Self-Organizing Systems

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giving us a universe of surprise

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Concepts

References

The study of scientific fact contributes to the growth of knowledge, but the study of scientific principles contributes to the development of understanding There can be power in knowledge of the fundamental and there can be wisdom in understanding the universal. There is more than enough power in the world, but not enough wisdom.

Martin Zwick in “Elements and Relations” (2013)

1. Paradigm Change Toward Holism

Definitions

Paradigm - a collection of understandings constructed and shared by members of a given community; the set of beliefs, concepts, and procedures that a particular group of people have accepted.

Reductionism - the concept that the behavior of a whole is reducible to the behavior of its constituent parts.

Holism - the concept that parts can cooperate and function as a coherent unity with characteristics different from any of the parts; the whole is more than the sum of its parts.

Background

To many of us, most of the time, the real world seems to exist outside ourselves. But when considered more carefully, as Kant insisted, we actually know only the world that we perceive with our senses and our brains. Our world may differ dramatically from the "reality" of other human beings since they perceive the world from different points of view. Our points of view are conditioned by our culture and shared within it. What we think to be external reality can only be an internally constructed concept of something we call reality - a paradigm.

This is not to deny the existence of an external reality but only to remind us that our conception of it may be influenced by the paradigm we share. As for example, compare a paradigm of the external world that includes the existence of ghosts with one that does not.

Discussion

Paradigms are important and useful. They help to define and describe the world we live in and thereby assist us in making sense of phenomena. For good or bad, they also can unite groups of people to a common world-view. Paradigms also enable us to investigate and manage the phenomena around us. But paradigms can also be confining. By implication, paradigms define and limit those problems and methods of inquiry which may legitimately be pursued by practitioners, as the following example will show.

There was a time when the dominant paradigm was that the Earth and all things therein were created for the benefit of humans. The world was simply a stage upon which human beings were to work out their own lives and destinies so that they could achieve salvation or fall to hell. Included in this paradigm was the concept that crystalline spheres carried the moon, the planets, and the Sun in their paths around the Earth. The Earth and the human beings that inhabited it were at the very center of the universe.

A paradigm change: from geocentrism to the pale blue dot

We are all aware of how wrenching and difficult was the change from that comforting paradigm to one of a universe in which the Earth is a small planet revolving around a third rate star. The evidence that astronomical observations brought to rational minds forced the abandonment of the Earth-centered view. This appeal to nature itself as the final arbiter of what was correct or incorrect was the shift in paradigm that ushered in the modern scientific approach to the study of the world. The new paradigm which developed included the idea that the universe is ruled by rigid mathematical law. Overjoyed that the motion of the heavenly bodies could be accurately predicted, Newtonian scientists extended the paradigm and began to view all of nature as a vast clockwork mechanism.

Another example of how a paradigm can influence our view of things was the shared belief of early experimenters that electricity was some kind of fluid; a fluid that could flow through wires as water flows through a pipe. Containment experiments could then be performed in which electricity was “poured” into Leyden jars (containers) and stored there. The language of that paradigm is retained when we use the term electrical currents.

There are, of course, many different varieties of paradigms dealing with different areas of human life. Several of them can be in operation simultaneously and one may be in conflict with another. For example, the dominant economic paradigm is the belief that continuous technological advancement is not only beneficial but is necessary for the well being of society. For some people this paradigm is in conflict with the environmentalist one which holds that excessive exploitation of resources puts the natural world in peril.

The current paradigm of science – reductionism

In this view complex systems are simply complicated collections of simpler systems. To understand them it is necessary to break down the complex system into its constituent parts and study those parts. For example, to a reductionist the essence of thought will eventually be made known by studying the brain's biochemistry and its neural interactions.

Reductionism has been justified because many systems in nature can be understood by isolating and studying one part at a time. The process has brought us to our present state of knowledge. However, when the functioning of complex systems is reduced to the actions of relatively simple parts the result is often a mechanistic view of phenomena.

The triumph of Newtonian physics encouraged a mechanistic view of everything. Both the weather and human body are still often referred to as machines. The ultimate expression of the reductionist point of view was that given by the French mathematical physicist Marquis de Laplace (1749-1827) who declared that if an intelligence knew the location and the velocities of all the particles of matter in the universe and all the forces that acted on them then "nothing would be uncertain and the future, as the past, would be present to its eyes." In that view the future is completely determined by the past.

Psychology has not been immune from the influence of the reductionist paradigm. Under behaviorism, for example, living organisms are considered as only stimulus/response units whose behaviors, with the proper conditioning, can become regular and predicable. While this view has had some experimental success, it is now generally held that living systems are much more than simple reaction machines.

We are beginning to understand that much can be left out when we maintain that "the whole is simply the sum of its parts." Another major criticism of reductionism is that it leaves us uncertain of how novelty enters the world. Reductionism tells us nothing about how properties at one level emerge from those at lower levels.

The process of paradigm change

Paradigms change because our knowledge is incomplete and as new discoveries are made contradictions or anomalies arise. These call into question an existing paradigm. At first the contradictions are challenged by the "old guard." The new view is "crazy" it "does not fit." But as the contradictions accumulate or, as an increasing number of investigators confirm them, a new vision of reality emerges. A paradigm change is in the making. The rise of quantum physics or the Einsteinian view of the curving of space are examples.

The discovery of the structure of DNA was a triumph of reductionist molecular biology. It was heralded as the master molecule of living organisms and began an ongoing revolution in biology the results of which are impossible to forecast. But biology is the ground in which the seed of holism flourishes. How is the origin and the development of living organisms to be accounted for? Can molecular biology explain migratory patterns? Can the functioning of an ant colony be discerned from a study of ant DNA?

The holistic paradigm

In this view the proper study of nature is not the effort to analyze it into its simplest constituents. It questions the intellectual approach that what is most fundamental in the universe are the elementary structures of which it is made. Holism holds that this approach misses what is of most importance. It misses the interrelationship among things. To understand the structure of things is to know only part of nature. Understanding the dynamical principles that change and influence those structures are also necessary.

Reductionism plus holism

This new perspective treats systems as wholes and searches for new tools and laws to understand complexity and the sudden emergence of new properties. If these laws of organization exist, they would not contradict well-established physical laws but would rather compliment them. The analysis provided by reductionism would be aided by the synthesis of holism to produce a deeper understanding of nature.

Changing times - changing paradigms

For the first half of the 20th century the dominant paradigm in science stemmed from the study of physics. Exciting discoveries in the subatomic realm and in astronomy dominated the scientific news. The ultimate reality was seen to be in the blind collisions of elementary subatomic particles. The origin of the living cell was believed to be an accidental combination in a primordial warm organic soup. Random mutations and environmental fluctuations made the evolution of living forms a matter of chance.

In contrast, the paradigm that includes the self-organization of matter into more complex configurations reduces the role of chance in the origin of living things. When a pre-biotic chemical system increases its molecular diversity beyond a certain threshold of complexity and there is an input of energy, an organization that has the property called "life" spontaneously emerges. The possibility of microbial life on Mars is a discovery which does not "fit" the paradigm of life as merely a lucky, highly improbable accident. Rather, if true, it would support the notion that there is a natural tendency for matter and energy to spontaneously form new and more complex combinations with new and unexpected properties.

There are indications that what seemed to be an absurd paradigm is becoming more acceptable. Ecological studies are moving us toward a more holistic view of the world. That new behaviors and properties emerge out of the interactions of parts of complex systems seems reasonable. We acknowledge this holistic point of view when we speak of the "personality" of an athletic team or refer to the mood of a piece of music as the property of the whole. The often repeated phrase "everything is connected to everything else" is another example of the changing point of view.

2. *The Systems View*

Definition

System - a group of parts so linked together by interactions that the group functions as a whole.

Background

The scientific world-view that began with the work of Galileo, Descartes and Newton and extends to the present day has been wonderfully successful. So much knowledge on different aspects of nature has accumulated that it is impossible for one mind to encompass it all. Scientists, of necessity, limit their areas of investigation. The current perception is that any "serious" scientist must be a specialist.

By definition, specialists limit their studies to phenomena in their field. Looking for causal relationships they fill our scientific journals with more and more detailed information. What is often lost amid the detail is the view of how the part is related to a whole functioning system. When a number of interconnected things are impacted by a number of different influences, who chronicles the result? It is generally agreed that the world is complex and interconnected but studying those interconnections is tough. To understand them we need something more than the specialist's view.

Discussion

The systems view is one in which the connections and interactions among parts are always present. For example, we arise in the morning in response to a mechanical system whose parts cooperate to make a sound at a pre-set time. We may shower and make use of the plumbing system of the house which is part of a larger public water supply system. Our body itself is a system composed of numerous sub-systems. We feed it with materials brought to us by a vast food supply system. If we enter a bus, train or car we are for a time enveloped in a mechanical system which is part of a larger transportation system. A school is a system in itself with many sub-systems operating within it. The systems may be physical or they may be manifest in the relationships of parts such as the hierarchical system of educational responsibility from principal to teacher's aide. The school is part of the educational system which is, in turn, part of a broad social system.

From the systems point of view we are surrounded by systems nesting within systems. Is there anything which exists on its own without a relationship to other things and which is not, in some way, part of a larger functioning whole? On the most basic level everything that has physical existence has mass and is attracted to everything else. Newton's apple and the Earth form a system; they are both attracted to a common center of gravity.

The systems view identifies parts of integrated wholes, studies their internal connections and their interrelations with other wholes. With multiple influences at work, the relationships can rarely be simple or linear. An important result of the systems view is the discovery of the coordination among parts that enables systems to have structure and to function. System researchers hope to discover common principles which prevail in the development of many different types of systems.

General Systems Theory

As early as 1925 Ludwig von Bertalanffy was advocating an organismic conception in biology. That is, living things are considered to be organized wholes or systems. The discovery of principles of organization was what von Bertalanffy saw as the main objective of biological science. This point of view has been slow to catch on but in recent years some biologists and ecologists have begun to agree with his approach.

In von Bertalanffy’s view it was obvious that ideas of wholeness and cooperation are vital parts of biological, behavioral and social science. Some sort of general theory of organization seemed necessary.

Part of this general theory, if it could be developed, would be the formulation of principles that would be valid for all kinds of systems. It would also express laws of organization. One example of such a law is the exponential law of growth. Exponential growth holds for phenomena as diverse as bacterial growth in a petri dish and human population increase. It also describes the progress of scientific research when measured by the number of publications produced. The point is that in completely dissimilar fields, with different causal mechanisms, there are similarities in the behavior and organization of systems.

General systems theorists search for properties and principles that pertain to systems in general: characteristics that are common to organized wholes. The questions they ask are intriguing and still unanswered: Is there a pattern of system dynamics that is common to biological, social, cultural and cosmic evolution of systems, or are there many different paths to the organization of systems?

Conclusion

The legacy of the Newtonian world-view has been a mechanical/mathematical description of nature. Although this description is useful, it is incomplete because it breaks down phenomena into parts. What is needed for the study complex interconnected phenomena is a science of organized complexity which will not leave out the relationships among the parts. Teachers can help students appreciate the systems view of the world by frequently asking a couple of simple questions, "What is the system involved? What are the parts? How do they work together? What organizes them?

3. *About Systems*

Characteristics of Systems – in general

Everyone is familiar with the word system. Look around and name as many as you can; in your body, in the room and then in the larger world. What do they have in common? Some characteristics are:

1. They are made up of parts.
2. The parts are mutually interdependent
3. The function of the whole is different from the behavior of the individual parts.
4. Energy flows through all of them.

Background

As the scientific understanding of nature has increased and deepened, it has become evident that the world is more interconnected than we could have imagined. To some minds the component parts of the universe are so strongly linked together that the line in Francis Nicholson's "The Mistress of Vision" – "Thou cans't not stir a flower without troubling of a star," hardly seems an exaggeration.

A more recent and more scientific illustration of interconnectedness and the sensitivity of some systems to small perturbations is the Butterfly Effect. In 1972 Professor Edward Lorenz of MIT presented a paper which discussed how the flap of a butterfly's wings in Brazil might set off a tornado in Texas. It began the modern study of chaotic systems where small changes in initial conditions can have large scale consequences.

Another illustration of interconnections among systems comes from the science of ecology. By stressing the interlocking relationships among organisms and the reciprocal influence between organisms and their environment, ecology has reinforced the idea that nature consists of systems within systems.

Definitions

System - a group of parts so linked together by interactions that the group functions as a whole.

Equilibrium - the state in which there are no differences in temperature and the concentration of matter is uniform.

Evolution - the process through which new structures, behaviors or concepts are produced from previous ones. (Evolution in this broad sense goes beyond the biological to include, among others, chemical, cosmic, social and intellectual evolution.)

Discussion

The fact that the word "system" is so frequently used indicates both the usefulness of the concept and the ubiquity of systems. Increasingly the world is viewed from a systems point of view. Besides biological and astronomical systems we recognize economic, mechanical, legal, political, educational and logical systems, to name a few.

Traditional science has been remarkably successful in finding out how things work by taking them apart and studying the pieces. The process is less successful when the entity examined is complex and the parts interdependent. Focusing on the parts tends to make the interactions disappear. Using concept mapping techniques in studying systems will help conserve the pattern of internal relationships and how the system as a whole behaves.

Characteristics of systems

1. Systems have both structure and behavior. For example, the structure of the human nervous system is an arrangement of nerves, ganglia and brain. Part of its behavior is to make a person aware of changes in the environment. Without the connected structure this behavior would not be possible.

2. *The behavior of a system is a product of the properties it exhibits.* Using the above example, the neurons which compose the human nervous system have the property of being able to convey electrochemical signals. Without this property there would be no behavior of the system.

3. *The parts of a system exhibit mutual dependence.* One way to identify the essential parts of a system is to remove the part in question. If the system keeps operating without change, that part was not a vital component of the system.

4. *Some systems are more dynamic than others.* They all do something. A system as simple as a molecule is dynamic in that it affects its environment with its electrostatic field and consequently has an influence on neighboring molecules. A specific crystal system refracts light in a specific way. A more dynamic system like a hurricane or a tornado severely affects its surroundings and then breaks down.

5. *Systems can produce novelty.* The properties of the whole system are more than the simple addition of the parts. (A theme throughout this book.) Put electrical resistors, condensers, wires, transistors and a power source together in a certain relationship and a new property emerges - the ability to detect radio waves. This ability is not in any of the parts. It originates in the special relationship among the parts and is usually impossible to predict.

