Lecture 4: notes on complexity
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systems and complexity

In the systems thinking course, we talk about systems. We provide definitions and classifications and try to develop a conception of the nature and behaviour of different types of systems. According to one of these classifications we can say that some systems are simple and easy, while others are complex and more difficult to understand. It so happens that the great majority of systems of concern to IE/OR are complex; and in systems thinking (ST) therefore, we are mostly interested in ***complex systems***.

There is a lot of research and a vast literature on systems and systems thinking. Most of this work has emerged and flourished after World War II and is still developing. The ***systems literature*** as such, is generally associated with management sciences, which also covers IE/OR. The origins of much of this are to be found in the development of OR that started in England just before WW II, although some of the central ideas were borrowed from biological research where it was felt that traditional scientific inquiry was incapable of explaining biological phenomena, and that some other, more robust approach was necessary.

In parallel to, but independently of the research on systems, there also emerged more recently in the last 20 years or so, an area of inquiry known as ***complexity theory.*** Researchers from the natural sciences such as physics, biology, geography, anthropology, meteorology, climatology and the like, as well as those from the social sciences are active in this area of research.

Although they have developed along distinct courses, I shall try to explain in these notes, that systems and complexity are both based on shared ideas that have emerged in response to the shortcomings of the scientific method in explaining and understanding natural and also social phenomena that are of primary importance to human inquiry. To do this, and without going into details, I shall first explain informally, what science and the scientific method are about, then summarise the central concepts of complexity, and finally underline the relevance of complexity to ST and OR.

science and the scientific method

Human inquiry looks for knowledge of nature, and natural as well as social phenomena. The way such knowledge is sought and the methods employed for acquiring it have changed and evolved throughout human history. One early way to know, was with reference to a higher authority who was thought to possess true knowledge. Ancient, as well as modern religions have long claimed access to such authority and this way of knowing has dominated human inquiry until about the 17th century. At this time, something of great consequence happened in Europe when an ongoing social process that had already started much before, culminated in the recognition of the cognitive powers of the human mind which would be capable of knowing without recourse to a higher authority. This realisation marked the beginning of the ***Enlightenment***, or the Age of Reason; and the understanding was that man would be free of superstition ever after.

The greatest achievement of the Enlightenment was probably the emergence of empirical sciences and the development of the ***scientific method***. Thus modern science, as we know it today flowered with the work of physicists such as Galileo Galilei and most brilliantly with that of Isaac Newton. The success of Newtonian mechanics in explaining the laws of motion and gravity had such a tremendous effect on human inquiry that the scientific method has since been recognised as the unrivalled way of attaining true knowledge.

The essence of the scientific method lies in its claim to ***objectivity*** and its reliance on observations and experimentation: Testable hypotheses are formulated as suggested by previously accumulated scientific knowledge and also in the light of new experience. They are then tested empirically following carefully specified procedures that are thought to eliminate subjective distortions and biases. If a hypothesis is able to survive many such replicable tests, it gradually attains the status of a ***generalisation*** or ***law***. Laws of science aim to provide ***explanations*** of and ***predictions*** about natural phenomena. Most powerful of these, are ***causal laws*** that are based on causation, or cause-and-effect relations. The scientific method, defined as such, is predicated on the doctrine of ***positivism*** which asserts that the subjective influences that might arise from the scientist -- ie. the observer -- can be eliminated from objective research, if proper attention is payed to method, and in this way truth can be discovered. In other words positivism assumes that the observer can observe impartially, in isolation from that which is observed. (This assumption is known as ***subject-object duality***.) ***Understanding*** is yet another, higher objective of science that might ultimately be achieved in subsequence to explanations and predictions; but this claim runs into difficulties if we adopt a strictly positivist outlook. In short, the central supposition of scientific inquiry, as underpinned by Newton's success, is the belief that the world is ***knowable*** and that human intellect is capable of knowing it.

Newton has been the most influential thinker in shaping our view of the world; indeed in shaping our conception of the nature of ***reality*** and of ***truth***.

