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THE ROYAL SOCIETY

The self-organization of space and time

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Self-organization is clearly relevant to biology, chemistry, Earth science, economics and other sciences that have to deal with big and complicated issues. This paper shows that self-organization also has a great deal to do with fundamental physics, including quantum mechanics, relativity, quantum gravity and cosmology.

This paper also aims to give some insight into what self-organization means and discusses questions such as the kinds of methods that can be used to understand self-organization and how self-organization relates to other modes of explanation such as reductionism.

Keywords: self-organization; space; time; unifying theories; string theory; theoretical physics

1. Introduction

In any system which qualifies as a universe—that is, any system that is closed with respect to the system of causes—mechanisms of self-organization will play a key role. There is a fundamental connection between a system being causally closed and the usefulness of mechanisms of self-organization in understanding it.

Universe could refer equally well to the physical Universe, the biosphere, a closed ecosystem, an economy or a society. The concept of self-organization is therefore relevant to economics, political and legal theory, as well as to the natural sciences.

The principle that there is nothing outside the Universe has two important consequences. The first of these is that there is no external organizer. This is an uncomfortable idea for human beings, because we are accustomed to making things. When we see something organized we wonder who made it and how it was made.

Scientists believe that in many cases there are no answers to these questions, so when we find complex structures we have to look for internal mechanisms of self-organization. Not everyone agrees, of course; there are many people in the world who do not believe in any mode of explanation besides that of an external maker.

The second implication, that the properties of systems in which self-organization is a useful explanation, can be characterized as being relational, is as important as the first for how we do science, but it is much less talked about.

2. The relational universe

The systems we are dealing with are made up of many parts or subsystems, and there are two ways to characterize the properties of these subsystems. The first is

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with respect to fixed references that are outside the system we are studying. The properties of such fixed references are known as absolute properties.

An example of an absolute property is the time as recorded during a biological experiment. In this case the time is generally taken from a clock on the laboratory wall, and for the purposes of the experiment the researchers are not interested in how the clock works.

The other way to describe a property of a subsystem is with respect to other subsystems of the system itself. Such properties are called ‘relational’. An example of a relational property is the price of a Canadian dollar in US dollars. There is no absolute standard against which the values of currencies are measured, so any analysis of the currency markets is based on the dynamics of an interrelated set of relational properties.

Since there is nothing outside the Universe, there are no references external to the Universe with which to define absolute properties. Any satisfactory analysis of a self-organized system must therefore be carried out in terms only of relational properties.

Interactions between subsystems can produce complexity and organization because there are generally no symmetries in the relationship of a given part to the whole.

Interactions between a subsystem and a fixed background, on the other hand, involve symmetries that have to do with properties of the background. According to a fundamental theorem of mechanics proved by Emmy Noether, symmetry gives rise to conservation laws—and conservation laws are constraints that can inhibit self-organization. As a result, interactions between a subsystem and a fixed background generally do not produce complexity and organization.

A background that is invariant in time, for example, creates a symmetry in which there is nothing to distinguish one direction of time from the reverse direction. This gives rise to conservation of energy. If the background is also spatially homogeneous, a similar argument gives rise to conservation of momentum. In each case the result is a universe in which there can be no increase or decrease in complexity. It is only when we consider relational variables that we can eliminate this symmetry.

Biologists are always talking about relational properties. The ‘fitness’ of an organism, for instance, is defined with respect to the ecosystem in which it lives, and not in some absolute sense, against an abstract, unchanging background. A certain molecule is said to be an ‘enzyme’ because of its behaviour in the context of a particular network of chemical reactions, not because of any property it possesses independently of this network of reactions.

Relational variables are created by the system itself, as it evolves. They do not exist *a priori*, but are defined in a context of relationships created by the dynamics of the system. Generally, a rich set of relational properties requires a population of diverse elements. If there were only one kind of molecule in a system, for example, there would not be any enzymes.

3. Why do self-organizing systems exist in nature?

There are several different ways in which internal processes generate complexity. Natural selection is clearly such a mechanism. Others are self-organized criticality, reaction–diffusion systems and some systems related to cellular automata. These different mechanisms cannot be reduced to each other, so there must be several distinct mechanisms of self-organization.

Do these mechanisms have any common elements apart from the fact that they create complex patterns from simple rules? One answer relates to thermal equilibrium.