6. *Systems produce patterns.* As a consequence of their continued existence, systems repeat a sequence of actions which can form patterns. Cardiac rhythms and brain "waves" are examples in the human body. Convection cells and cyclical chemical reactions produce physical patterns, as in the famous clock chemical reactions.

7. *There is a tendency for systems to combine to form more complex systems.* Hierarchical organizations of nested systems are common in nature. As systems interact they influence and modify each other and their environment. New behaviors and new properties arise out of the interactions. The human body with its various sub-systems is an example.

Some thinkers consider the tendency for systems to combine to be so important as to raise it to the level of a law of nature. The combined systems are often said to be higher level systems. The designation of higher and lower is not meant to be one of value. The distinction of higher and lower is made to identify those that are more complex from those that are simpler.

System energy states

Some systems, like a crystal, are very near equilibrium in that the flow of energy and matter through them have almost ceased and differences in temperature and concentration have been reduced. Other systems, like a hot cup of coffee in a room, are further from equilibrium but will inevitably move toward it as described by the Second Law of Thermodynamics.

There are, however, many systems that exist far from thermal, chemical or physical equilibrium. The Sun, the weather system, and all living things are examples. Systems far from equilibrium are often critically sensitive to changes around them, and their responses constitute the evolution of those systems. Those responses may produce dramatic changes. A star can become a nova or a brown dwarf. A collision between air masses can produce a storm front. Mutations occur when the genetic structure is altered. By amplifying certain fluctuations, systems far from equilibrium can move into new and radically different configurations. New and unpredictable variations with vastly different and new properties may emerge.

Toward a general theory of systems

The tendency for systems to combine and form new systems that are more complex, have more connections, and produce novelty could be the observational basis for the foundation for a general theory of systems. In the broad view this tendency may be recognized as a fundamental organizing principle of the world. In a narrower perspective it can be used to account for the complexity we see about us.

4. Self-Organizing Systems

Definitions

Self-organizing systems – systems which spontaneously form from the association of compatible parts. The forms and functions of the systems are new and arise from the relationships among parts.

Dissipative systems - systems which disperse energy and/or matter into their environment in the course of their self-organization and self-maintenance. Self-organizing systems far from equilibrium are dissipative systems. All living things are dissipative systems.

Background

Living things could not exist on the molten mass of the very young Earth. Now that it has cooled living organisms exist everywhere on its surface and under parts of its surface in a myriad of forms. The existence of these living organisms demonstrates the emergence of a new kind of organization of matter. According to the scientific view, this new organization emerged from non-living matter without supernatural assistance. Although the process is not yet adequately understood, there is experimental evidence for the self-assembly of amino acids (the building blocks of proteins) from inert materials. However, living systems are only one broad category of self-organizing systems. There are the inorganic systems of matter and the cosmological systems.

Discussion

Self-organizing systems exist on many levels, from self-organized atoms to gigantic clusters of galaxies. We designate the levels by their degree of containment (nesting) or complexity and use the words “higher” or “more complex” for those systems that are made up of many “lower” or “simple” systems.

Self-organizing systems can also be divided into groups according to their energy use. Some, like atoms, crystals and the planetary system, require no input of energy from the outside to maintain themselves. These systems are close to equilibrium. Other self-organizing systems maintain themselves only through continuous exchanges of energy and matter with their environment. They are not only absorbing matter and energy but are also shedding them.

Characteristics of self-organizing systems

Multiple components

Self-organizing systems are networks of many parts acting coherently. Each part operates according to its own nature but within an environment produced by its interactions with other systems.

Self-initiated interaction

It goes without saying that in a self-organizing system there is no "self." But it is important to emphasize that there is no agent or center inside the system forming it. In a self-organizing system like a candle flame billions of molecules cooperatively create the flame's pattern and properties. In the self-organized system of a free economic market there is no central command center. The prices of the goods are an outcome of the interaction of the participants and the processes involved.

Self-configuration

As a self-organizing system constructs itself the arrangements of it constituent parts is determined by the internal relationships of the parts. The cubic shape of salt crystals, for example, is determined by the lattice formed by the alternating sodium and chlorine ions.

Mutuality of influence - Interdependence

Just as system behavior is produced through the synergistic action of the constituent parts, the behaviors of the parts are influenced by their association within the system.

A consideration of flocking, schooling and herding behavior will make this clearer. The spacing and speed of movement of each animal produces the group behavior. However, the behavior of the group, speeding up or turning to avoid predation for example, will change the individual's behavior.

It is this kind of mutuality of action which makes self-organized systems so difficult to study in the traditional reductionist way of science. Everything is in flux. The system is influenced by the parts and the parts are changing because of the interactions within the system. There are many feedback arrangements at work.

Communication (Information exchange)

Since the action of a self-organizing system is a product of the internal interactions of the parts, there must be some way in which the parts influence each other for the system to function. Should this information exchange fail, the system would cease to operate. How could blind birds form a flock?

Self-maintenance - Adaptation to change

Within limits, a self-organizing system has the ability to preserve its form and to reorganize itself in the face of disruption. The flickering of the candle flame and the sweeping turns of a school of fish are examples. The system is constantly reforming itself as it responds to changes in its environment. It is the many feedback arrangements involved that tend to maintain the system.

A special note on feedback and self-organizing systems

In all self-organizing and self-maintaining systems feedback is, of necessity, an essential element. The notion is imbedded in the concept of interconnectedness of system parts and mutuality of influence. However, explanations using feedback mechanisms become extraordinarily complex when dealing with self-organizing systems.

In a simple feedback system the change in output can be fed back to influence production and link the parts. But when more interconnected parts are added to a system it very quickly becomes impossible to disentangle the feedback circuits. In some cases the feedback may have diverse effects on different parts. For complex systems the concept of simple feedback is usually inadequate.

Some more characteristics of self-organizing systems

Collective new properties are produced

An aggregation of things that coalesce into a self-organizing system becomes something more than a collection. As the parts establish mutual relationships, the system as a whole acquires new collective properties. When enough neurons come together and interconnections are established among them, the property called consciousness comes into being. The collective property is not within any of the parts. It is a product of the interconnections.

Divergent property of dissipative systems

The concept of dissipative systems originated in the work of Ilya Prigogine for which he won the Nobel Prize in 1977. Dissipative systems operate far from equilibrium. They take in and disperse considerable quantities of matter and energy and exhibit instabilities which make their courses impossible to predict. Although the actions of such systems are bounded by the limits of physical laws they have many ways of proceeding within those limits. Examples are the touchdown points and paths of tornados, the branching points of plants, or where the reaction wave will start in the famous Belousov-Zhabotinskii oscillating chemical reaction.

As has been mentioned living organisms are obviously dissipative systems. From the same starting point in a constricting maze the second path of a subject animal is never the same as the first it traveled. Even genetically identical twins have different eye iris patterns and, in time as they interact with their environment, develop other differences. For dissipative systems there are divergent pathways. Many directions, all equally possible, are open to them and, as they move into a particular set of sequences, they create new possibilities that might not be available had they moved differently.

Biological evolution is the result of this divergent property. The path of species development must obey physical laws and environmental constraints but can never be predetermined. Self-organizing makes the future so interesting.

Summary

Using the above characteristics self-organizing systems can be described as those systems that have multi components and that initiate their own interactions and configurations. Such systems exhibit an interdependence of parts and there is communication of some sort among the parts. They are able to maintain themselves and adapt to changing environments. Often new properties are produced when they self-assemble and those systems that are far from equilibrium change in very unexpected ways.

Conclusion

The ability of systems to self-organize and spontaneously and unpredictably develop new behaviors or structures brings novelty into the universe. Within the deterministic laws of physics, self-organizing systems bring the unexpected, making the future unknown and unknowable. Through these systems nature is creative.

The second law of thermodynamics describes a universe running down to changeless equilibrium. The development of self-organizing systems shows a universe increasing its levels of complexity and organization, albeit locally, at the expense of entropy increase elsewhere. This is further discussed in Section 19.

5. A General Hypothesis of Self-Organizing Systems

Perhaps now, after the previous discussions, it is time to put forward the general hypothesis upon which this book is based.

Hypothesis –

There is a tendency in the universe for parts to spontaneously assemble into systems, and for systems to combine to produce new states of increased organizational complexity.

This is a non-random process based upon the properties of the components. Systems affiliate with compatible system partners. The new organization may be characterized by abrupt transitions and the emergence of new structures, properties and/or processes. Systems produced engender feedback arrangements in which the new structures and properties act to change the environmental conditions and thereby induce more novelty in the universe.

For the process of self-organization to take place an input of energy is always necessary.

Note 1: The skeptic will say, "Where is the evidence for the postulate above?" All one can say is to look around. The world is full of systems when the eye is open to them. There is no living thing that can exist alone. It must be part of a larger interaction. The realm of inanimate matter is replete with parts linked by their interactions.

For a hurricane to form it must absorb energy from the ocean surface. A molecule cannot exist without the interconnectedness of its atoms. The very atoms of which all matter is made are built out of the electrostatic relationships of subatomic parts.

The hypothesis cannot proved or disproved by experiment yet it remains a strong suggestion of how the world comes together.

Note 2: The hypothesis as stated refers to operations starting from basic particles conceptualized as material objects i.e. electrons as point objects. The view that fundamental reality are fields of various sorts and that entities such as electrons and quarks are wave-like manifestations of such fields is acknowledged but does not alter the basic premiss.

Note 3: The systems referred to are dynamic ones. Systems in thermodynamic equilibrium may not be participants in the hypothesized process.

Discussion

For self-organization of a system to take place a set of conditions is necessary.

1. At a minimum the parts to be organized must have a requisite degree of affinity, characteristics that will make them "stick."

2. There has to be a force, an organizing principle, at work that will bring the parts together.

3. The parts need to be within the range of an organizing principle. An obvious example: the electrostatic attraction principle cannot function if the particles are too widely separated.

4. For the system to continue to exist bonds must develop that are strong enough to hold the parts together in the face of environmental perturbations.

5. For the system to function the parts must maintain interactive relationships in order for them to function within the system. Each part, in some sense, must "feel" the presence of the other parts and react to what the other parts are doing. This stems from the basic system characteristic of interdependence of parts.

These conditions, necessary for system building, must be quite prevalent since so many systems abound in nature. One can say that the universe itself is one vast system that contains many subsystems.

6. *Organizing Principles*

Previous mention has been made of organizing principles. Their importance requires a separate section.

Definitions

Order - a special arrangement in which parts of a whole are in some regular relationship or repeatable pattern as, for example, in a crystal.

Organization - a complex of relationships among components that act in a cooperative, systematic way. As used here it refers to processes rather than structures.

Organizing principles - those forces and processes which shape matter and behavior into patterns and patterned activity, and which are necessary to bring parts together to form systems. Examples; electrostatic attraction is the organizing principle which molds matter into atoms, molecules and compounds; profit making is the organizing principle that makes an economic system work.

Background

The terms order and organization are sometimes used interchangeably; as when someone says that something has poor organization, meaning poor order. The use of the word "organization" as a noun has confused the meaning even further. It is important to clearly differentiate between order and organization.

Organization and Order

Our language has made the differentiation between order and organization difficult. Organization refers both to an act and to something that has been made into an ordered whole as when a corporation is referred to as an organization. As used here organization is always a process. Order is the result of that organizing process. Crystallization is a organizational process. A crystal lattice is the product

The internal arrangement of an amoeba cannot be called ordered as a crystal is. The amoeba does, however, represent an excellent example of organization in that its messy (unordered) collection of parts does operate in a cooperative, systematic way and produce an organism with the emergent behaviors called life. Much more on emergence in Sections 11 through 14..

Discussion

Faced with the all pervasiveness of the Second Law of Thermodynamics how can we account for all the order and organization we encounter? If we compare the universe as it was shortly after its beginning with its present form we see systems building upon systems producing increased complexity, a cosmic evolution. We are forced to the view that there is a tendency for parts to spontaneously assemble into systems that have order and organization, (the general principle of self-organization) and for systems to combine. In a universe ever drifting toward decay and disorganization the tendency toward order and organization is a creative current simultaneously flowing in the opposite direction.

The analogy has been drawn to that of a stream or current, ever flowing toward dissolution in the vastness of an ocean which nevertheless forms eddies that move in the opposite direction to the general flow of things and temporarily form all the structures that we know.

Organizing principles

The observation that order and organization are the result of some principle of organization is so familiar that when any pattern is recognized the existence of an underlying principle is assumed. The pattern of properties of the elements led Mendeleev to propose the law on which the Periodic Table of the Elements is based.

The fundamental organizing forces of the universe

Gravity

Weakest but most extensive of the four great organizing principles is gravity. It is interesting that of all the forces of nature it is the only one that operates over cosmological distances. Within the early fireball, energy congealed into particles with mass and, according to the Einsteinian view, mass has the emergent property or ability to curve space.

Strong nuclear force

Organizing the universe begins with a organizing principle that operates on the smallest of scales. By holding subnuclear particles (quarks) together, the strong nuclear force constructs protons and neutrons and the rest is history. It is the history of an evolving universe of galaxies, stars, planets with oceans and atmospheres and, at least in one case, of living things.

Weak nuclear force and the electromagnetic force

At other scales of operation the weak nuclear force and the force of electromagnetism come into play in organization. There is a single theory unifying these two forces which are now identified as one "electroweak" force. However, the weak nuclear force plays no role in holding structures together and is only responsible for nuclear decay processes. Therefore, the weak nuclear force does not qualify as an organizing principle. The overwhelming importance of the electromagnetic force as an organizer is obvious since among the significant structures resulting from it are atoms and molecules.

Should Einstein's dream of unifying all these fundamental forces by one theory ever be realized, it would then be proper to say that there is one great fundamental organizing principle which manifests itself in the universe in three different ways.

Once these fundamental organizing principles were at work in the universe and different systems of matter were formed by them, other physical organizing principles came into play.

Other organizing forces or principles

Convection

The organizing principle called convection is a derivative of gravity since its action is driven by gravity. Convection tends to organize matter according to its density. Its importance is demonstrated by the variety of phenomena it produces such as, the dynamics of stellar interiors, the structure of the planets and the movement of continents, weather systems, ocean currents, volcanic action, and Bénard cells in a dish pan which are all brought into existence by convection.

Natural selection

In Darwinian evolution the organizing principle is natural selection. It provides the impetus that, by elimination, favors those structures and behaviors of living things that so elegantly fit them for their particular environments.