His influence has been so powerful that many of the concepts he introduced to physic; like inertia, momentum, stability or equilibrium have been directly adopted by other disciplines such as economics and the social sciences, and even permeate our everyday language. Our view of the world is still the mechanistic view of Newton.

Newton also invented the differential and integral calculus, which enabled him to derive the laws of mechanics. Calculus works mostly by linearisation; by approximating smooth curves by linear line segments. If the curve is not smooth, calculus fails. So mathematicians invented the concept of ***analytic functions*** to make the idea of smoothness more precise, even though nothing much in nature is really smooth. Scientists nevertheless, worked with analytic functions and ***analysis*** came to be the central method of inquiry. According to this, just as we can understand a curve by dividing it into infinitesimal line segments, so can we understand nature by dividing it into smaller parts, each of which can further be divided into still smaller parts etc. The idea is that the knowledge of the whole can then be obtained by bringing together the knowledge of the parts. This process is also known as ***reduction***. The key strategy of reductionist science throughout history has been to focus attention on very simple systems consisting of just a few components that are idealised in structure and function, that are assumed to respond linearly to influences and to be more or less isolated from the remainder of the world. Nature could be difficult to understand not because there was any fundamental obstacle standing in the way of the scientific method but only because it was complicated; meaning there were very many components intracting with one another in very many possible ways. Nevertheless nature was still governed by context-independent laws that could be objectively determined and predicted.

This way of thinking has become second nature to the educated western mind and is still the path that modern man follows generally when he inquires into truth. Furthermore, analysis or reduction that is employed to understand reality has also in a way defined that reality as analysable or reducible and hence knowable. This whole construction is the ***Newtonian paradigm*** of the world which asserts roughly that,

- objective knowledge is possible
- cause-and-effect acts linearly, in one direction
- phenomena are either deterministic or predictable
- phenomena can be understood by division into smaller parts

etc.

complexity

The Newtonian view of the world and the method of inquiry it created worked very nicely for more than 200 years. Then came quantum theory of subatomic particles with its own laws of mechanics that put an end to Newtonian determinism and predictability. Nature was not as simple as it was thought to be. After a while biologists also realised that reductionism was going nowhere and organisms could be properly studied only in relation to their environment. The discovery of ***fractals*** everywhere in nature showed calculus did not help; not all shapes were smooth no matter how closely we looked. In short, the Newtonian view which implicitly assumes that we can predict and intervene in the world to achieve our goals was in serious difficulty.

The new realisation was that many of the systems that surround us are ***complex***, and some scientists thought that universal laws, rather like Newton's laws of motion could be discovered about similarities among seemingly different instances of such systems across all disciplines of science, engineering and management by taking advantage of recent advances in mathematics and computer science. This field of inquiry is now known as complexity theory and although research is active there is as yet no single theory of complexity. In the following, I shall try to outline the most prominent concepts and notions.

nonlinear dynamics and chaos

Notions of complexity have originated in a number of disciplinary areas such as biology, physics, mathematics etc., as I have already mentioned. Surprisingly, one area was the application of Newton's laws itself, to the movement of heavenly bodies. ***Linearity*** in Newtonian mechanics means that the effects of different influences can be superposed to add up to a resultant effect; it does not mean that the laws of motion governing the trajectories of, say stars and galaxies are linear. Now for the case of two bodies, such as the earth and the sun, these laws that are mathmatically nonlinear, can be solved analytically with the well-known solution that the trajectory of the earth around the sun is an ellipse. If we know the initial position of the earth, using this solution, we can determine the earth's position at any future time. Everything is deterministic. Furhermore even if we repeat the calculations for different initial conditios, the same elliptical solution is obtained; that is the solution is ***stable***.

