Complexity Theory And Attempts To Quantify It

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A complex system is a functional whole consisting of interdependent and variable parts. Unlike a conventional system (e.g. an aircraft), the parts need not have fixed relationships, fixed behaviours or fixed quantities, thus their individual functions may also be undefined in traditional terms. Despite the apparent tenuousness of this concept, these systems form the majority of our world, and include living organisms and social systems, along with many inorganic natural systems (e.g. rivers). Complexity Theory states that critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties. This theory takes the view that systems are best regarded as wholes, and studied as such. This is due to the inherent non-linearity of strongly interconnected systems- the whole is not the sum of the parts. The approaches used in complexity theory are based on a number of new mathematical techniques, originating from fields as diverse as physics, biology, artificial intelligence, politics and telecommunications. Complexity theory is used in a variety of fields.

Let us now look at the different kinds of complexity -

1. Static Complexity

The simplest form of complexity is that related to fixed systems. Here we make the assumption that the structure we are interested in does not change with time. For example, we can look at a computer chip and see that it is complex (in the popular sense), we can relate this to a circuit diagram of the electronics and compare alternative systems to determine relative complexity (e.g. number of transistors). We can do the same thing for life forms.

At this point we have to decide as to how to quantify ‘complexity’ so that we can say that something is more complex than something else.

To approach such questions we need to look for patterns as well as the statistics of quantity. After all, we can keep the number of objects the same but shuffle the arrangements to get a pattern which is evidently more complex. When the number of objects is very large and so is the number of ‘values’ each property can take, then the number of possible patterns is enormously large and this can strain the analytical (pattern recognition) ability of current mathematics, even for relatively trivial systems. In nature multiple levels of structure exist in all systems, and this added to fractal complication (e.g. complexity of molecule, plus cell, plus organism, plus ecosystem, plus planet etc.) makes even this static simplification mathematically difficult to quantify.

2. Dynamic Complexity

Here we add the dimension of time. Function is one of the main modes of analysis we utilise in science, we ask the question 'what does the system do?', followed by 'how does it do it?', and both these presuppose actions in time. Science relies heavily on testing or confirmation, and this presupposes that we have multiple samples (either spatially or temporally). The forms of mathematical description that we employ will therefore have to be such that we obtain the same answers each time, and this has major implications for complexity theory. We are forced, currently, to artificially reduce the complexity of the phenomena we study to meet this constraint. A person has many aspects, but we describe them only by those that do not change with time (or do so predictably), e.g. name, skin colour, nationality (or address, job, age, height). Complexity theory however requires that we treat the system as a whole, and thus have a description that includes all aspects (as far as practical).

3. Evolving Complexity

Now we turn to a class of phenomena usually described as organic. The best known examples of this relate to the neo-Darwinian theory of Natural Selection, where systems evolve through time into different systems (e.g. an aquatic form becomes land dwelling). Classification of complexity thus takes another step into the dark, since if we cannot count on there being more than one example of any form how can we even apply the term science to it?

To answer this question we need to go back to patterns. In any complex system many combinations of the parts are possible, so many in fact that we can show that most combinations have not yet occurred even once, during the entire history of the universe. However, not all systems are unique - there are symmetries present in the arrangements that allow us to classify many systems in the same way. By examining a large number of different systems we can recognize these similarities (patterns) and construct categories to define them (this is, in essence, what the Linnean taxonomy scheme for living organisms is based upon). These statistical techniques are fine, and give useful general guidelines, but fail to provide one significant requirement for scientific work, and that is predictability. In the application of science (in technology) we require to be able to build or configure a system to give a specific function, something not usually regarded as possible from an evolutionary viewpoint.

4. Self-Organizing Complexity

This is the most interesting type and the one most relevant to complexity theory. Here we combine the internal constraints of closed systems (like machines) with the creative evolution of open systems (like dogs). In this viewpoint we regard a system as co-evolving with its environment and so we must describe the system functions in terms of how they relate to the wider outside world. Co-evolutionary systems, like ecologies and languages, are extremely adept at providing functionality, and if this is a requirement of science, we may be able to side-step the how question and tackle the desired predictability in another way. We can design the environment (constraints) rather than the system itself, and let the system evolve a solution to our needs, without trying to impose one. This is a very new form of organic technology, yet one already beginning to show results in such fields as genetic engineering and circuit design. From the point of view of complexity theory we wish to be able to predict which emergent solutions will occur from differing configurations and constraints of the environment.

Given that we have identified a potentially complex system, how do we then quantify it ? Let us now look at some specific techniques being used by complexity researchers in an attempt to add mathematical precision to the subject :

(a) Entropy - Entropy as a measure is the opposite of order (or information in Shannon's formulation). The main problem in this approach is that a single figure does not distinguish symmetrical or otherwise equally complex systems, and it says nothing about the actual structure present**.**

(b) Algorithmic Information Theory - Kolmogorov and Chaitin developed this technique. Here one tries to describe complex systems by using the shortest computer program which can generate the system. Thus the length of the program becomes a measure of the complexity. The drawback is that this has a high value for random noise which is not regarded as complex. Such an approach also takes little account of the time needed to execute the program. There's a lot of work going on to address these issues.

(c) Phase Transitions -Self-organizing systems are found to move from one phase to another - static or chaotic states to a semi-stable balance between. This property relates to the physics idea of phase transitions (e.g. the state change from ice to water), pioneered by Wilson. Attempts to quantify this point are seen in Langton's work on lambda and similar measures. The chief disadvantage is that such analysis is so far restricted to low dimensional systems (few variables).

(d) Attractors- Identifying the possible stable structures in connected systems requires the concept of attractors, and this idea is employed in work on neural networks by Hopfield, feature maps by Kohonen, and discrete networks by Wuensche. This is the best current technique for analysing internal network structure, but is difficult to do for realistic, high dimensional, systems.

(e) Coevolution- Using the biology concept of fitness allows us to model systems as ecologies, where the parts coevolve with each other. This can be extended to model multiple systems, as in Kauffman's NKCS model, and we can derive system wide fitness measures.

Alternative Approaches

There are some other new approaches which are being developed -

Game Theory - In political science, we have the theory of interactions based on decisions and relative advantage. This quantifies decision fitness at an individual pair level, but is harder to apply to more diffuse systems. The important aspect here is the distinguishing of positive from negative evolutionary paths - goal directed behaviours.

Spin Glasses - This technique, again from physics, uses a lattice of interacting points and is chiefly seen in complexity work under the guise of cellular automata, which can be used to model many physical phenomena (as in the work of Rucker). The technique, while excellent for simulation, proves mathematically difficult, but is important in relation to the demonstration of emergence, higher level structure.

References –

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