Profit motive

In human economic activity the desire toward personal benefit may be seen as the general organizing principle. That desire is made evident in the drive for food, shelter and clothing and for security and comfort. Personal benefit can certainly be extended to kin or group benefit. The ability to possess these goods has become institutionalized by the possession of money. Thus it seems justifiable to call the organizing principle of human economic activity the profit motive. On a large scale what emerges is a self-organized market system.

Organizing principles to be found

Non-physical organizing principles are not well known. What shall we call the principles that organize herds, flocks of birds, and schools of fish? Do they have common characteristics? What principle organizes the six-sided symmetry of a snowflake but allows for such diversity of detail that there is nearly infinite individual variation? Can patriotism be an organizing principle that functions to organize a nation? An interesting organizing principle that enables humans uniquely to form large populations that live cooperatively in cities and even nation states has been proposed by social psychologist Jonathan Haidt. He suggests that the motive of protecting sacred sites or values is the principle that drives human beings to build systems like cities and national governments.

Naming the principles is insufficient. Their modes of action need to be rigorously explained and perhaps then mathematical formulations may follow as has been the case with many physical principles.

Organizing principles at work

– two examples, one astronomical – one political

Step 1. *An organizing principle begins to operate on simple subsystems and a more complex structure is formed.*

Astronomical	Social
Under the influence of gravity dust particles coalesce. From a featureless dust and gas cloud a central protostar is formed and bands of matter sweep around it.	Under the influence of an organizing principle we might call familial attraction, individuals of a small group of ethnically similar people decide to live in close proximity after they move to a strange city.

Step 2. *The organizing principle extends its power, brings other subsystems into the system and extends the organization of the material.*

The protostar collapses into a star. The bands of matter self-organize into planets. asteroids and moos with complex structures and atmospheres.	As people of the same ethnic background move to the city they feel more comfortable living near the original group. An ethnic neighborhood develops.

Step 3. *New properties emerge from the more complex systems.*

As gravity pulls the star together the concentration of matter becomes sufficient to initiate nuclear reactions. Radiation suddenly rushes outward. The star begins to shine. With the development of cores, crusts, atmospheres planets become increasingly complex systems. They can exhibit new properties of their own as when a planet develops a magnetic field.

The old traditional practices may take on a subtly different flavor in the new environmental setting. Under influences from the surrounding culture the old ways are modified until a new ethnic group may appear, i.e. Italian/American, Reformed Jews, Latinos, with new practices.

Step 4. *The new complex system is subject to fluctuations produced by the flows of matter and energy in its environment or within the system itself. Self-maintenance begins.*

Gravitational influences between neighboring planets and their star's gravity shape the orbits of the planets. The gravitational attraction of the planets causes bulges in the shape of the star. Asteroids collide with the planets changing them in drastic ways.

The ethnic group responds to challenges to their way of life from the surrounding environment. They intensify their traditional celebrations. They choose leaders and representatives who will protect them.

Step 5. *When the energy flow that maintained the system far from equilibrium diminishes, the Second Law takes over.*

The star dims or collapses and explodes depending on its initial size.

As the desire to maintain the old ways diminishes the community disperses. Their beliefs, values and customs are diluted or co-opted by the dominate social group.

As Jacob Bronowski described the action of the Second Law - **that which was special becomes unspecial.**

7. *Patterns*

Recognizing the relationship between systems and patterns

Definitions

Pattern – a periodic repetition of structures or behaviors; a repetition of forms and/or actions.

Order - a special arrangement in which parts of a whole are in some regular relationship or repeatable pattern as, for example, in a crystal.

Background: Patterns and life

The recognition of patterns seems to be central to human life. The adaptive value of pattern recognition is so great that it has become a pleasurable activity in its own right. To see a pattern emerging from the seemingly chaotic makes the perceiver smile.

For early human beings, pattern recognition was adaptive because it reduced the uncertainties and danger of the world. It is of obvious importance, for example, to be able to distinguish between the pattern projected by the body of a tiger from that of forest leaves. Recognizing behavioral patterns could alert individuals to expected changes that then could be anticipated. When the herd animals began to behave in a certain way, they were preparing to move on, and it was time to pack up and move to stay with them. Understanding weather patterns was, and still is, important to survival. When to plant and when to carry an umbrella can be important decisions.

Patterns reveal the regularities of nature. Discovering those regularities is the business of science. The "eureka moment" is still the goal of all scientists. In the moment when a sequence of seemingly disjointed events is identified as a general pattern of behavior that a discovery is made. Behavioral pattern recognition permits prediction and then nature comes to be perceived as a place of order and law, which we can hope to understand and manipulate to our advantage.

The categorization of patterns is an important part of infant learning. Two circles above a vertical line which is above a horizontal line is the pattern of a human face. The subtle differences of these features enables an infant to distinguish its mother's face from others. A child will be disturbed and may even be frightened if an image of eyes, nose and mouth is presented in some mixed up way.

Patterns are so much a part of human life that there seems to be a human impulse to create or find them. Music and art are all about pattern formation and discernment. All living systems develop ways to recognize patterns and pattern change and take action on the basis of such recognition. When a paramecium bumps into and obstruction it backs up. With another bump the paramecium backs up again and perhaps there is a third bump before it backs up and changes direction. The change in direction might be called the recognition that there is a periodic repetition of a behavior, a pattern, that is nonproductive for paramecium health.

Discussion

Every law of nature implies that there are predictable and repeatable occurrences of phenomena. The pattern of activity of unsupported objects in a gravitational field is that they invariably move toward the source of gravitational attraction. Any occurrence of order in nature is now taken as indication of the existence of an underlying law. The patterns of self-organization so evident about us are therefore thought to be expressions of unknown laws whose discovery is the goal of system theorists.

Patterns and systems

There are two kinds of patterns; static and dynamic. One is formed by the regular position of objects, while the other is formed by repeated actions. This is the distinction between structure and behavior. In either case, pattern formation is the signature of a system in operation. By definition, a system involves a dynamic relationship among its parts. A system functions as a whole and produces the product or behavior that is consistent with its properties and the relationships of its parts. It does not behave randomly. Its repetitive and, with sufficient understanding, predictable behavior lends the consistency which we recognize as a pattern. The rotation of the Earth system produces the pattern of our nights and days.

8. *Complexity*

Because systems tend to combine and become more structurally complex the concept of complexity is a central one in the study of self-organizing systems.

Definition

Complexity - a scientific definition is in the process of development. At the present there is no consensus on the exact meaning of this term. Its definition varies in different disciples.

A common meaning - something is complex when there are a great number of interacting elements with many interconnections.

Background

The common definition above is unsatisfactory because a large number of things with all their interconnections may still be a simple system. A glass of water contains a huge number of molecules. There are many internal interconnections yet the glass of water does not fit our concept of a complex system. What is missing is some coordinated activity; or a structure with many and varied parts. Those are the things we expect to be part of complex systems.

Discussion

Perhaps the concept of complexity is so hard to define because it is a subjective idea. We tend to think that those things that are complicated are complex. But complicated things can become simple with understanding. Is then their complexity lost? The ordinary driver looks under the hood of a modern automobile and is bewildered by the intricacies. The experienced mechanic says, "Look! It's simple." He tweaks a gizmo and the stalled engine comes to life. What is complex seems to depend, to some extent, on what the observer brings to the observation.

Recognizing complexity

1. Internal complexity

There are different ways in which a system can be considered to be complex. The first of them, mentioned above, is when a great many in dependent parts within a system are interacting with each other in a great many different ways and many interactions are occurring simultaneously. This is internal complexity: arising from the organization and the interactions. Clocks may have internal complexity but they still produce a relatively simple action: the same repeated pattern of change.

2. Behavioral complexity

Regardless of a system's internal complexity, a system can be considered to be complex if its behavior is controlled by many variables or is unpredictable. Simple systems are predictable; they offer no surprises. If a system surprises us, acts in ways that are counterintuitive, we assume that complex functions are at work. Such a system has behavioral complexity. In mathematics, for example, the "simple" equation $z \longrightarrow z^2 + c$ describes what is most probably the most complex mathematical object ever invented: the Mandelbrot set. The behavior of the values generated by the equation in a complex plane as pictured on the computer screen are unbelievably varied and unexpectedly beautiful.

The computer is to the study of complexity what the microscope was to microbiology. It makes the study of the field possible.

3. Property complexity

Similar to behavioral complexity but important enough to warrant a separate designation is property complexity. Systems which exhibit a more diverse number of properties must contain a multitude of factors and interactions to produce them and deserve to be called complex. A maple leaf has the properties of color, special shape and photosynthesis.

4. Structural complexity

A system with many feedback loops is hard to understand because of all of the subtle and changing inputs and must therefore be considered to be complex. Such a system can be said to have structural complexity. The system is continuously modifying itself by changing the interactions among its variables. Consider the difference between a greenhouse and an ecosystem.

5, Informational content

This is the idea that complexity of a system is measured by the length of the shortest possible description of that system. In this view, if the most concise description of a system is lengthy the system is complex. If it is easily described it is simple. (For contrast consider the Mandelbrot set mentioned above; simple to describe in mathematical terms but wondrously complex.)

6. Hierarchical depth

The more levels a particular object contains, the more complex it is. The universe, containing all levels, is the most complex system we know. An atom used to be considered the most elementary (meaning simple) particle. We now know that its nucleus is a complex structure made up of different kinds of quarks and gluons seething with interactions in bewildering complexity. The number of "nesting" systems contained within a system relates to the idea of hierarchical depth.

7. Organic complexity

Biologists have suggested that the complexity of a living organism can be gauged by the number of different cell types in its organization. This is similar to the idea of internal complexity already mentioned but restricting it to living things. Clearly a worm is more complex that an amoeba and humans are more complex systems than either.

Discussion

If, in general, systems tend to increase in complexity, what might account for this? One hypothesis is that increased complexity expands the ability of a system to respond to a changing environment. This would enhance the system's survival and make for increase in complexity in the Darwinian sense. Some organisms, notably human beings, expand their response to that of attempted control over the environment. This concept would involve the notion that systems "progress" by becoming more "advanced" by greater control of their surroundings and their lives. The philosophical question of the relationship between increased complexity and freedom is an interesting subject but one which is beyond the scope of our discussion and will not be addressed here.

Conclusion

An individual system may exhibit many of the different kinds of complexity described above and may do so simultaneously. Researchers have begun to try to develop a science of complexity and move it away from the subjective frame of reference. This is an important task. In our increasingly technological world we are beginning to recognize our need to deal with complex systems. New concepts and methods are required. These may be forthcoming as the study of complex systems continues.

Many educational institutions have recognized the importance of the subject and have organized departments for the study of complex systems.

9. Synergy

The ideas of synergy and synergism in many ways mirror those of self-organizing systems. We discuss it here because it illustrates cooperation among systems and the emergence of novelty.

Definition

Synergy - the cooperative action of a combination of entities in which the total effect is greater than the sum of the effects of the individual entities.

Background

The concept of synergy is most often associated with the work of R. Buckminster Fuller (1895 - 1983), the mathematician/engineer who designed the geodesic dome and who was responsible for many other innovations in design. His main work, contained in two volumes, *Synergetics* and *Synergetics 2*, has been described as the study of spatial complexity. His emphasis was on three dimensional geometry and a holistic approach to nature, which he saw as a web of interacting patterns.

Fuller used the word synergy to describe an important property of systems. He said, "Synergy means the behavior of whole systems unpredicted by the behavior of their parts taken separately." This, of course, is another way of saying the whole is greater than the sum of the parts. The word has come into general use as a description of the change in behavior when two or more entities act together. Often the reference is to the action of the combination which is more than the sum of each separately. The word is derived from the Greek, combining syn (together) with ergon (work).

Discussion

Fuller gave some interesting examples which illustrate the synergetic property of systems. If there were but one mass in the universe there would be no way to detect its ability to curve space. Two masses in interaction constitute the simplest of systems. The attractive force between them comes as an unpredictable surprise.

Gravity is a synergetic product of a system of masses. That its strength is in direct proportion to the product of their masses and changes inversely with the square of the distance between them was the surprise that delighted Newton. ($G = m_1m_2/d^2$)

The behavior of alloys is another example of synergy. A common observation is that a chain is as strong as its weakest link. How strong is a chain of alternating links of iron, chromium, and nickel? The tensile strength of iron is 60,000 pounds per square inch. That of chromium is 70,000 pounds per square inch and nickel tensile strength is 80,000 psi. But put these metals into combination and chrome-nickel steel is produced. The alloy has a tensile strength of 350,000 psi. Fuller was convinced that nature worked through synergistic reactions. For him all things were connected and the connections developed characteristics of their own.

Lawrence Henderson in an early influential work, *The Fitness of the Environment (1913),* emphasizes the interdependence and the cooperative effects of the different properties of the elements. According to Henderson it is the *combined* properties of carbon, hydrogen and oxygen that "form unique assemblages which are of biological significance." Without the synergetic effects of these combinations of elements the development of living organisms would have been impossible.

Synergetic reactions are well known in the medical community. It is important to the medical practitioner to know what medications are currently being taken before new ones are prescribed. A study published in *The Journal of Toxicology and Environmental Health* in May, 1996 suggested that the Gulf War Syndrome reported by some soldiers might have been caused by exposure to ordinarily harmless doses of two or more chemicals that together might cause nerve damage. They reported experiments in which low doses of chemicals to which the troops were exposed were given to chickens. Individually they had no effect. But when given in combination the chickens suffered severe effects, sometimes including total paralysis and death.

Synergetic reactions are the same as the new properties that emerge from the increasing complexity of systems.

10. *Hierarchy*

Because new systems come into being from previously existing ones they often appear to be nested within and dependent on one of lesser complexity. The totality of everything might be listed this way:

Universe
- Galactic systems
  - Galaxies
    - Star clusters
      - Stars
        - Planetary systems
          - Ecosystems
            - Socio–cultural systems
              - Groups, families
                - Multicellular organisms
                  - Cells
                    - Organic molecules
                      - Chemical molecules
                        - Atoms
                          - Sub-atomic particles
                            - Quarks
                              - Space/time field

Definitions

Hierarchy of inclusiveness – the relationship among systems in which smaller systems make up and are nested in a larger system; as in the above.

Hierarchy of control – the relationship among systems in which the more dominant system controls the actions of the less dominant; as in a pecking order.