If however, we attempt to calculate a trajectory involving three bodies, such as the earth, the moon and the sun, Newton's equations cannot be solved analytically. In fact the French mathematician and philosopher Poincaré proved that no closed-form solution -- ie. a single equation that provides the answer -- exists for the three-body problem. Numerical calculation of the solution using computer algorithms is still possible though. But these approximations show, contrary to Newtonian determinism, that even when the initial conditions are only slightly different long term solutions can diverge from one another exponentially. In other words the solution is not stable, in fact the long-term prediction of the behaviour of the system is impossible, even in the case of Newtonian mechanics. Behaviour of this type is characterised by ***nonlinear-dynamics*** and is said to be ***chaotic***. Nonlinear dynamics govern many other physical phenomena such as the formation of cracks in glass or the formation of the surface of mountains and forests, or earthquakes. One popularised example is the assertion that the flap of a butterfly's wing in the Amazon can give rise to a storm, say in Japan; the point being that since we cannot determine all initial conditions including the position of butterfly wings, it is not possible to predict a storm with complete certainty. So, according to this, chaos deals with deterministic systems capable of having exponentially diverging trajectories over time; which means that even simple systems can be unpredictable. It is surprising that the implication of Poincaré's results were not fully understood at the time.

Although chaos appears to be related to complexity, it is in fact simpler because it is associated with the unpredictability of simple systems. Such systems are expected to end up in a steady-state, a state of thermodynamic equilibrium or ***maximum entropy***. Complexity in any system on the other hand can be defined as the degree to which the system maintains a thermodynamic ***disequilibrium***. Without going into further detail complexity can also be described as multidimensional chaos.

boundary and environment

We cannot talk about a system unless there is a ***boundary*** that separates the system from its ***environment***. Environment is whatever is not included in the system. This definition may not be of much use however, since, clearly the system interacts with the environment and so part of the environment could well be considered to be included in the system. For a system to function and escape thermodynamic equilibrium, import of energy from the environment is essential. We could say that parts displaying interactions that are denser in connectivity and strength are included in the system and parts that display interactions that are not that dense are included in the environment. Whatever the difficulties, the concept of environment and the concept of a boundary separating the system from it are essential for a system. For example life would not be possible unless the cell-wall separates the cell from its environment. Determining where the boundary of a system lies is called ***boundary-setting*** or ***closure***.

Boundary-setting is clearly not at all straightforward. Density of interactions could be a useful guide only in the case of very simple or trivial sytems. For more complex systems, the question of closure is problematic and brings up another important concept of complexity; the concept of ***scale***. It would be convenient if we were able to regard systems around us at different levels of scale so as to simplify understanding. This is called the ***separation of scales*** and it can work in some cases. In fact the achievements of Newtonian science and the development of a complicated technology has been possible without an understanding of complexity because scientists were able to separate scales. In mechanics for example, Newton's laws can define dynamic processes such as motion. Motion can also take place in the atmosphere where molecules of gas are in constant motion. Although this molecular motion is fast changing and therefore complex, we can also regard it at a higher scale in terms of resultant averages such as temparature and pressure. So what we do here is to assume some sort of uniformness or at least an average composition and thereby disregard the lower level complexity. This is a case of separation of scales. When such separation is not possible it means we have to deal with complexity directly. In other words there are now strong couplings of processes at different scales and we can no longer rely on an artificial closure. We must consider the system at all levels of scale.

emergence

Emergence is collective behaviour or structure or properties. It is what parts of a system do together that they would not do by themselves. For example H_2 and O_2 are gas molecules, but H_2O has behaviour and properties that are not the qualities of these gases. For another example we can note that competition is an emergent quality of two teams, a football and a football pitch. These examples indicate that emergent behaviour or qualities will arise at a higher scale from behaviour that takes place at a lower scale. But even though emergent qualities are not apparent at lower scales, this does not necessarily mean that it is not determined by behaviour or qualities at lower scales.

Emergent behaviour can be either complex or simple. For example even though the sun and the earth are complex, earth orbiting the sun is a simple emergent behaviour.Collective behaviour of cities, or governments or democracies on the other hand will result in emergent complexity.

It should be clear that emergent properties cannot be studied by taking a system apart and looking at the parts; each part must be studied in the context of the system as a whole. This is the principal reason why reductionist thinking fails to understand complex systems.

adaptation and evolution

Complex systems are capable of adaptation, that is of changing behaviour in response to the environment. Studying only the direct impact of the environment therefore is not sufficient, it is also necessary to understand how the system will change its behaviour in response. Living systems are obviously adaptive but much simpler systems, such as water flowing around or over pebbles, also exhibit adaptive behaviour.