When a system is in thermal equilibrium its entropy is maximized, the amount of information it contains is minimized, and we do not find mechanisms that generate complexity in time. The fact that various mechanisms of self-organization exist in nature therefore tells us that the whole Universe, or at least large parts of it, must be far from thermal equilibrium.

From the point of view of a physicist or a cosmologist, that is surprising, because the great age of the Universe—*ca.* 10^{17} s or 10^{40} Planck units—should have provided plenty of time for it to reach thermal equilibrium. Moreover, it is thought that, in its early stages, the Universe was indeed very close to thermal equilibrium.

Understanding why the Universe is not yet in thermal equilibrium is a question that has troubled physicists for more than a century, ever since Boltzmann and others formulated the statistical interpretation of the second law of thermodynamics. The second law, they realized, implies equilibrium, uniformity, the absence of complexity and the absence of life.

Boltzmann's own answer was that the universe we see is just a small fluctuation away from equilibrium in a universe that spends almost all of its time in equilibrium. This argument is clearly unsatisfactory. It makes no sense today, when the Universe is known to have existed only three or four times longer than life on Earth.

A modern explanation has to do with the existence of gravity as one of the fundamental forces. By pulling objects together, gravity acts against the tendency of the randomness of molecular dynamics to homogenize systems. Gravity creates inhomogeneities.

Gravity is by far the weakest force, particle for particle, but it has infinite range and is always attractive. This means that gravity dominates on the largest scales—planets, solar systems and larger objects—and has the peculiar property that, under the right circumstances, it can keep a system out of thermal equilibrium for a very long time.

If gravity were as strong as the electrical force, the Universe would quickly collapse into homogeneity. But gravity is weaker than the electrical force by a factor of around 10^{38}, and this allows inhomogeneities to persist for billions of years. One such inhomogeneity is our Sun, without which there would be no life on Earth.

Without this weak gravitational force, the Universe would have been in thermal equilibrium for most of its history, and there would be no self-organization. Physicists can imagine many different universes, distinguished by different relative strengths of the various forces. It is remarkable that most of these imaginary universes could not support a significant amount of self-organization. That fact that we live in a universe in which there is self-organization seems apparently to be due to some special features of the fundamental laws.

4. Self-organization and the laws of physics

So far the argument has been about why physicists believe that the existence of self-organization depends on the fundamental laws. Now it is time to discuss the fundamental laws themselves. Why is the Universe governed by one set of laws and not another? It transpires that other aspects of self-organization seem to be involved in the selection of the fundamental laws.

The most fundamental laws have to do with space, time and motion. The distinction between absolute and relational properties discussed above is very relevant here, and in fact this distinction first arose in considerations of space and time.

Most traditional Newtonian physics deals with isolated subsystems of the Universe: a solar system, a ball moving in the Earth's gravitational field, a puck sliding on an inclined plane. In these cases it is possible to measure quantities such as position, time and motion with reference to a frame defined as external to the system being studied, and assumed to be unchanging. Thus Newtonian physics treats space and time as absolute quantities, and the same is true of ordinary quantum theory.

But what happens when we want to model the Universe as a whole? There are no clocks or other reference systems outside the Universe. A rational theory, in which all the quantities are measurable by observers who are also inside the Universe, requires everything to be defined in terms of relational quantities. Thus, in a cosmological theory space and time must be relational.

The right, and indeed only scientifically coherent, view of space and time is the relational view championed by Newton's rival, Leibniz. In the 20th century this became the basis of Einstein's theory of general relativity, the first theory in which space and time are genuinely relational. Einstein and Leibniz both realized that position and motion have no meaning except relative to other things in the Universe, and that time has no meaning or measure except relative to some physical process which we use as a clock.

The following two conclusions can be reached about how physics and biology may be related.

(i) Fundamental properties in physics, such as space and time, have something in common with biological properties: they are all about relationships, not absolutes.

(ii) Were there no gravity there would be no biology. Without gravity the Universe would be in equilibrium and there would be no processes of self-organization to create the complex structures that characterize biological systems.

These two conclusions are themselves connected through Einstein's theory of general relativity, which says that gravity is a direct consequence of the relational character of space and time.