Background

The idea that a hierarchical order of things was a natural one must have come to humankind very early in its intellectual development. In its first form it manifests itself as a pecking order. The stronger, more dominant individuals are literally on top of the weaker ones. Lowering one's head, eyes or body are signals of submission. Many animal groups other than human, exhibit this behavior.

As early human society developed, it was the common feeling that the individual belonged to a tribe or clan, that the smaller was part of a larger group. This sense of belonging constitutes another kind of hierarchy. It exists today in the attitude of allegiance to ethnic or national groups and, in some individuals, the sense of being part of the family of humankind. The feeling is so strong that many people find life fulfillment in group belonging and many others long to experience "being part of something greater than one's self."

There is another version of the idea of hierarchic order that has developed recently out of ecological studies. It is a hierarchy of composition in which the larger unit is made up of smaller ones but the element of control is not the dominant factor as it is in the previously mentioned hierarchies. In ecological hierarchies the elements of mutual influence and cooperation are key. It is this view of mutualistic interdependence that is part of self-organizing systems.

Discussion

The concept of hierarchic order in the universe is fundamental to the general theory of systems. The universe is seen to develop from atomic particulates to galactic systems, pausing on the way to develop stellar, planetary, chemical, biological, and cultural systems. The architecture of nature indicates that the building blocks on one level combine into new structures with new properties. This is one of the fundamental organizing principles of the world.

The human body is a familiar example of a hierarchical system in the sense defined above. Atoms make up molecules which in their billions make cells. Cells make up tissues and organs are constructed out of those tissues. Tissues and organs have properties that are not those of the individual cells. Muscle tone and kidney function are examples. Various combinations of tissues and organs make the systems within the human body. The cooperation of the systems (circulatory, digestive, nervous, etc.) enable the body to function as an integrated unit. Reciprocally, experiences of the whole organism affect the interior workings of the body's organs.

Higher and lower levels of hierarchy

Often in the discussion of hierarchical systems the terms higher and lower levels are used. These are not indicators of value nor do they necessarily indicate increased complexity. They serve to indicate which systems are components and which are collections of the systems under discussion. The solar system is at a higher level of hierarchy than its planets. The planets, however, have structures considerably more complex than the overall structure of the solar system. The same can be said of the individual cell whose interior functions are more complex than the action or functions of the tissue of which it is a part.

Nevertheless, it still must be recognized that at higher levels of hierarchy there is usually greater diversity of structure and function simply because higher levels are made up of many lower-level systems plus all their interrelations.

The philosopher Michael Polanyi put this idea in an interesting way: "Lower levels do not lack a bearing on higher levels; *they define the conditions of their success and account for their failures, but they cannot account for their successes, for they cannot even define it."* Note (Italics in the original)

Emergence at higher levels of hierarchy

As biologists and ecologists examined nature, they found a pyramid of levels. This, as noted, was not a new idea. What is new is the notion that at each higher level of organization new structures and functions appear. These new properties emerge from the new organization of systems and are quite impossible to predict from the lower levels of organization. As an example; there seems to be no way that mental phenomena could be predicted only from an understanding of the how the neurons in the brain are organized. Thinking, planning, imagining, and the other features of mental life are new functions that emerge from a special organization of neurons.

The differences between prokaryotic cells (DNA dispersed throughout the cell) and eukaryotic cells (DNA enclosed in a nucleus) is another example of biological emergence. Eukaryotic cells have thousands of specialized internal structures each about the size of a prokaryotic cell. These organelles have assorted metabolic functions that permit the eukaryotic cell to do things the more primitive prokaryotic cells cannot do. Considerations such as these lend themselves to a concept of an evolutionary process in which new characteristics emerge and enrich higher levels of organization.

Arthur Koestler and the holon

Although well known for his political novels (particularly *Darkness at Noon*) and for his essays, Arthur Koestler (1905–1983) was also an excellent writer on science. His study of the development of our concept of the universe from the early Greeks to Isaac Newton, *The Sleepwalkers (1959)*, was detailed and insightful; albeit heavily biased against Galileo. He was particularly original in the fields of psychology and holism. In *The Ghost in the Machine (1967)* he set forth his concept of the holon as a unit of hierarchies. A holon is defined as an entity which has the dual tendency to behave as a unit and, at the same time, act as an integrated part of a larger whole in multi-leveled hierarchies. An individual is a holon in that he or she, while capable of acting alone, is also a member of a social group. There is an interesting Appendix in the book entitled "General Properties of Open Hierarchical Systems" (pages 341-348), in which he outlines his ideas about holons and hierarchies.

The above mentioned Appendix is repeated in Koestler's *Janus: a summing up (1978)* but with the important addition of 15 pages of new material in front of it. The new Appendix is entitled "Beyond Atomism and Holism – The Concept of the Holon." Koestler's stated effort was to reconcile the fact of existence of independent parts with the concept of the integrated whole. He hoped to "get beyond reductionism" and present "a comprehensive system, which rejects materialism and throws some new light on the human condition."

11. *Emergence*

Although mentioned many times before the property of systems called emergence is what really makes the subject of self-organizing systems so interesting and important in our understanding of the world. The process is so common as to be hum drum and yet it is mysterious; as when a change of temperature makes a quantity of water suddenly as solid as a rock. If it wasn't such a common experience the transformation would appear to be miraculous; a collection of flowing water molecules self-organizes into a matrix of ice crystals with order and the emergence of new and basically unpredictable properties

Definitions

Emergence 1 – the process whereby new and unexpected structures and processes come into existence from the synergistic combination of simpler structures and processes previously existing.

Emergence 2 – the philosophic doctrine opposed to reducibility which declares that in a hierarchical system each level may have properties and modes of behavior peculiar to itself and not fully explicable by analytic reduction. (P. B. Medawar in *The Life Science*)

Emergence 3 (broad form) – The idea that there is a tendency in nature for matter and energy to spontaneously form new and more complex combinations which can, in turn, unite into other combinations of increasing complexity. These combinations bring new and unexpected properties into the world. The properties so produced cannot be reduced to or explained by the less complex parts of the combination.

Background

Often the simplest questions are the hardest to answer. Why are there are so many different things in the world? Where do new things come from? Surrounded, as we are, with the processes of emergence, little attention has been paid to them. New and unexpected structures and processes come into existence in all branches of science, but no systematic study has been made of the general properties of emergence itself.

Discussion

The development of the universe following the primeval explosion of the Big Bang is the primary example of emergence. At each stage new forces, structures, and processes appear. Elementary particles, atoms, molecules, stars, galaxies, radiation, gravity, nuclear and electrostatic forces, and time itself came into being. With the emergence of these new things the universe became more complex.

Although reductionism can assist the understanding of many of the phenomena that constitute the universe, it is only by considering collective phenomena and their interactions that the rich and variegated world we live in begins to emerge.

"The whole is *different* than the sum of its parts," captures the idea of emergence. Implicit in this conception is that an increase in complexity of organization results in different levels of being. The levels are distinguished by their different properties or modes of behavior. Although a particular level may be made up of components from other levels the new organization is significantly different. It has new properties and processes that are different from those of its components.

A familiar example

Consider the atoms that make up a living cell. The properties of carbon, oxygen and hydrogen are all different from each other. However, they are similar in respect to their organizational pattern. We can call this the atomic level.

In various combinations atoms make up the molecules of the cell, and the properties of these molecules are different from the sum of their atomic properties. For example, some of the properties of molecules are due to their folded structure, something unknown on the atomic level. A protein molecule has this folded structure.

When an organization of molecules forms a cell a remarkable new constellation of properties appear. A cell can assimilate, grow, reproduce, react to its environment and behave in ways unknown to molecules and atoms. In short, a new level; a living system has emerged.

Going further, at new organizational levels, specialized cells working together in tissues and organs produce new things. In one configuration of cells new chemical products like hormones are produced. In certain organs reproductive cells are produced. In another configuration of specialized cells the emergent product is thought. Together specialized cells produce a human being.

Yet other levels of emergence are displayed when a human being forms a family, and multiples of them form a colony, a society which has its own constellation of laws and properties.

A universe of surprise

Emergence emphasizes the creation of novelty. It gives us a universe of surprise. If, in nature, a brain with the property of consciousness can evolve, what else that is presently unimaginable to us may evolve?

A set of interesting and unanswered questions arises from a consideration of the emergent nature of things. It is the subject of threshold. At what concentration of neurons does the property called consciousness appear? How many individuals make a colony? How much complexity of connection is necessary before new properties arise? Is it possible that there is a generalization about the threshold of organization that can apply to many different kinds of organization?

The laws of nature

The glory of the scientific endeavor is the discovery of Laws of Nature. The fact that the universe is law-governed has enabled human beings to begin to understand a small portion of their world. Scientific laws are security anchors in a sea of uncertainty. The Laws of Nature, from the point of view of emerging systems, can be called fundamental organizing principles. For example, the law of gravity is the organizing principle that constructs star systems and galaxies out of gas and dust. The law of electromagnet attraction is the organizing principle by which molecules emerge into existence.

The second law of thermodynamics is well established as a fundamental principle of nature. It tells us that matter and energy tend toward a less organized, more uniform state. Will we, in the future, recognize a general law of emergence as one of the fundamental organizing principles of the world in which the tendency toward complexity is described? We know relatively little about how complex behavior throughout a system emerges from local interactions. We may also find it universally true that in the hierarchy of nature each emergent level brings into being its own unique laws. It may be expedient to redefine progress in the natural world as the emergence of new complexities.

12. *Emergence – Origins of the Concept*

Background

There is an ancient world view that "there is no new thing under the Sun; that which has been is that which shall be." The cyclical view of life is a natural extension of the observations of seasonal change, of death and rebirth, and of decay and regeneration. It was the dominant view in a world in which change was hard to recognize in an individual lifetime. In such a world there is no discernible "progress." It is not the world we live in today. This change in perspective separates ancient and feudal times from what we call the modern world.

A philosopher of the ancient world who did see that novelty was part of existence was the historian Heraclitus (533-475 B.C.). His maxim was, "You cannot step twice into the same river; for fresh waters are ever flowing in upon you." Plato, who quoted him in order to refute his ideas, says that Heraclitus taught that "nothing ever *is*, everything is becoming."

Discussion

Despite the increasingly rapid changes brought about by the Industrial Revolution, there was no intellectual development of the concept of emergence. The idea that change can bring new things into the world was not the common point of view until the way was prepared by the acceptance of Darwin's theory of evolution. If evolution could, in time, bring new species into being it was then imaginable that the developing processes of the world had produced new and unexpected arrangements of all kinds.

The first use of the word "emergent" to refer to phenomena that were new and not explicable by the properties of their components was by George Henry Lewes (1817-1878). In his book *Problems of Life and Mind (1879)* Lewes contrasts the word "emergent" with the word "resultant" and introduces the idea that it is through emergence that novelties enter the world.

An early attempt to establish a philosophic interpretation of nature as a whole with emergence as one of its principles is the work of philosopher Samuel Alexander (1859-1938). Early on he accepted and incorporated the idea of Minkowski and Einstein that space and time were not independent entities and that the only reality was space/time. His Gifford Lectures of 1916-1918 were published in two volumes as *Space, Time, and Deity (1920)*.

In that book he stated "In the course of time as new complexities of motion come into existence, a new quality emerges, that is, a new complex [entity] possesses, as a matter of observed empirical fact, a new or emergent quality... Physical and chemical processes of a certain complexity have the quality of life... The higher quality emerges from the lower level of existence and has its roots therein, but it emerges therefrom, and it constitutes a new order of existence with its special laws of behaviour." "Mind is, according to our interpretation of the facts, an 'emergent' from life."

In Alexander's view, there were two fundamental concepts in the understanding of the universe. They were space-time and the tendency of matter to move toward increasing complexity with new qualities [properties] emerging. This idea is at the heart of the concept of emergence.

A contemporary of Samuel Alexander was C. Lloyd Morgan (1852-1936), whose book *Emergent Evolution (1928)* was also the result of Gifford Lectures given at the University of St. Andrews in Glasgow. Morgan's lectures were delivered in 1922.

Morgan expanded on the idea of emergence. He asked, What is it that is emerging? His answer was, "Some new kind of relation." At each ascending step of increasing complexity of matter new ways of acting on, and reacting to other entities appear. In what sense are these actions new? They are new because "their specific nature could not be predicted before they appear in the evidence." For an illustration he uses the phase change of water to ice. In Morgan's view the lower density of ice compared to that of water represents a new relationship among the water molecules. As ice they are in a crystalline relationship vastly different from their relationship to each other as liquid. The phase change brings new emergent properties along with it.

Emergence and vitalism

It should be made clear that those who began to espouse the idea of emergence were at pains to distance themselves from any form of vitalism. (That is the doctrine that living organisms must possess some kind of life-force, beyond physics and chemistry, that makes it possible for them to live.) Those favoring emergence also denied Henry Bergson's idea that a new force, the elan vital, was at work in the evolution of new forms. For them it was simply a matter of fact that, as Lloyd Morgan puts it, "One starts with electrons and the like; one sees in the atom a higher complex; one sees in the molecule a yet higher complex... In nature the progression continues to an organism which simply has a different kind of complexity."

The modern view seems to take the notion of emergence somewhat for granted. The idea that more complex organizations have special properties not possessed by their component parts seems completely reasonable. To a large extent the subject has been tied to the development of the systems view of the world and to the concepts of biological organization.

Why are there so many different things in the world?

An answer to this strange question may be in the principles of emergence. It is one of the characteristics of self-organizing systems that they produce new structures and processes. That is, they create emergents. These in turn, create other emergents, multiplying the structures and processes of the world; a feedback process that increases the number of things in the world.

13. *Emergent Properties*

Definitions

Property - the name given to the way an organization of matter interacts with its environment.

Consider, for example, the property of color. A leaf has the property greenness because its pigments selectively absorb all the colors of the incoming light save green. We say the proton has the property of positive electric charge because it repels other protons and attracts negatively charged electrons. A property then, as used here, is a description of an object's interaction with the world.

Emergent properties - those novel ways of acting that come into being with the increase in organizational complexity of systems.

Emergent properties are constructions of a whole system and do not belong to the component parts of the system. Emergent properties are collectives that disappear when the communicating relationship within the system is disrupted. Good examples are the properties of pressure and temperature of a gas.

