of these loops, or it can switch between those two loops, we can see that better now. Dynamic representation.

So as you can see, is that the state loops around one of these areas but occasionally it jumps from one of the areas to the other. And in this transition point here, where the state can switch between the two different parts of the attractor, very, very small differences in the current state determine whether it switches or not. As Lorenz said, chaos means that the present determines the future, but the approximate present does not approximately determine the future. And as it turns out in the following years, many, many systems in nature actually show this type of behaviour. I just give a few examples here, weather the prototypical example of course, has chaotic properties in many cases, which means that we can, we can show general patterns that reoccur and we can also predict weather in the short term, but our predictions very quickly become very, very inaccurate.

Simple mechanical systems can be chaotic. If we built a pendulum out of two connected rods, then we can see chaotic behaviour, you can see the trajectory over here.

And even the paradigmatic example of predictability, the movement of planets around the Sun turns out to be chaotic, actually. So we can predict the movement in the timespan of 100, or 1000, or even 1000000 years. But after a few million years, we enter the realm of chaos and we are unable to predict anything beyond that point.

Finally, final example, population dynamics, as we saw before, in the 19th century, people who were convinced that this was one of the nice and predictable phenomena in nature, but it turns out if we look properly, population dynamics can be chaotic and very chaotic. And this is not just a theoretical result, these have been found in nature actually, these chaotic dynamics.

So to sum up, a system is chaotic when it shows huge sensitivity to initial conditions, at least in some parts of its behaviour. This can occur even in very simple systems. And many systems in nature actually are chaotic. So this is not a rare occurrence. And that essentially means that for these systems, even if we have extremely exact measurements of the current state, the behaviour in the future, very quickly becomes unpredictable.

The next thing I'm going to talk about is criticality. Now I've taken this figure from a neuroscience publication, you will see how that's relevant in a minute. So, look at the top left of this figure, you have a pile of sand and somebody sprinkling additional sand onto it. What will happen is that this pile of sand becomes steeper and steeper, until at some point, it loses stability, and you'll get an avalanche of sand running down the side. For our purposes, the interesting thing about this behaviour is that it is impossible to predict when this avalanche will occur. When sprinkling sand on top of the pile, we might get an avalanche at any minute. We don't know when.

If we look at the distribution of avalanches of a time, however, we see clear patterns emerge. So this is a plot of the distribution. So what we see is that there are very many small avalanches and very few large ones. Similarly, there are many short time periods between avalanches, very few large ones. This type of relationship is called a power law and it's kind of ubiquitous in nature in many different contexts.

The connection to neuroscience by the way, is that if we look at cascades of neural activity of a specific kind in a rat brain, we get very, very similar patterns. This type of behaviour it's called self organised criticality. Criticality, because the system enters a region of criticality where it all of a sudden changes state to different behaviour. So in this case, the sand flowing down the side, and self organised because the system does so on its own. So you don't have to tune the system in any specific way, it essentially develops towards the critical point on its own.

And this type of behaviour is interesting and relevant for our purposes. For two reasons, the first one is it makes systems very unpredictable. The second one is that it means that systems developed towards non equilibrium state on their own. As with chaos, when people started looking for it, it turns out that half criticality, self organised criticality is quite common in nature. Classical example our earthquakes so we have tension building up between tectonic plates that get released, that gets released in an earthquake and magnitude as well as timing of earthquakes is essentially an unpredictable, we can find general patterns but when the next earthquake will occur, and how bad it will be. It's very difficult to foresee.

Solar flares show self organised criticality. Climate change has some properties of self organised criticality to it. So there are parts of the system that might flip suddenly, to a different state.

To sum up, self organised criticality means that systems can spontaneously flip from one state to a different one. Many systems in nature exist, that are far from equilibrium and in this state of criticality, and importantly, they will develop towards that criticality on their own without us influencing them. And for systems with self organised criticality, it is difficult or impossible to predict when the phase transition will occur and how it will look like.

The next type of dynamics I want to talk about is emergence. If we look at these different types of animals, what you can see is that they have, they have a very striking type of coloration in common. So they're all patterns rather conspicuously? How does it come about?

It turns out, it's actually pretty simple. Alan Turing developed a model in 1952, where he took two substances, an activator, that activates itself, as well as the other substance, the inhibitor, and the inhibitor inhibits the production of the activator. So we have substance A, that produces or activates A and B, and we have substance B that only inhibits substance A. If these two substances diffuse with different speeds in the medium, we get patterns. That's essentially all there is to it. This is the type of patterns that get the we get out of this type of system, we can then modify them a bit with gradients and things like that, you know, to get stripes, and you can extend the system in various kinds of ways to get more complicated patterns. But the basic structure remains the same, the basic idea.

So what's important about that? First of all, what we see is that we have a very simple model that can explain many biological patterns. But second of all, more importantly, we have a homogeneous system. So we have a system without any patterns in it and consisting only of identical elements, that spontaneously generates structure. And that is called emergence, this type of phenomenon. It turns out that this type of behaviour is also very common.

In biology, the basic tearing patterns actually occur not only in colouring, but many aspects of morphogenesis are based on similar mechanisms. If we look at bird swarms, for example, what we have is very conspicuous macroscopic patterns of bird swarms aggregating and moving collectively. However, the laws that produce this behaviour are really simple and only happen on the basis, on the level of individuals. So we need basically three mechanisms to produce a swarm, we need cohesion, where individuals move towards the densest area of the swarm separation where individuals attempt to maintain the minimum distance between themselves and their neighbours and alignment where individuals try to move roughly in the same direction as the neighbours if we have this, this rule, these three mechanisms. I'm paired up with some some cut off thresholds for distance, we get beautiful swarms.

Ripples and sand are an emergent property of the interaction between wind and sand cones, the underlying mechanism can be pretty complicated. There are many different kinds of ripples apparently, that can occur. But the fact remains that we have a homogeneous state at the beginning, so a flat expanse of sand, and just minute variances in grains, highs and number of grains can lead to the emergence of these ripples.

Traffic jams, another classical example of emergence. And the way that works is that you have, in principle, identical cars and drivers. But there are small random fluctuations, which means that if traffic is dense enough, at some point, somebody would have to break the person behind that person. If the distances are small enough between cars, which is given if the traffic is dense, we have to break as well. But there's a small delay because people react not instantly, which means that the third person behind the second one will have to break as well, but more sharply than the second one. And this way, the delays escalate. And from a homogeneous structure, a homogeneous situation, we get a structure, a traffic jam. Cities are a structure that emerges from the many individual economic decisions that individuals make in a society when they decide where to move into or to work.

So, to sum this up, even homogenius systems with no discernible structure, you have consists of many identical parts. Interactions between those elements can lead to the emergence of structure. Usually, this happens through the escalation of small stochastic variations. These interactions that can lead to emergent structure can be extremely simple. As we saw in the swarm example, there are three really really simple rules that lead to a macroscopic pattern. And there are many phenomena in nature that are the result of emergence.

Weather system shows merchants, what kind of structure we will get at the end is very difficult to predict if we only know the rules of the system. So, what we saw in this part of the talk was that complex systems can show various kinds of surprising behaviour that makes them extremely difficult to predict under certain circumstances. That also means that deriving simply macroscopic laws of behaviour for these systems will often fail in particular, it will be extremely difficult to derive these macroscopic laws when knowing only the laws that govern the elements of the system. Therefore, explanatory modelling is crucial to understanding such a system and any modelling in that context needs to take interactions between components into account.

Thank you for listening.