5. Fine tuning and unifying theories

Self-organization in the physical Universe requires large differences in the strengths of the various fundamental forces, and that the existence of several kinds of atoms requires further delicate balances in certain parameters of fundamental physics. Does the fact that our Universe meets both these conditions itself have something to do with relationality or self-organization?

The standard model of particle physics, the basis of our understanding of the laws of physics, contains around 20 numbers representing quantities such as the masses of all the particles and the strengths of all the forces. These numbers are free parameters, meaning that the standard model gives no insight into their values. Instead, physicists derive their values experimentally and plug the numbers back into the model.

If the 20 parameters of the standard model represent a 20-dimensional space, it turns out that the region within this space in which life could exist is tiny. If all the parameters were chosen randomly, physicists believe that the chance of a Universe in which life could exist would be about 10^{-240}.

Why the parameters that apply to our Universe fall into the tiny region that allows life is the mystery of fine tuning. The oldest solution to the problem of fine tuning is that underlying the standard model is another theory that is more elegant, more compact and has no, or very few, free parameters. In this hypothesis the parameters of the standard model are no longer free, because they are determined by the underlying theory.

Belief in such a theory implies the existence of a realm of pure mathematics which underlies our sensible world. This is Platonism: a kind of mysticism in which mathematics replaces God. Platonism and religion share the idea that the answer to the question of why there is life in the Universe exists in terms of something eternal and absolute that, although hidden, underlies all we see.

6. String theory

Theoretical physicists find this idea very attractive, and a few years ago they discovered an excellent candidate in the form of string theory. At that time there was no experimental confirmation of string theory, and this situation seems unlikely to change. Although string theory is not necessarily true, it is the best thing science has produced to address the issue of the fundamental laws of physics.

At first, string theory was thought to be unique. Better understanding, however, showed that it is highly non-unique. In fact string theory comes in a huge number of versions that give rise to different universes, in different dimensions, with different combinations of elementary particles and forces. String theory turns out to have many more parameters than the standard model it was invented to explain.

String theory is now broadly accepted, but for many physicists its complexity means that it cannot be the fundamental theory they seek. Platonic reasoning says that the fundamental theory must be unique. String theory is non-unique, so it cannot be the fundamental theory.

Instead, the idea of a unique fundamental theory has been transferred to a hypothetical theory, called M theory, now thought to unify and underlie the many different string theories. Though many physicists believe it exists and have worked hard to develop it, M theory has never been written down. So the expectation that mathematical consistency will save the day and explain the values of all the parameters is not doing well at present.

7. Other explanations for fine tuning

Other ideas have been proposed to explain fine tuning—the fact that the values of the fundamental constants dovetail in a highly unlikely way that has allowed complexity and life to arise in the Universe.

One is the strong anthropic principle. This says that there is a God who made the Universe, and that God tuned the parameters so as to make possible the existence of intelligent beings. Realizing that fine tuning—and hence their own existence—was highly unlikely to be due to chance, these intelligent beings would infer the existence of God and love him as their creator.

Another view, the weak anthropic principle, posits a huge number of universes in which the parameters are chosen randomly. If there are at least 10^{240} universes, the argument runs, there are likely to be a few in which the dials are set so that life can exist in them.

A large number of physicists believe in some version of the weak anthropic principle, but it is an empty explanation. Had biologists resorted to this type of reasoning, for instance, modern biology would not exist.

Unfortunately, none of these proposals—unifying theories, anthropic principles—provides a satisfactory answer to the mystery of fine tuning. Instead we seek a new methodology, a new way to explain the operation of systems that can be delicately tuned to allow more structure and organization than one would otherwise expect. The new theory should also be able to make predictions that are falsifiable, which M theory and the anthropic principles do not.

Inspiration from outside of physics has led to an idea called cosmological natural selection. This is a self-conscious copy, not of biology (because biology is too complicated to copy), but of the logic by which biology works. More specifically, it is a copy of some mathematical models of biology that are probably already discredited among biologists.

8. Evolving universes

Extrapolation backwards in time, using models that incorporate what is known of the laws of physics, shows that the past Universe was denser and hotter than it is now. Going back far enough (*ca.* 14 billion years) yields the Big Bang, a point at which the Universe appears to become infinitely hot and infinitely dense.

