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The Science of Complex Systems

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Introduction
Complexity Science is not yet a science, but it is a movement towards a new science. There has been a debate about using the terms 'complexity science' and 'complex systems science'. Professor Bourgine prefers the term ‘complex systems science’ because 'complexity' is a much more ambiguous word. First he discussed the nature of complex systems. The subject can be approached in two ways: either in terms of its ‘extension’ involving a search for examples of complex systems in a number of different areas or in terms of human ‘intention’ which is to do with the ways in which scientists can understand such systems.

The list below contains examples of both natural and artificial systems that intuitively seem to exhibit properties of a similar kind. As science begins to discover what such systems have in common the distinction between artificial and natural systems disappears and because more and more adaptive artificial systems are being designed the same kind of studies can be made to solve the same kind of problems.

Realms in which complex systems exist:
Multiple organisms
Cognition
Law
Economy
Road traffic
Telecoms
The Web
Society
The eco-sphere

Using the list we can ask different questions of each system. If we take ‘cognition’ for example, we can ask questions from many different points of view such as physics, psychology or philosophy.

The other approach is to try to form a concept of what is meant by a ‘complex system’ using epistemology or philosophy and see how particular systems match up to it. It may then be possible to refine the concept mathematically and to use computers to model a proposed system. Complex systems science involves both these methods.

Professor Bourgine defined reconstruction as an attempt to describe the dynamics of a complex system both from first principles and from data available. Two important considerations arise from this; one is the question of emergent properties and the other is the question of governance or how complex systems might be influenced to benefit human beings.

In the last 30 years mathematics, in particular computer science and statistical physics, have yielded some very deep results and there has been much accumulation of sophisticated data about complex systems. The data is not just limited to statistical information, but is obtainable from a number of sources including sound recordings and moving images. The data is no longer one-dimensional.

It is also necessary to produce dynamic models that are scale free, but in essence the approach is exactly the same as it has been in physics for the last three centuries. Data has been reconstructed by proposing some laws and working on mathematical models to express and unite those laws. These two kinds of activities have provided physics with some very nice tools to make predictions.

Questioner 1 asked about the importance for the scientific method of achieving an appropriate level of description. Designing an aeroplane, for example, requires a fluid dynamics description of the air flowing over the wings. It does not require a description of the structure of the molecules of air or the quarks inside the nucleus. Theories of economics are traditionally based on macro-data, not data on what a single individual does or does not do. It was wondered whether Professor Bourgine was suggesting that a complex system should be approached at all levels. Because disciplines in science were interest relative people were trained by asking what the appropriate level of description was.

Professor Bourgine affirmed that in studying complex systems it was important to make the dynamics explicit for all levels and to do it by looking at the data at all levels. That was probably true in biology as well. If genetic structure was changed in some way, it was as important to know what happened at the level of the multi-cellular organism as what happened at the cell level. The important question being asked in complex system science is, ' what is the emergence from one level to the next?' There may be two or more levels of emergence that have to be explained. It was not only necessary to make the dynamics explicit for each level, but to describe the overall emergent function. In social science, a ‘bottom-up’ description of a social system could be employed starting with the individual, or a ‘top-down’ description, starting with the assumption that people do what they do for social reasons. The relationship between these two different approaches can be understood by introducing the concept of emergence so that both become complementary. Either way a model has to respect the principle of commutation.

There is a similar requirement in explaining individuation. In a complex system individual nodes or components may result via emergence from the internal network or the external network. It is difficult to talk about emergence as a 'top-down' effect because it is contrary to our epistemological sense, though someone suggested 'downwards causation'. 'Reconstruction' is the inverse of 'simulation'. If scientists have a program A and obtain a result B it is simulation. If they have a description B and search for a program A, that is reconstruction. Kolmogarov complexity is an important principle in the science of complex systems and is by definition the length of the smallest program that allows reconstruction of the description. This formulation is very close to what is known in science as Occam's razor which means that scientists should aim at the simplest and most elegant reconstruction. It is important for educational purposes and very like modelling except more rigorous.

Questioner 2. wondered how an effect which had multiple causes could be described with the concept of 'downward causation'. Professor Bourgine replied that the philosopher W. V. O. Quine had said that series may underdetermine the facts since there may be many more possible causal chains as explanation, but the Kolmogarov maxim will reduce, at any given time the choice that a scientist has to make. Practically it may be impossible to construct the smallest program but it is an ideal to strive towards. There are many degrees of freedom in reconstruction. It depends, for example, whether a person approaches the problem as an engineer, a designer or a scientist.

The last point about reconstruction concerns'noise' or the apparently random data that occurs in any complex system. The degree of complexity depends how far a programme goes in reconstructing a series that includes noise. Generally, in science it is sufficient to reconstruct up to the noise to go further means a shift from a deterministic reconstruction to other formulations which are stochastic. It is a shift from differential to stochastic equations. Differently structured noise, however, can have very different consequences.

There is a difference between reconstruction and explanation. Explanation is more ambiguous, reconstruction is more abstract. Reconstruction can be made the core of a model. Explanation does not necessarily have an implication for the future and is more historical. Whether one reconstruction can be judged better than another depends upon whether the focus is on specificity or generalisation. In science it is not sufficient to merely have a catalogue of particular instances -underlying principles have to be discovered.

Governance of a complex system can also be seen as an inverse problem. It can be carried out by people having first hand experience of particular systems, but it can also be approached via the reconstruction of a complex system that indicates its viability or resilience. Given that a complex system has a certain viability or resilience, we have to choose a strategy that will exert some governance over an indeterministic system. There is a very important debate about which class of strategies should be used – whether to aim for distributive or centralized control. Distributive control is exerted on different parts or elements of the system and centralised control like the control of an army. It may better to have centralised control when the situation is difficult or dangerous, but in normal cases distributive control is much more compatible with the rich structure of a complex system. What is needed in human society, for example, is for all forms of institution to coordinate their degree of control. Incentive can be the means of distributive control. In science, for example, the Nobel Prize functions as an excellent distributive control.

The science of complex systems is a new paradigm and the idea of prediction is changing. ‘Fine grain' models often attempt to capture a system in greater detail for prediction or control, but was a fundamental idea of Prigogine that we should not try to predict what will happen, but try to predict what can happen. That may seem easier, but technically it is much more difficult to capture the dynamics. Statistical physics is a powerful tool, but it is very technical and not very theory laden. Prigogine would like an exact description of the dynamics, but uncertainty is probably inherent. Risk assessment tries to calculate the odds that something will happen and known risk is when you can calculate the probability with a degree of certainty. If you flip a coin for 'heads' or 'tails' you know the probability for each is 50/50 and that if you flip the coin enough times that probability is proved. In economics however there is much more risk of a second order which is unknown risk. It is necessary to add to the dynamics of known probability the dynamics of the uncertainty that surrounds the probability.