Background

Progress is a value laden term. To say that the world progresses is to declare that change is taking place and that the direction of that change is agreeable to the person making the statement. Much of what is called progress is the emergence of new products, processes and properties that result from the increased complexity of the organization of materials. Often the aim of scientific endeavors is the production of new emergent properties. Technology is the result and it is the proverbial two-edged sword. But if the world progresses at all it is by means of emergent properties.

The point of view taken here is that humans emulate nature by combining simpler systems into more complex ones in the search for new properties.

Discussion

In the beginning there was only the primordial fireball. All was energy and disorganization. Expansion cooling allowed matter to condense and permitted the strong nuclear interaction to organize atomic nuclei. Then the force of gravity began its work. These forces along with the weak nuclear interaction and electromagnetism constitute the forces that fabricated our emergent universe.

All through the subsequent history of the universe derivative emergent properties have appeared as new systems formed.

As examples the following table lists some systems and some of the emergent properties associated with them.

Self-Organizing System	Emergent property
The atomic elements	Chemical reactivity
Atomic and molecular aggregates	Weight, temperature, density, smell
Sugar carbohydrates	Sweetness
Orientation of polar molecules	Magnetism
Volume of gas molecules	Pressure, temperature
Transparent body	Refraction
DNA	Self-replication
The biological cell	Life
Biochemical systems	Enzymatic catalysis
Chloroplasts	Photosynthesis
Many biological systems	Sexuality
All living organisms	Homeostatic actions, reproduction, assimilation and growth, response to stimuli

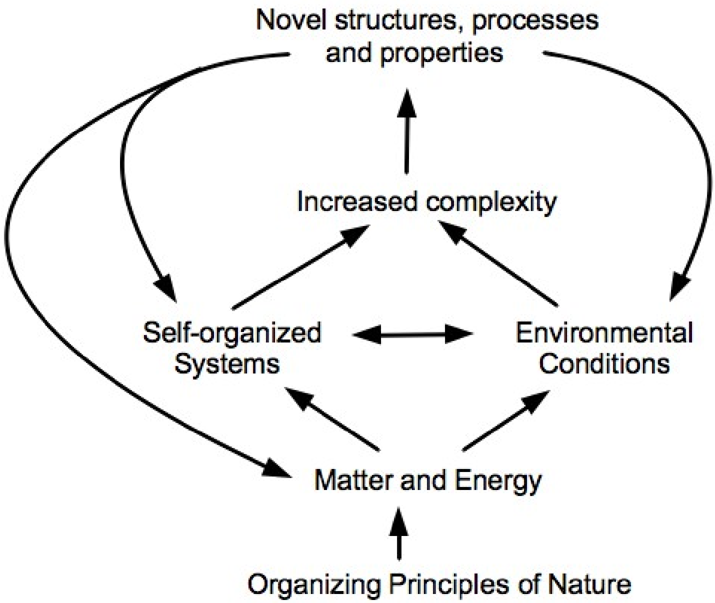
Self-Organizing System	Emergent property
Some insect groups	Social interactions
Some animal groups	Flocking, schooling, herd formation
Nervous system	Sensation
Neural cell aggregate	Brain function
Brain	All subjective experience
Human population	Mortality patterns
Human social system	Cooperation among individuals

Thresholds for emergent properties

Some properties emerge only when sufficient masses of matter are involved. For example, diffusion, convection and conduction of heat take place among large numbers of molecules. A large number of neurons must be linked for consciousness to emerge. For a human social system to show cooperative behavior there must be a minimum of two individuals.

The whole subject of necessary thresholds for emergence to take place is an area for future research.

14. *Emergent Evolution*



Background

Evolution as used here is more than Darwinian. It is not limited to living organisms but rather incorporates them and relates to the formation of everything.

Tracing through the diagram above: Everything is based on the organizing principles of nature. They organize matter and energy from which self-organized systems and environmental conditions arise. Those products tend to produce increased complexity and out of that increased complexity novel structures, processes and properties emerge.

The novelties have feedback effects on matter and energy which can result in new self-organized systems of further increased complexity. They also tend to produce changes in the environmental conditions. This feedback process is self sustaining as long as there is input of energy. It brings new things into the universe.

That is not to say that all systems behave in this way. That other great tendency of nature embodied in the 2nd Law can never be forgotten. Most systems respond to environmental change by becoming more disorganized and less complex. Stars as well as living things die. In the long run of the universe it is entropy that always wins.

Those new structures or processes that successfully produce other structures or processes tend to continue to exist. The products are, as it were, the next generation of things. Although entropy always trumps organization it does not nullify the real successes of emergent evolution.

Definitions

Emergence – the concept that there is a tendency in nature for matter and energy to spontaneously form new and more complex combinations with new and unexpected properties.

Evolution – a sequence of developmental changes that produce different forms, behaviors and concepts from previously existing ones. The new forms, behaviors and concepts continue to exist if they successfully work or function.

Discussion

The co-evolution of organisms and the environment

Just by its presence very living thing affects its environment in some way. In a system that contains more than one kind of living organism the environment in which they all live is affected in more than one way. Environmental change is made more complex. There is a co-evolution process at work where environmental change influences how species develop and organisms change the environment. A prime example is the addition of gaseous oxygen to the Earth's early atmosphere by the action of cyanobacteria. The oxygen in the atmosphere triggered vast changes in animal species.

Today any ecosystem consists of a multitude of sub-systems of organisms of different species. Each of these affects the surroundings in subtile and profound ways and vastly complicates the environment. New niches may be created that provide a home for new species. In effect each new species produces an environmental stress that can set the stage for other new species. Emergence is spontaneous and self-sustaining.

It is not to be overlooked that although environmental change engenders pressures toward the emergence of the new it is also an agent of elimination of the old. The appearance of a new species (humankind, for example) may so alter the environment as to cause a loss of species diversity which decreases natural complexity. Such is the world we are living in right now. However, our new human made environment brings about new constructions of a different sort, i.e. cities, transportation systems, or communication systems. These, in their own way, increase overall complexity.

Emergent evolution and civilization

No one will deny that today's industrial/technilogical culture is vastly more complex than the culture of centuries ago. Contrast a village system based upon a farming economy relying on animal energy with a modern cosmopolitan system with its machines and electronic technology. Whence comes this increase in complexity? The diagram on the previous page may help to explain part of the process.

For one example, an increase in population can provide the environmental stress that stimulates the self-organization of food delivery systems to towns and cities. Markets develop with new properties. Entrepreneurship, capitalism, competition, contractual obligations are but a few of the new processes that emerge. Financial credit systems follow. Banking institutions and legal systems develop. As new ways of food storage, preservation and transportation are invented the physical dimensions of the food delivery system enlarges.

Each one of these changes, like an increase in the number of niches in an ecosystem, provides the opportunity for new activities, jobs, and specialists among the workers. The necessity for increased education arises and educational systems emerge.

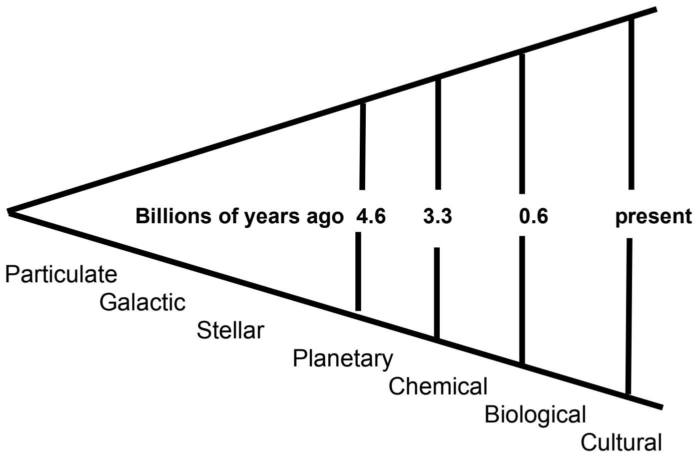
Novelty drives out the old

If a species is less able to cope with its new environment or if it is less efficient in its use of energy it tends toward extinction. A new species that uses that same niche will drive out the old. New inventions in an industrialized environment act in a similar way. The internal combustion engine removed the horse from its role as a principal source of mechanical energy and changed it to that of a pet in industrial countries. The engine was stronger, more efficient, did not get weary and required less care. The horse drivers, harness makers, blacksmiths, whip, buggy and wagon makers disappeared. But the internal combustion engine moved civilization to new levels of complexity. In addition to creating new industries and professions, it promoted the organization of vast highway systems, intricate traffic control systems, and gasoline service systems. A more complicated story could be told of the influence of the use of electrical energy and the emergence of our electronic age.

The increased complexity of our civilization is, in its way, a natural outcome and the result of many self-organizing systems. Not all of it but much of it is not a product of human planning. In fact, in the name of efficiency, much time and energy is spent in trying to reduce the complexity of many aspects of human life. New products and processes are continuously being developed. Partially because of this increased complexity of technology the standard of living has risen and the average length of human life has been extended. Increased technological complexity has also expanded the development of human potential by growth in the range of actions available. That is not to say that increased technology is in all ways good. Environmental degradation, the fast pace of modern life, and the increased ferocity of war are some of the downside effects of our technological age.

As more complex systems emerge from simpler ones they can, metaphorically, be considered to be on a step up or onto a higher level. It then may be stated that even in human affairs a natural process of self-organization to higher levels emerges out of lower ones and the evolutionary process of civilization is one of emergence toward greater complexity.

System evolution in an expanding universe



Based on a NASA chart

Produced by Wright Center for Science Education, Tufts University

15. Evolution and Complexity

Definitions

Evolution – (in the general sense) the process through which new structures, behaviors or concepts come into being from previous ones with, generally, an increase in complexity.

Evolution – (in the biological sense) the process by which new species of living organisms develop from older forms by genetic transmission of slight variations preserved by natural selection.

Na**tural selection – in the biological sense)** the process through which those genetic variations that assist in survival and reproduction of organisms are passed on to succeeding generations. Those variations that do not assist survival lead to extinction.

Natural selection – (in the general sense) the process that enables the existence of those simple systems that succeed in achieving the lowest energy level consistent with the maintenance of their structure. Or, in the case of complex systems. those that make most efficient use of energy tend to continue their existence and drive out those that do not.

Background

Darwinian evolution is the grand organizing principle in biology. The word evolution is therefore strongly associated with the development of living forms. But astronomers speak of the evolution of stars and galaxies from unorganized matter and of the evolution of the universe itself. Social scientists discuss the evolution of modern societies from less complex forms of human organization. Historians of technology refer to the evolution of products; the telephone, for example.

The use of the same word to describe these widely different products and processes of change implies some sort of relationship among them. General systems theory and the study of self-organizing systems would authenticate this relationship.

Discussion

On the most basic level, the laws of physics are such that a uniform distribution of matter tends to be unstable. Under the influence of the organizing principles of electromagnetic attraction and gravity matter tends to aggregate into structures. Thus are born elementary particles and galactic systems. Bracketed between these widely different scales of development there are the successive evolution of stars, of planetary systems, and of chemical, biological and cultural systems. Overall, evolution, in the general sense of the term, tends in time to produce more highly organized patterns. This disposition of the universe toward organization appears to run counter to the well-known tendency toward breakdown and uniformity embodied in the 2nd law of thermodynamics. (more on this in Section 19)

From a broad point of view one kind of evolution gives birth to others; an evolution of evolution. Chemical evolution precedes biological evolution which must, of necessity, be the forerunner of the evolution of social organizations.

Complexity evolving

W. Brian Arthur writing in Scientific American (May, 1993) "Why Do Things Become More Complex?" advances the idea that "the secret of evolution is the continual emergence of complexity." Although complexity is one of those concepts that are hard to define, we know it when we see it. From weather systems to organisms to "smart" phones to economic markets, complex systems are all about us. We do not have any trouble recognizing relative complexity when we say that one thing is more complex than another. Who would disagree with the statement that chess is a more complex game than checkers?

Questions arise however: where did complex systems come from and why are there so many of them? As mentioned before, systems that more successfully respond to stress and change take the place of less competent systems. This usually is accomplished by an increase in complexity of structure or of behavior. Arthur points out that some systems adapt and improve performance by the addition of subsystems and he suggests that a general law of evolution exists: "complexity tends to increase as functions and modifications are added to a system." The functions and modifications are those behaviors and structures that, in the physical realm, make the system better able to maintain itself against thermodynamic breakdown and, in the biological realm, better able to reproduce.

As an example of this increase in complexity which increases viability is the emergence of cells with enclosed nuclei (eukaryotic cells). They are vastly more complex than the bacteria that live without enclosed nuclei (prokaryotic cells). The modern theory of cell evolution maintains that the complexity of eukaryotic cells is due to successive entrapments of various simpler prokaryotic cells. The different functions of the ingested cells account for the multitude of behaviors and structures of the captor cells. These more complex cells are the basis for all multicellular organisms. Without this evolutionary change there would be no animals or plants on Earth today.

Evolution and Complexity – a critical view

Stephen J. Gould (Scientific American, Oct. 1994), the late eminent paleontologist, maintained that the idea that evolution is an increase in complexity is a "bias inspired by parochial focus on ourselves, and consequent over attention to complexifying creatures."

He suggested that the evolution of parasites is an example of successful movement away from complexity. In addition, he strongly objected to the representation that the history of living organisms is a sequence leading to humankind. He took exception to the illustrations in museums and textbooks that show a progression of living forms from invertebrates to fish to reptiles to mammals. In his view it neglects the fact the most successful and most numerous organisms are still the simple prokaryotic cells.

Bacteria live in every conceivable habitat on and in the Earth. They also exist in some places we would think incapable of supporting living organisms like hot sulfur springs, volcanic vents in the ocean floor, or within rock layers deep underground.

Gould objected to the idea that biological evolution in any way could be called progressive. He noted the long period of time, almost 3 billion years, when the only forms of life on Earth were one-celled organisms. The first multicellular animals appeared less than 600 million years ago. He argued that "our continual desire to view history as progressive, and to see humans as predictably dominant, has grossly distorted our interpretation of life's pathway."

According to Gould, "every once in a while, a more complex creature evolves and extends the range of life's diversity" in the direction of increased complexity. But the movements toward greater complexity he says are rare and episodic and do not constitute a series. Rather they are, in his view, accidental "tumblings" into the region of complexity's space while, as time passes the number, the variety and indestructibility of bacteria continue to increase. He points out that there is very little empirical evidence to show that increased complexity is the thrust of evolution. He concludes "that for each mode of life involving greater complexity, there probably exists an equally advantageous style based on greater simplicity of form."