The moment when things became infinite is called the singularity. Of course, temperature and density cannot really be infinitely large, so what actually happens at this point is that some new laws of physics must take over to give a sensible picture of what happened at the Big Bang. Understanding these new laws is a problem known as resolving the Big-Bang singularity.

Resolving the Big-Bang singularity involves looking backwards in time. A similar problem, which concerns the forward direction of time, is to predict what happens during the collapse of a black hole. During this process, the interior of the black hole gets denser and hotter, until at some point it too becomes infinitely dense and hot.

One solution is to make each of these problems the complement of the other, so that a new universe is born out of the collapse of a black hole. In every black hole is the creation of a new universe, and before our Universe there was a black hole in some other universe.

This idea goes back to the 1960s. One of its original champions, the physicist Johnny Wheeler, speculated that, every time a universe was created, the dials would spin, producing a universe with new values of the parameters of fundamental physics. He called this 'reprocessing the universe'.

However, if the dials did not spin at random each time a universe was created, but instead shifted by small random amounts, then the parameters of each universe would differ by small amounts, on average, from those of its ancestors. On this reasoning the end result would be a ‘population’ of universes analogous to the population of a living organism. Variations in the values of the physical parameters of each universe are analogous to variations in the genes of an organism.

By treating this as a situation that can be modelled by old-fashioned population biology, it is possible to look at whether the population of universes evolves on the parameter space. This is the idea of cosmological natural selection.

There is some justification for suggesting that universes might indeed evolve in this way. Since each black hole represents a future new universe, we might expect evolution to move towards universes that contain many black holes. The number of black holes turns out to depend strongly on the values of the physical parameters of the universe, providing a test of the theory: the present settings of the dials should be those that make the production of black holes most probable.

Researchers cannot yet say whether this is the case, but they have started working on the problem. It turns out that most known black holes (and there are at least 10^{18} of them in the visible universe) result from the death of massive stars. So the creation of black holes requires stars, and we can ask whether the values of the parameters in our universe seem likely to maximize the number of stars. Given our limited understanding of how stars form, this does indeed seem to be the case.

The most important thing is that cosmological natural selection is testable. To kill it, all that is required is one convincing argument that a change in the parameters would greatly increase the number of black holes. Unlike M theory and the anthropic principles, the theory of cosmological natural selection is ‘real’ science.

9. Complexity and variety

A definition of complexity invented in the early 1990s by the author and Julian Barbour applies explicitly to any system whose properties are expressed as relations between subsystems. The basic idea is that the more variety there is among these relations, the more complexity there is. To say this more precisely, we define a quantity called ‘variety’ as the inverse of the amount of information needed to distinguish each subsystem from the others, using just the information about the relationships between the subsystems. The more distinguishable the subsystems are, the higher the variety.

This definition of complexity is superior to others that measure just the amount of information in the system, or measure entropy or related quantities based only on notions of probability. The problem with these other methods is that there are two reasons why the entropy of a system may be low.

A system that is very complex promotes self-organization, and it has low entropy because it is far from random. A regular lattice is also far from random, so it too has low entropy, but it will not give rise to self-organization. The notion of variety distinguishes systems that are improbable because they are uniform from systems that are improbable because they are rich with unique internal relations.

The essence of our idea is that, in a system that is less varied, you have to look further to find features that tell you uniquely where you are. Compare an old European city with a modern American suburb. The old city is complex because all its streets and buildings are different: set down on any street corner, an observer can immediately tell where he or she is. A suburb has low complexity because many of its streets look alike, so the observer finds it harder to orient him- or herself.

We have studied this idea not only in connection with biological systems but also with respect to space and time itself. We considered the network to represent the network of distance relations in space, and tried to reproduce properties of the real world by asking that the network of spatial relations should maximize or minimize variety.

The idea is that we locate ourselves in space by purely relational variables, so that if the Universe has many distinct positions, each must be distinguished from every other by a unique set of relations to the rest of the Universe. To use Leibniz's terminology, the view of the Universe from each point in it must be as unique as possible. This is speculation, but it illustrates how ideas of complexity might play a role even in defining what we mean by space and time.

To summarize, the basic conjecture is that, in a system defined by relational properties, mechanisms of self-organization work by increasing the variety of the system. If this is true, it may explain how structure and complexity arise in systems, whether they are biological, economic or physical. What these different systems have in common, we believe, is that they are described by relational variables that refer to how subsystems interact with each other.