Adaptation is not a centralised process, it occurs even as parts of the system act under local information only, as happens in the case of the changing of the shape of a school of fish swimming, or a flock of birds flying. In animals ***goal-seeking adaptation*** works through ***feedback loops*** and can result in ***learning***. Another example is the behaviour of the stock market that is determined by many players acting on local information. This last example is consistent with Simon's notion of ***bounded rationality***; individuals are unable to forecast the higher level consequences of their actions and so they optimise locally. Yet the resultant behaviour has an emergent logic. This view is central to the efficiency claim of free-markets, as Adam Smith first proposed.

Evolution occurs as a result of collective adaptation over generations.

It should be clear that prediction in human systems is problematic precisely because such systems are adaptive.

measures of complexity

How complex is a complex system? This question can be answered on the basis either of ***structure***, or of ***function***, or perhaps more fundamentally, of ***information*** ***content***. According to this last, the complexity of a system can be based on a measure of the amount of information needed to describe it. It can be expressed in terms of the amount of computer memory needed, as first done by Claude Shannon when he introduced the theory communication in the 1950's. One bit of memory can contain two messages, 0 or 1. Two bits can convey 2^2 or four messages; which are in decimal equivalent 0, 1, 2 or 3. These messages could be assumed to correspond to the possible states in the ***phase -- or state -- space*** of a complex system. To specify which state the system is in, we must first number all the states so that each one is identified by a label. Therefore if a system can be in any one of say, 8 possible states then the string of memory we need is 3 bits long since $8 = 2^3$. This relation can be written as $3 = \log_2(8)$. So the number of bits needed to communicate information about a system having Ω possible states must be $N = \log_2(\Omega)$. Complexity in this sense, is measured by message length and you can try and imagine how large N must be in the case of a system such as a human society or a modern economy. These ideas are central also to what we call ***computational complexity*** in computer science and discrete mathematics.

We conclude the discussion of complexity by noting that modern physics is coming to regard information as the most fundamental entity of the universe, perhaps even more fundamental than subatomic particles.

systems thinking, OR and complexity

Complexity theory suggests several equivalent definitions for a complex system, such as

- a complex system is a system that responds to its environment in more than one way; or as,
- a complex system is a system formed by many interacting parts displaying emergent qualities.

This last definition happens to be a very good definition for a "system" as we understand it in systems thinking and OR. So what is the relation between systems thinking and complexity theory? Are concepts of complexity new, or are they the same as those of systems thinking? The best answer I can give is that commonalities between the two are very strong. Complexity theorists just happen to have started their inquiries not from within the OR and systems tradition but from elsewhere in the sciences. This movement is preoccupied with establishing the universality of laws governing the dynamic processes of variation and selection. In a way, complexity scientists are attempting the restore the universality of scientific generalisations that they have subjected to questioning in the first place. Whether this effort will succeed remains to be seen. There is legitimate concern that concepts and findings of complexity theory may not translate directly into management science especially because the quantitative approaches of complexity will probably be of not much use in the case of complexly adaptive socio-technical systems. But the fact remains, I think, that these distinct strands of inquiry are showing signs of converging.

When OR started, the search for useful models and theories assumed that we could simplify and squeeze out the essence of the world so that we might capture a part of social reality for decision making. Although OR knew that the world was complex, it also appeared simple enough to produce robust models that could be used in applications. With growing realisation that the systems OR deals with are complex, prediction now appears to be getting out of reach, and the concern of both OR and science might be moving towards better understanding and structuring debate about the world.

The central attributes of complex systems are certainly shared by human activity systems and hence an understanding of complexity will help us understand human systems.

References

The literature on complexity is extensive and diverse. Three accessible references, one written from the viewpoint of science and the others from management can be a good start for further reading:

- Michel Baranger "Chaos, Complexity, and Entropy" http://necsi.org/projects/baranger/cce.pdf

- Richard Seel "Complexity and OD" http://www.new-paradigm.co.uk/complex-od.htm

- Jonathan Rosenhead "Complexity theory and management practice" http://human-nature.com/science-as-culture/rosenhead.html