Responding to Gould

It is certainly true that the adaptable bacteria will outlast human beings just as they have outlasted so many other species in the history of life forms on our planet. Complex organisms share with complex machines the increased likelihood of malfunctioning. An environmental catastrophe can, and has, wiped out hundreds of thousands of complex species. As long as the Earth orbits the Sun, bacteria will probably grow and prosper. Yet it is the conviction of many scientists that once the threshold of multicellularity is crossed, complex plant and animal forms inevitably arise — that, far from being accidental, as Gould argues, the development of complex organisms is to be expected, although their exact forms may be a matter of chance. Admittedly, there is a paucity of scientific studies that show increased complexity as the inevitable consequence of evolutionary change, just as there is very little scientific evidence against it. The study of the complex is very difficult. Part of the problem is that we have no scientific approach to problems involving coincident action when many variables act through many feedback loops. Our studies are generally limited to linear problems. Isolation and the study of one variable at a time is the laboratory rule. We need a biological calculus that will facilitate the study of how complicated things change under multiple and simultaneous influences. Perhaps when we have such a calculus more exact studies of complex systems will appear.

The problem with "progress."

The idea that evolution represents some kind of "progress" in the world is one which has been superseded. The term progress is too subjective to be useful. It is too closely related to something that is presumed good for humans. However, there is a sense in which the word progressive can legitimately be applied to evolution. If we remove the value judgment and define progressive evolution to mean only that structures later in time build on features of those that have gone before, then evolution is progressive. The new includes the old as, for example, the vestigial organs that survive in all of us.

From chance alone – to chance plus self-organization

It was not so long ago when, in our biology classes, we taught that the origin of living systems was due to a chance encounter of complex molecules in some primordial amino acid soup in some warm, tidal pool. Darwin himself thought the development of adaptive characteristics was due to the slow accumulation of chance changes. Our students were told that the long expanse of geological time provided the opportunity for natural selection to make the "fit" of organisms so precise.

The study of self-organizing systems can provide a different point of view. The tendency toward self-organization may turn out to be the helpmate of natural selection.

Organization emerges

Consider the simple case of crystal formation. By chance a solution of molecular components may experience conditions of density and temperature which make crystal formation possible. But once these conditions have been met the molecules will, by virtue of their inherent properties align themselves into particular spatial relations and form a crystal. The point is that the formation is not due to the random encounters of particles. The crystalline order emerges from the solution whenever conditions are right, a self-organizing process. The same may apply to the formation of living material.

When the evolution of inanimate matter to living organisms is presented solely as a result of natural selection working on random changes under the stress of environmental change, it seems a completely accidental process. Although natural selection of random mutations is a necessary condition for evolution, it may not be the only influence. As will be discussed in Section 17 , "Cells - Self Organizing Systems," several processes may have been at work to produce the first living cells.

From the organization of molecules, to the folding of proteins, to formation of cells, the tendency toward the development of complex self-organizing systems gives natural selection material to work with. Thus, it seems, chance and organizational tendencies may be cooperating partners.

16. *Chemical Self-Organization*

A chemistry teacher is very familiar with the self-organization of matter into more complex forms. That is what chemistry is all about. What the chemist does is to arrange the environment, set the initial conditions, so that the molecules will proceed to develop toward the desired product. Molecules do this self-assembly as they respond to the conditions. The organizing principles are the laws of electrostatics with their production of chemical bonding. What is to be pointed out here is the more basic self-organization of the elements themselves. The natural outcome of the self-organization of the atoms is the emergence of the order of the Periodic Table of the Elements.

Definitions

Element – a pure substance of which all the parts (atoms) have the same structure and properties and cannot be separated into parts without losing their structure and properties. Occurring in nature in 92 different forms – from hydrogen to uranium.

Periodic law of the elements – the chemical and physical properties of the elements are the periodic functions of their atomic number and electronic configurations. The chemical activities of elements are a result of the number of electrons in the outermost (highest energy or valence) level.

Pauli exclusion principle –– no two electrons can have the same set of quantum characteristics in an atom at the same time. Therefore, only 2 electrons of opposite spin can exist in the lowest energy level of an atom. Other electrons fill successively higher energy levels in orbitals governed by this exclusion principle.

Orbitals – the sub-levels of the energy levels that surround the nucleus of an atom

Octet rule – a general rule for low atomic number elements which states the energy levels of complex atoms above the first tend toward completion with 8 electrons in the outer energy level.

Note on electron spin: Elementary particles have a property akin to angular momentum and physicists describe it by giving it a quantum number although nothing is spinning. Each orbital of an atom can hold only two electrons and they must be of opposite spins.

Background

The organization of atoms from the elementary particles is an example of self-organization on the most basic physical level. A number of rules and principles have been developed to explain the self-organized complexity of chemical combination.

A necessary condition for the existence of matter is that it form stable configurations. Stability, of course, is a relative term since the time intervals involved are not rigidly defined. We do not expect a volume of helium atoms, for example, to disintegrate as we attempt to determine its mass. Trying to determine the mass of a quantity of uranium 227 is a little more difficult since half of it decays into other elements in minutes.

The number of relatively stable arrangements of elementary particles that self-organize themselves into atoms is limited to the ninety two elements and their isotopes. But when atoms combine into molecules the number of possible arrangements is virtually unlimited. The discovery that just three particles (proton, neutron and electron) can generate all the ninety two varieties of matter and the infinite number of molecular combinations that can be made from them is one of the supreme intellectual achievements of humankind. The Periodic Table of the Elements should be recognized as one of the great masterpieces of scientific accomplishment.

Discussion

It is by observing the behavior of atoms of an element in the presence of other substances that the chemical properties of the element can be deduced. We know now that the chemical behavior of the elements is determined by the arrangement of electrons in the atom's outermost energy level or shell. The Pauli exclusion principle accurately describes the way atomic structure is organized. The innermost energy level of an atom is filled when there are two electrons in it. The second level requires eight electrons to fill it. When an atom has more than eight electrons in the third level a fourth level begins to form for the ninth and tenth electron and the third level begins to hold more electrons. As electron clouds assemble around nuclei containing many protons, the third level can be forced to hold up to eighteen electrons.

The order of filling of the fourth and higher energy levels gets even more complex. By spectroscopic examination it has been discovered that energy levels have sub levels and that within each sub level there are multiple paths called orbitals. Each orbital can only hold two electrons. And true to the Pauli exclusion principle they are of opposite spin.

Self-organization of atoms – Stellar nucleosynthesis

Matter began to self-organize itself within a fraction of a second after the big bang that initiated our universe. It is then that quarks coalesced into protons and neutrons and when a proton could capture an electron hydrogen formed. Helium nuclei formed when the strong energy input from the initial big bang or the tremendous temperature and pressure in the interior of stars overcame the mutual electrostatic repulsion of protons. The energy forced the protons so close together that the strong nuclear force could act and bind them into atomic nuclei.

The self-organization of atomic nuclei continues within stars as hydrogen nuclei are fused into helium nuclei and the hydrogen core shrinks. These stellar interiors heat up as energy is released from nuclear fusion reactions. Reactions that were not possible before begin. Carbon nuclei form in that moment when two helium nuclei are briefly forced together and are struck by a third. An oxygen nucleus forms when carbon is struck by another helium nucleus. The ordering principle that leads this self-organizing process of nuclei production is that by which systems tend to rearrange themselves into more stable configurations, or lower energy states. The process is called stellar nucleosynthesis.

The process continues within the stars. Oxygen nuclei are bombarded by other nuclei and it is transformed into silicon and sulfur. More fusion accompanied by the decay of some unstable combinations produce different nuclei all the way up to iron. There the stellar furnaces, like that of our Sun, reached the limit of their productive capability. The iron nucleus is the most tightly bound of all the elements.

Heavy element production – Supernova explosion

Up to this point massive amounts of nuclear energy are released as lighter nuclei fuse together. To make nuclei heavier than iron requires energy input. Nature does it with another bang. A supernova explosion of intense pressure synthesizes new heavier elements and spreads them out into the universe. Some are radioactive and begin to break down immediately. But through neutron bombardment the nuclei of all 92 of the chemical elements are eventually made. Thus does nature organize the building blocks of everything.

Atomic formation

Once nuclei are formed and escape the heat of their star mothers, the organizing principle of electromagnet attraction takes over the task of atomic organization. Each nucleus picks up a crowd of electrons equal to the number of its protons and an electrically neutral atom is formed. Because electrons have a dual nature and sometimes behave like waves rather than particles they can exist only at distances from the nucleus that fit their whole wave length. Thus electrons surround the nucleus in discrete energy levels or “shells.”

There is a tendency for atoms to complete the electron capacity of their outermost energy level. They do this by losing, borrowing or sharing electrons with other atoms. Therefore, how an atom reacts with other atoms, what it can combine with and what it will reject is determined by the structure it presents to the world of atoms, that is, by the number of electrons in its outermost energy level. Elements with similar electron structure will have behaviors in common and can be put into family groups. It is the structure of the atoms which determines their chemical properties and their behavior and their grouping in the Periodic Table.

The atomic nucleus can be thought of as an evolving entity as it is transmuted within the heart of stars into increasingly complex structures. This is a form of emergent evolution. Here the term evolution is used in the broad sense as the process through which new structures, behaviors, or concepts come into being from previous ones.

Self-organization of compounds by chemical bonding

Compounds form when atoms combine. As mentioned above, atoms tend to interact in such a way as to wind up with completely filled outer energy levels. They either lose or gain electrons from their reaction partners (ionic bonding).

A common example of ionic bonding is the combination of sodium and chlorine. The sodium atom has a single electron in its outer energy level. It is a very reactive metal. The chlorine atom has seven electrons in its outer energy level. It lacks one electron to make the level complete. It is a poisonous gas. When the two reactants come in contact, chlorine atoms grab the outer electrons held only loosely by the sodium atoms. This makes each sodium atom an ion with an electric charge of +1 and each chlorine atom an ion with a charge of -1. The opposite charges bind the ions together into a crystal of common salt with all its well-known beneficial properties. In a similar way all the multitude of chemical compounds form, each possessing its own set of properties.

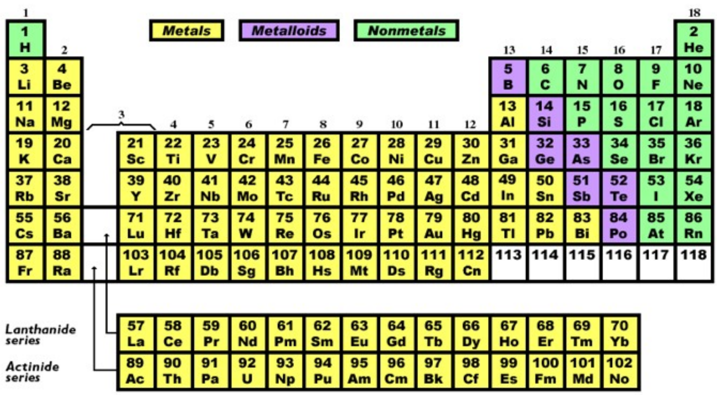
In other cases of chemical bonding electrons in the outer energy levels are shared so that both atoms have filled energy levels (covalent bonding). The water molecule is the result of this covalent bonding. The oxygen atom has six electrons in its outermost energy level. Two more will complete it. Hydrogen atoms have one electron surrounding their nuclei. This inner energy level of hydrogen would be complete if one more were within it. Two hydrogen atoms and one oxygen atom can strike a deal. If electrons from the two hydrogen atoms visit the oxygen's outer energy level and two of the oxygen's electrons can spend time around the hydrogens' nuclei all three atoms can have filled energy levels.

By both ionic and covalent bonding atoms get attached to each other and form more complex structures with new properties.

The Periodic Table of the Elements

Of all the intellectual constructions of human culture the periodic table is surely one of the greatest. It stands with Darwin's theory of evolution, as a tool that brings understanding to a chaotic mass of knowledge. It explains how the elements are related to each other. It displays the pattern of order out of which the world is built. Today we account for its regularity with our knowledge of atomic structure, but when it was first proposed by Dmitri Mendeleev in 1869, atomic structure was unknown. He worked by associating properties of the elements with their increasing atomic masses. There was no apparent reason why the properties of various elements should repeat themselves as they did. There had to be a deep connection.

Patterns often reveal laws of organization and the periodicities in the table challenged scientists to explain them. Their search for a physical reason for those periodicities produced the modern atomic theory.



The periodic table is now an everyday working tool of chemists and a common feature on the wall of chemistry classrooms. The fact that it codifies so much information in such a concise presentation obscures its remarkable significance. In it is described the structural organization of atomic nature. It allows us to see, step by step, system by system, how matter becomes increasingly complex. By using the knowledge embedded in the table, chemists have been able to construct new compounds with new properties. The table is a concise statement by the human mind of the order found in nature.

Self-organization of carbon compounds

It is the unique organization of carbon atoms that makes living organisms possible. The six protons in the nucleus dictate that there shall be six electrons in the energy levels surrounding the nucleus. The Pauli exclusion principle decrees that there will be two electrons in the inner energy level leaving four in the outer energy level. This is just half of what is necessary to complete the energy level. Each carbon atom can therefore form four covalent bonds, more than any other element.

The ability of carbon to form long chain molecules by bonding to hydrogen and itself forms the economically important hydrocarbon class of compounds.

```
     H              H   H             H   H   H
     |              |   |             |   |   |
 H – C – H      H – C – C – H     H – C – C – C – H
     |              |   |             |   |   |
     H              H   H             H   H   H
  Methane          Ethane            Propane
```

When carbon, hydrogen and oxygen combine, many new compounds like alcohols, sugars, and fatty acids originate. Throw nitrogen into the combination and amino acids and the proteins of living organisms form. Each of these compounds has distinctive properties which cannot be deduced from the properties of the elements from which they are made. They are emergent properties.

It is an interesting discovery that complex hydrocarbons, as well as water, carbon monoxide, ammonia and small amino acids, are found to have formed in interplanetary space. The origin of living organisms on Earth may have been aided if some of the molecules important to living organisms rained down on our young planet from space.

Self-organization of complex protein molecules

Within the living cell proteins are assembled as long chains of amino acids. The sequence of amino acids in the chain is determined by the sequence of the DNA in the cell. This is called the *primary* *structure* of the protein. Electromagnetic forces along the chain can change the single strand of amino acids into a helix shape or into a sheet with pleats producing the *secondary structure* of proteins. They are important to the structure of living organisms because they form the fibrous proteins. One third of all protein in vertebrates is made up of collagen, a fibrous protein. It is a major part of tendons, ligaments, bone, cartilage and skin.

Other electromagnetic forces can twist the amino acid chain into an intricately folded, three dimensional shapes; the *tertiary structure.* These proteins are the globular proteins with complex biological functions. They are the enzymes, antibodies, and membrane receptors without which living organisms could not exist.

The folding process that self-organizes complex protein molecules does not stop with the formation of tertiary structures from one kind of long amino acid chain. Many proteins start out from combinations of more than one chain and then are subject to the folding process. As many as four different chains may be the source of a molecule.

The insulin hormone is an example of a protein formed from two different amino acid chains. The hemoglobin molecule is a product of four chains. When two or more chains organize themselves into molecules the *quaternary structure* of proteins is formed.

Summary – the importance of chemical complexity

It is obvious that this change in structure of complex molecules is self organized, necessary for life, produces new structures and new properties.

The premier self-replicator molecule is the now famous DNA molecule. The explanation of how the double helix splits open and the replication of both strands of DNA takes place is the triumph of molecular biology. The understanding of the functioning of DNA and how it codes for the production of inherited properties is the key to the understanding of the evolution of all living things

17. *Cells: Self-Organizing Systems of Life*

Definitions

Symbiosis_— the association of two or more organisms of different species that are interdependent and where each gains benefits from the other.

Serial Endosymbiosis Theory (SET) — the theory that complex cells emerged from fusions of different kinds of bacteria.

Amphiphilic molecules — molecules that have one end which attracts water molecules and the other end which attracts oil molecules.

Organelles — small structures within cells that perform specialized beneficial functions. The following are two examples of organelles:

Mitochondria — small bodies within all cells, except bacteria, which contain their own DNA and enzymes. They use oxygen and store chemical energy in the form of adenosine triphosphate (ATP) which is used by the cells.

Plastids — small bodies within plant cells. They can act as storage bodies or, when they contain chlorophyll, become the site of photosynthesis.

Background

One of the enduring surprises of biology is the fact that all living organisms (with the exceptions of viruses, bacteria and single celled organisms) are made up of multiple copies of the same unit of structure. From whale to ant, from human to oak tree, the basic structural unit is the cell. The human body is made up of about a million, million (10^{12}) cells. Cells average about 12/1000th of a millimeter in diameter and are remarkably complex. They all have some common internal structures such as, a round nucleus containing chromosomes. They have cytoplasm with mitochondria, and other organelles for producing proteins, lipids, and enzymes of staggering variety.

The most important function of all cells is the conversion of outside energy to energy for all living activities. It is this energy conversion which enables the cell to organize itself, to produce and repair its own parts and then to power cell division that results in copies of itself.

Discussion

Basic cell theory says that cells come from cells but says nothing about how cells began. The question of the self-organization of the first cell is perhaps the most nagging unanswered question in biology. In order for cells to form in the first place, the substances of which they are made must somehow be held together and kept from diffusing into the environment.

The self-organization of the cell membrane

A group of chemicals in a solution are always being dissipated by diffusion and thermal mixing. When the first membrane formed and enclosed a chemical mix, living cells became possible. The structure of cell membranes is now known to be composed of lipid molecules. These are members of a class called amphiphilic molecules, longish molecules with chemically active ends. One end is hydrophilic and is attracted to water molecules. The other end is lipophilic (hydrophobic). It has an oil-like structure and it repels water molecules.

In an aqueous environment a group of amphiphilic molecules will turn their water-loving ends toward the water molecules while their water-repellent oil-like ends tend to attach together. They form into a two molecule thick layer with heads out on both sides and tails inward. It has been shown that a plane of such a bilayer can collapse into a sphere. The amphiphilic molecules tend to organize themselves into a hollow ball with their oily center layer providing a water barrier. The products of chemical reactions that take place inside such a hollow ball are protected from diffusion. Products can be concentrated within it. In living cells this double layer membrane has large protein molecules imbedded in it that act as pores and allow materials in and out of the cell.

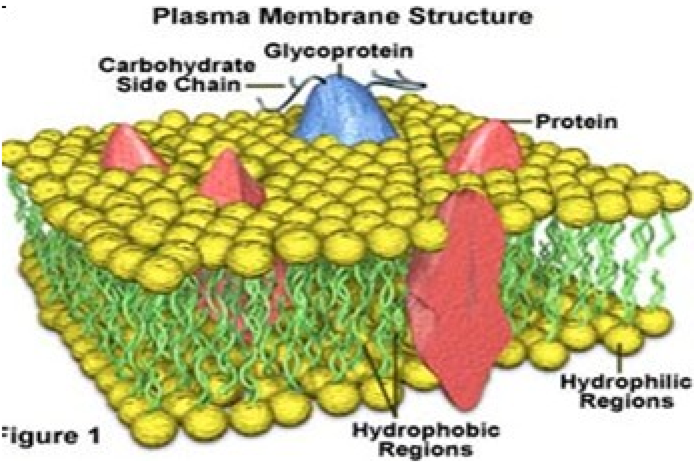


Figure 1

Source: micro.magnet.fsu.edu

The behavior of the membrane is due to its structure. The "head" of amphiphilic molecules is electromagnetically asymmetric. Water molecules are also electromagnetically asymmetrical and these two asymmetries attract one another. On the other hand, oil molecules are electrically symmetrical and so are the "tails" of the amphiphilic molecules. This gives them an oily property and accounts for their attraction to each other rather than to water molecules. It is these properties of amphiphilic molecules that makes possible a new structure – the cell membrane: the essential element for a living cell.

The self-organization of complex cells

For more than half of the total history of living organisms on Earth, some two billion years, the main character was the relatively simple prokaryotic cell. These bacteria, with their genetic material composed of one long strand of floating DNA, are still the most successful of living self-organizing systems. The big evolutionary jump to eukaryotic cells with a closed nucleus containing up to a thousand times as much DNA as the prokaryotic cell and with many other complex organelles was, until recently, one of the great mysteries of biology.

Lynn Margulis of the University of Massachusetts has been the prime mover of serial endosymbiosis theory (SET). This theory, for years ignored but now generally accepted, holds that eukaryotic cells emerged from prokaryotic bacteria by a multistage symbiotic fusion of different kinds of free-living bacteria. Bacteria that could use oxygen in their respiration became the mitochondria. The plastids of plant cells are descendants of phototrophic bacteria that use light energy to produce carbohydrates. And spirochetes that have a whip-like structure which enables them to move became the undulipodia (waving feet) or cilia of some cells.

As SET gained credibility the narrow view that the evolution of species was solely the work of natural selection operating on random mutations expanded to include mergers as a means of producing new forms of living systems. Further studies may lend support to the idea that symbiosis may be a more important source of evolutionary novelty on the cellular level than genetic mutations.

Let me remind the reader that if symbiosis is an important process in evolution we must say that understanding self organization is vital to understanding the beginning of life..

The self-organization of the embryo

Surely one of the most fascinating examples of self-organization is the development of a single fertilized egg into a complex, multicellular organism composed of dozens of different kinds of cells with hundreds of adaptive structures and thousands of different metabolic processes and behaviors. Although much remains to be learned, the notion of concentration gradients is helping biologists to understand this process. Concentration gradients are the differences in concentration produced when chemicals diffuse into an environment — from maximum at the place of origination to minimum at the edges of the diffusion.

From studies with the long-suffering genetic laboratory animal, the fruit fly *Drosophila*, researchers have confirmed the existence of morphogenetic (changes in inherited structures) gradients that control the development of the larva. For example, the concentration of a protein called bicoid is strongest at the head end of the egg. Bicoid activates a gene for head and thorax development. If bicoid is transferred to the rear pole of a normal egg the embryo develops a duplicate head where the abdomen should be. In the normal egg the initial Bicoid gradient is established by special nurse cells which deposit mRNA for bicoid on the head tip of the unfertilized egg while it is developing.

Another control protein has been found in *Drosophila.* It is called dorsal and stimulates the dorsal/ventral pattern in the larva. When the concentration is altered the front and back development of the fly is misdirected. The abnormal organisms produced when these chemical gradients are changed serve as proof that gradients are the mechanisms that control normal development.

Independent cells self-organize for social benefits

Algae cells - cooperation for reproduction

The ancient blue-green algae reproduce asexually. But before any one of them begins to bud they first assemble into groups. The experience of being in among others in some way seems to provide a necessary chemical or physical stimulus for reproduction. (Reported in Science Times, The New York Times, April 30, 1996)

Bacteria - cooperation for movement

An unnamed rod bacillus without cilia has been observed to lie unmoving on a nutrient agar surface until cell division has increased its numbers to 10 or 12. The assembled group, resembling a raft of floating logs, acquires the ability to move across the surface. The property of locomotion arises from their interaction. It may be that the production of a coat of slime is necessary for movement and that the threshold amount required needs the cooperative efforts of a group.

By assimilating nutrients and reproducing as they raft along, the numbers increase until hundreds of thousands are joined in a moving colony. Presumably, this behavior would assist the colony to find a new source of food. (Personal observations – 1996)

Bacteria - cooperation for protection

Recent researches have reported a "social life" for bacteria. What is described as a new field of biology is the study of bacterial group behavior. The common Escherichia coli and other bacteria seem to be able to communicate with each other and act together.

Masses of bacteria, when exposed to noxious stimuli, bunch up into tight balls that form "fantastic geometric patterns" on agar surfaces in petri dishes. Researchers at Harvard University have discovered that when the bacteria are exposed to hydrogen peroxide or antibiotics they secrete amino acids. The secretion induces the bacteria to aggregate into tight little balls. While the outer bacteria may die, those inside the balls are protected and survive.

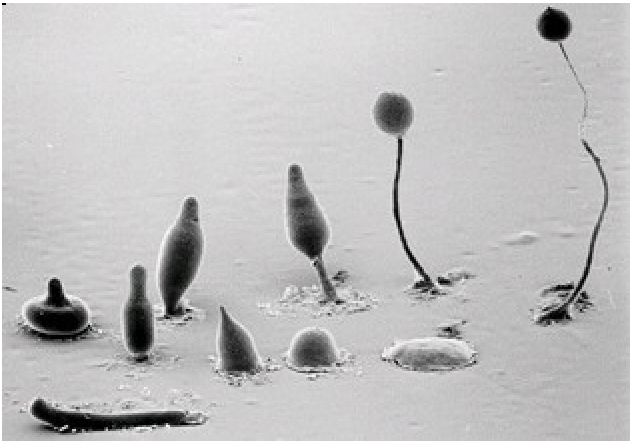
James Shapiro of the University of Chicago, whose laboratory has been studying this kind of bacterial behavior for many years is quoted as saying, "For 300 years or more, scientists have searched for the simplest unit that they could take apart, dissect and use to study the system. But we are entering a period in which, in some cases, we have come to the limit of that approach, We need to understand more about how the properties of the whole arise. We are searching for new principles." (Reported in Science Times, The New York Times, Oct. 13, 1992)

Social amoeba - cooperation for movement and reproduction

Before we leave the topic of cells as self-organizing systems the truly remarkable soil amoeba *Dictyostelium discoideum* should be mentioned. It is a good example of the beginnings of multicellular organization. Because of its unique life cycle, it has been extensively studied and can be grown in the classroom to illustrate a self-organized cellular system.

The life cycle is separated into three distinct stages. At first individual amoeba grow and reproduce by simple cell division on the forest floor. When the bacteria on which the *Dictyostelium* feed are exhausted in the area thousands of cells aggregate in response to an emitted chemical signal and form themselves into a slug-like creature, just visible to the naked eye, With feeding at an end the individual amoeba become part of a multi-cellar organism that moves as one body to another location.

The slug-like aggregate organism releases a layer of slime on which it glides. The slime trail is in part responsible for *Dictyostelium's* common name "slime mold." When the movement stops, the cells differentiate and form a stalk structure with a round spore case on top. When many slugs form the stalk structure the mass looks like a mold. Each of the spores contains a living cell which, when it falls onto a suitable surface, will open and new amoeba will emerge and initiate another life cycle.



There is nothing more wonderful to contemplate than the self-organization of living systems; in particular the union of complex egg and complex sperm to the most complex structure known, the human brain. With Darwin we reflect that... "There is grandeur in this view of life"

18. Societies: Self -Organizing Systems

From the social insects with their hives and nests to flocks, schools and herds nature has been forming systems where individuals acting cooperatively results in the good of all. Human societies are no exception. While a consideration of human societies might seem to belong to the realm of social science rather than science the holistic view proposed in this book extends to include a brief consideration of this topic.

Definition

S**ociety** - a group of organisms of the same species whose cooperative efforts enhance the survival of the group. A necessary feature is the capability for communication and interaction.

Background

Ants, termites, wasps and bees, emerge from their larva stage knowing how to act. Built-in genetic instructions determine their behavior and that behavior enables the group to survive and prosper. Species other than insects have found social organization an efficient method for survival. A new discovery reported in Science News, June 8, 1996 is that a species of snapping shrimp inhabiting Caribbean coral reefs forms colonies of as many as 200 individuals within local sponges. Genetic analyses suggests that most of the colony members are offspring of a single queen and possibly a single male. All the shrimp fiercely defend their colony against intruders, even other shrimp, but will readily accept members of their own colony.

In advanced societal groups new properties emerge. For example, the specialization of individuals becomes a possibility. The insect queen can be an egg-producing specialist because her food, grooming, housing and infant care requirements are taken care of by other specialists. Societal life permits specialization and specialization enhances the survival of the society. Human societies, for example, function only because of the specialized roles that individuals perform. To survive, pre-agricultural societies not only needed the services of the hunter but also those of the flint knapper, the weaver, tanner and, most importantly, the women gatherers of wild grains, nuts, fruits, and roots who also functioned as food preparers.

In villages of early agricultural society when humans became food producers rather than hunter-gatherers, the specialization of roles increased. Farmers, shepherds, tool makers, homemakers, weavers, educators, health workers, ecclesiastics, traders, story tellers, politicians, soldiers, and others all pursued their individual activities. Out of their interactions the self-organization of a society emerges.

Discussion

There are three characteristics of societies; specialization, communication, and emergent behavior. The amount of organization among different societies varies. For example, elementary forms of society do not have as much specialization as that of more complex societies. Bird flocks, fish schools, and locust swarms are examples of societies where all the members have similar behavior. In wolf packs and lion prides specialization of action becomes apparent. In human societies, as noted above, specialization is prevalent.

Since each member modifies its own behavior depending on what other members are doing, communication among members is obviously necessary. Communication among the members is the key to societal behavior. This communication may be by pheromones, sound, or body language or, in human societies, speech and its symbolic representation, writing. And, of course, now by smart phones and computers.

It is interesting to note that societal behavior is an emergent. Every member of a society does his or her "own thing." Whether it is the ant responding to its genes, or martyrs responding to their "call," individual behavior is always individual. As each person in human society pursues his or her individual goals, the behavior of the group or community emerges. This is especially observable in economic activity.

"The invisible hand" - Economic systems as self-organizing

The early economic theorist Adam Smith (1723-1790) espoused the underlying principle of the self-organization of human society. In his Wealth of Nations (1776) he argues that the selfinterested actions of individuals promotes the interests of society as a whole. It is through the pursuit of personal gain that an organized market system is produced. Production and exchange of goods are coordinated by the "invisible hand" of supply and demand. The result is the emergence of an economy which will regulate itself if left alone. According to Smith, the capitalist "neither intends to promote the public interest, nor knows how much he is promoting it... He intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of his intention."

Examples abound. Assume that an enterprising individual has invented a gadget which makes work easier or life more interesting. He offers this gadget for sale to his neighbors. His motive is not to better the lot of humanity but to make his own economic position more secure. The gadget is sought after by more and more people. The producer, noticing the demand for his product, raises his price. For a while he enjoys large profits. Other entrepreneurs, seeing the benefits that could be theirs start producing the gadget or a similar one. They offer their product at a price below that of the originator. The expanding production tends to reduce the cost. In Adam Smith's view unbridled competition will benefit society through a self-adjusting process which will provide what people want at prices just above production costs.

Many people feel that markets should be left alone because, as Smith said, "no human wisdom or knowledge could ever be sufficient to manage the affairs of such complexity." But humans, being what they are, continuously try to "improve" on what are essentially self-organizing systems. The failures of the planned economy of the former Soviet Union seem to lend credence to the words of Adam Smith.

Although central planning has proved inadequate to direct human societies toward the general good, unconstrained free markets have also generated evils. They produce uneven distribution of wealth and power for the few. Government tries to adjust the balance by imposing higher income and inheritance taxes on the rich. Some say that such taxes interfere with the free enterprise system. The debate goes on and on with each election.

Human social structure as self-organizing

It is, however, the uneven distribution of wealth which acts as another sort of self-organizing principle. It produces the social structure of human society.

In the past, social position, a pecking order for humans, used to be a product of birth. Certain families were considered to be "special." In today's industrial society, wealth and the economic power that goes with it, is the organizing principle which produces class structure. Economic power raises individuals above their fellows because those below acquiesce to it. It is the general population in a culture who establish the social structure system by the way they act toward other members of the society. That system is not directed nor planned. It organizes itself out of the individual behaviors.

Human society - a natural progression toward complexity

There is an historical direction in the development of human societies. Hunting-gathering changed to agricultural-pastoral on which was built the industrial and now our technological society. This is a progressive development in the sense that each change incorporates the past.

Within each age technological innovation has sought to increase energy efficiency and the power of human action. From the wheel to the space shuttle; from the digging stick to the tractor and multiple plow; from the whispered word to the thundering Internet – technical innovations have changed human life. With each advance has come increased complexity. With more choices and greater power of action living becomes ever more complicated. While some people long for simplicity and less complication many welcome this progression because, as they see it, with increased alternatives comes increased freedom to choose and an increased range of human possibilities.

Conclusion

These ideas lead to the hypothesis that laws governing the evolution of natural systems may also govern the development of human societies. From a broad perspective human beings are still the natural products of evolution and their cities and all their Earth changing projects are as natural as birds nests and beaver dams.

Perhaps future studies of self-organizing systems will reveal not only the workings of biological systems but help to better understand the development of human social systems.

19. *Thermodynamic Law and Self-Organizing Systems*

The important consideration of the relationship between thermodynamics and self-organizing systems has been left to the end because thermodynamic laws are so all-pervasive that their existence overshadows all and it provides a opportunity for summing up..

Definitions

The 2nd Law of Thermodynamics

1. In a closed system (one isolated from its environment) the heat flow out of one part of the system cannot be transformed completely into mechanical energy. It is always accompanied by heat flow into a cooler part of the system. Therefore no engine can work at 100% efficiency. There is always a transfer to unusable heat due to conduction and friction.

2. Heat never flows spontaneously from a cooler body to a hotter one.

3. For a closed system the direction of spontaneous change is from order to disorder.

4. The entropy of a closed system always increases or remains the same.

5. The entropy of the universe tends toward a maximum.

Entropy

1. the quantity of heat "loss" during energy transitions; or, in heat engines, entropy is the amount of heat which cannot be converted into work because it is dispersed into the surroundings.

2. the measure of disorder in a system.

Closed systems - those that are isolated from their environment.

Open systems - those that continuously exchange matter and energy with their environment.

Dissipative structures - systems far from equilibrium which maintain a high degree of organization by dissipating entropy to the environment.

Background

No general discussion of self-organizing systems would be complete without relating that discussion to the 2nd Law of thermodynamics which has been held to be the most primary law of physics.

The world view evoked by the 2nd Law is one in which, in general, things fall apart, everything tends to level out, and disorder increases until all that is left is only the quiet vibrations of molecules. No further change can take place.

A world full of self-organizing systems seems to be in direct contrast. Things tend to become more complex. They build themselves up from simpler structures. They create more order and organization in the world and, as time goes on, more and more special arrangements are achieved.

Discussion

The two views expressed above would seem to be in conflict. Indeed, some science writers have suggested that there are two “arrows of time.” The first arrow is the general tendency toward entropy increase. Before and after can be distinguished by amount of energy disorganization in a system. Given two pictures - a glass with water on a table and one of pieces of glass on the floor with water spreading out - one can easily say which was taken first.

The suggestion of another arrow of time is based on the observed tendency toward increased organization and complexity. In the beginning there was a primeval structure that produced the big bang, powerful but relatively simple. Today, about 13.7 billion years later, there are multitudes of physical structures from atoms and molecules to astronomical objects of bewildering variety. Highly organized patterns of chemical, biological, and cultural systems have evolved. Along with the increase in numbers of structures comes an increasingly complex web of interrelationships.

Thus, our universe seems to have two large scale tendencies: one destructive and inevitable — the leveling out of things; the other constructive and equally inevitable — the organization of things. The universe is steadily running downhill in the sense of the disbursing of its energy, while at the same time parts of it are running uphill in the sense of building structure through self-organization.

We know what the final end is likely to be but
self organization spreads a lovely light.

Can the growth of structure and organization be reconciled with the 2nd Law?

An important characteristic of self-organizing systems is that they are open systems; systems which give and receive matter and energy to and from their environment.

Traditional physics and chemistry study closed systems where the 2nd Law is easily applied. To resolve the difference in perspective between that of the 2nd Law with that of self-organizing systems a new approach was needed. A leading figure in the development of what has begun to be called non-equilibrium thermodynamics was Ilya Prigogine of the Free University of Brussels. For his work relating to chemical systems far from equilibrium he was awarded the Nobel Prize in Chemistry in 1977.

Prigogine coined the term "dissipative structures" to describe those systems which display a high degree of organization through the exchange of matter and energy with their environment. In choosing this phrase he wanted "to emphasize the constructive role of dissipative processes in their formation." Dissipative structures maintain themselves only as long as some form of work is done on them. They spontaneously self-organize when conditions permit and "reflect the interaction of a given system with its surroundings."

If the flow of matter and energy to a dissipative structure ceases its organization disappears. An essential feature of dissipative structures is the exportation of the entropy they produce into the environment. The total entropy of the universe therefore increases. What Prigogine has shown is that the spontaneous formation of organized structures is not forbidden by the 2nd Law.

The work of the Brussels School has gone further. The study of non equilibrium processes has shown that dissipative structures are subject to abrupt spontaneous changes of behavior. At certain thresholds of complexity a kind of phase transition may occur, or bifurcations in developmental pathways may present themselves. Which direction the system goes is unpredictable. In this way dissipative structures can reorganize themselves into new and unexpected forms. Prigogine has called this "order through fluctuation," and has written, "What seems certain is that these far-from-equilibrium phenomena illustrate an essential and unexpected property of matter."

A revolutionary view of the 2nd Law is being revealed. It is not simply the inexorable arrow pointing toward degeneration and a universal equilibrium where all change ceases. The processes of energy transformation must include the tendency toward the formation of transient organized structures under far from equilibrium conditions which can evolve and produce new structures and behaviors.

Beyond reconciliation, toward partnership

Not only does the 2nd Law permit the evolution of complex systems but the process of structuring is actually promoted by the Law. This is the claim of the late Jeffrey Wicken, professor of science at Behrend College, Pa. Wicken especially focuses on living systems; organisms, populations, and societies. He regards them as "patterns of entropy production whose stabilities are maintained by certain purposive internal organizations."

In chemistry Le Châtelier's principle expresses the idea that if stress is applied to a system at equilibrium, the system will change in the direction of reducing the stress. A physical example of this is the change of ice to water when pressure is applied. The stress of pressure, even without a change in temperature, forces the system to change. Since the volume occupied by water is less than that of ice the ice system changes in that direction.

Wicken sees the evolutionary process as something like an extension of Le Châtelier's principle in that living systems must also adjust to applied forces or energy gradients. Although Le Châtelier's principle applies to systems in equilibrium and Wicken is talking about systems far from equilibrium there is the possibility of a synthesis of the ideas.

The total biosphere can be considered to be a system whose equilibrium is being upset by the input of energy. It is continually being bombarded by energy from the Sun. Through the process of photosynthesis there is a conversion to chemical potential energy. This potential energy puts a stress on the biosphere. The stress is relieved by "the evolutionary process in its movement from the simple and unorganized to the complex and highly organized."

Natural selection, then, is a consequence of thermodynamic flows through the biosphere. The means of relieving the energy gradient built up by photosynthesis is by the generation of more complex organisms that are, presumably, more energy efficient.

A new species or a new technology that makes more efficient use of this energy flow will likely be favored and will be selectively preserved. All organisms, the biosphere itself, become part of the Earth system which adjusts to the energy input from the Sun by heat radiation out into space. Thus there is no incompatibility between the 2nd Law and biological evolution.

In this analysis the tendency toward the dissipation of energy is the source of the development of complex organisms. Life is not an accident due to the chance aggregation of molecules. It is a natural outcome of the flow of energy or, as Wicken puts it, "a necessary consequence of thermodynamic laws."

Notes:

Quotes re emergence (various sources)

"The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each new level of complexity entirely new properties appear."

P. W. Anderson, "More is Different," *Science,* Aug., 1972

"Weather is an emergent property: take your water vapor out over the Gulf of Mexico and let it interact with sunlight and wind, and it can organize itself into an emergent structure known as a hurricane."

P. W.Anderson quoted in *Complexity* by M. Mitchell Waldrop

"The origin of life and the origin of man were evolutionary crises, turning points, actualizations of novel forms of being. These radical innovations can be described as emergence, or transcendencies, in the evolutionary process."

Theodosius Dobzhansky, *The Biology of Ultimate Concern,* 1967

"Life is not a circular process, doomed to endless cycles of recurrence, each emergence to a higher level brings with it unexpected and unpredictable elements... When processes reach a certain point of development, they reveal unexpected characteristics which surpass the limitations of their earlier conditions."

Lewis Mumford, *The Conduct of Life,* 1951

"Internal complexity can translate a simple change into a wondrous alteration of quality... Perhaps the greatest evolutionary invention, the origin of consciousness, required only an increase in brain power."

Stephen Jay Gould, *Bully for Brontosaurus,* 1991

Suggestions – activities for the classroom

• Discuss paradigm shifting as progress in science.

• Ask students to make a list of systems. Who has the longest list after 5 min?

• Trace the energy flow though any system.

• How is a city like an organism?

• Elicit the common characteristics of all systems.

• Using a windmill as an example discuss how the parts are interconnected so that it functions as a whole.

• Repeat the above with a toilet, water supply, reserve tank, control mechanism, and waste system as parts.

• Melt sodium thiosulfate in a test tube to a clear liquid. Cool in a water bath. Induce rapid crystallization by scratching the inside of the test tube or dropping a crystal in. Feel the heat released. Energy flow.

• Discuss heat zones in a candle flame, a dynamic system.

• Examine how is self-organization is related to the origin of life.

• In what way are ant nests and bee hives systems?

• Describe the Stanley Miller/Harold Urey experiment as a system.

• Play a video clip of Bénard cells forming in heated cooking oil.

• Discuss, or better – demonstrate, a chemical clock system.

• Demonstrate the B/Z chemical reaction system which self-organizes radiating circles of color.

• Get standing wave structures in water by rubbing the edge of a wine glass or applying vibration to an aluminum pan with powder

• Turn your students on to the Mandelbrot Set via the Internet's many sites. The most fascinating mathematical system in the world.

• Ask why a sports team is a like a system. Team spirit is a emergent.

• Point out that mood is an emergent of music.

• Ask why it is called a weather *system.* What are parts of a tornado?

Suggestions – activities for the classroom (continued)

• Discuss the social structure of your community. Does a pecking order structure emerge?

• Have students test a needle floating on paper Then rub the needle with a magnet. Does it now act as a compass? The new magnet field of the needle is an emergent.

• Ask the students what they think Heraclitus meant when he said, "You cannot step into the same river twice."

• Look at an egg as a system. Have the students describe its properties. If it is broken into a pan and heat is added what are the new properties? Ask where the new properties came from?

• Put a copy of the diagram on Page 49 on the chalkboard. Ask the students what it is trying to say,

• Discuss feedbacks, positive and negative. Ask for examples.

• In a review of the interior structure of the cell have the students explain the function of each of the parts. Ask them to explain how "Sometimes the whole is greater than the sum of its parts" applies.

• Ask if there is a ethnic neighborhood in town. How was it organized? Who did it?

• Discuss the operation of a laser. What emerges?

• Be sure the students understand the 2nd Law of Thermodynamics. It can be stated in different ways –

There is no free lunch. You can't even break even.

If you think things are mixed up now, just wait. It's all downhill.

Entropy isn't what it used to be. Disorder – awful but lawful.

It all levels out. Breaking up is not hard to do.

The 2nd Law makes mountains into molehills.

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