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Seized by Agreement, Swamped by Understanding

Living Systems - Autonomous Unities

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The question which is never entirely resolved is: what is life? Biology, claims to stand for the study of life and living things, yet we would say that it cannot make a thoroughly clear distinction between living and non-living, except in some very obvious cases. There are textbook definitions, of course, based on certain notable properties such as the ability to metabolize or reproduce, but these are arbitrary. If we are familiar with the characteristics of a particular animal or plant, we know enough to be able to pronounce that it is dead when certain internal and external behaviours are no longer evident. Even this has difficulties - such as revealed in the arguments about whether to switch off a human life-support system or not. When you find a squishy object on the seashore, can you be sure if it is alive or dead - or never living? The same dilemma confronts medical scientists and microbiologists trying to decide, for example, whether viruses are living, or quasi-living, or intermittently living, or what.

Biologists are coy about defining life because, even with the closest scientific scrutiny, there are difficulties. The tools of science have revealed much about biochemistry and heredity, enzymes and genes, but very little about precisely what is life. James Lovelock [1], with a background in atmospheric chemistry, not biology, expressed surprise about this when he sought to establish criteria for the presence of life in outer space. Some biologists even hold that the operational value of life as a concept has declined, that a definition of life is not possible, or would be meaningless [2]. This bizarre situation appears to have arisen out of our history of mechanistic biological explanation which has relied almost entirely on the reductionist or analytical kind of description. We are not content to leave it at that so we will attempt to find a more satisfying explanation.

Trying to Find the Origins of Life

One way of approaching this is to consider the closely related question: where and when did life originate - how did it begin? According to geophysicists, the Earth is at least 5 billion years old and has had a solid surface of rocks for about 4 billion years. Its atmosphere then would probably have consisted of methane, ammonia, hydrogen and helium - which is very different from today. Living organisms as we know them consist of complex organic (carbon chain) molecules which may seem a distant step from simple substances like ammonia and water, but a famous experiment by Stanley Miller [3] at the University of Chicago in 1953 showed that it was certainly possible to obtain molecules such as amino acids from simple mixtures in a laboratory bottle when sufficient electrical energy was applied. Perhaps a part of the explanation can be found in a particular chemical sequence leading to the production of compounds like nucleotides (see later) which are distinctive of living things today.

At least since the advent of evolutionary theory, which is attributed principally to Darwin, the widespread belief has been that all life forms, including ourselves, have developed progressively from the most humble beginning, *i.e.* from a common ancestor. The major working hypothesis about this came from the Russian-English combination of Alexander Oparin and J.B.S. Haldane who envisaged life's cradle as a primaeval soup which bubbled away until conditions were right for the chemistry of life to begin. An alternative idea of Fred Hoyle and others was that some essential ingredients arrived from elsewhere in space, on board meteorites, but this has been a less popular view. The oldest fossils, of microscopic spheres which resemble modern bacteria, are about 3.5 billion years old, yet not even the simplest of multicellular organisms, which we know as animals and plants today, seems to have appeared until half a billion years ago. We ourselves appear in the fossil record of only 35,000 years ago. So the evolution of the cell itself was by no means a brief affair! It requires further explanation than simply a sequence of chemical changes.

Shortly we will consider the rather different approach taken by Maturana. He admits to having been much troubled, as a young Professor, by the question asked by his student: when life first appeared in the world, what precisely was it that happened? He and Varela described how they rejected such criteria of life as chemical composition or a list of properties because one could never be sure that the list was complete - what would be the criterion of that?. They chose, as the criterion of life, a statement, not about its structure or its properties, but about its *organisation* - the notion of organisation which was discussed in the previous paper. But first, we shall look more closely at the cell itself - the basic unit of a living system.

Organisation and Structure of Cells

Those most ancient fossils which are thought to be relics of a living thing because they resemble modern bacteria, do so in one distinctive way: they have a definite boundary which is more or less spherical. Robert Hooke, the curator of instruments for the Royal Society in England in the mid-seventeenth century, is generally accredited [4] with giving the name *cellulae* (meaning "small rooms") to such objects which he saw in a thin slice of cork. However, Lorenz Oken had speculated in 1805 that organic beings originated from, and consisted of, vesicles, or cells - that this was a basic living unit from which all complex organisms developed (rather than being created). [5] The advent of microscopy subsequently enabled a "cell theory" to become established, notably by Theodor Schwann and then Rudolph Virchow, amongst others.

So it has come to be accepted that the unity which is of singular importance in biology is the living cell, that all organisms consist of one or more cells, and that all cells arise from pre-existing cells. The significance of the cell membrane in the way we choose to define this unity cannot be over-emphasised. To it we attribute the cell identity. Yet that, in itself, is not characteristic of life. It is the molecular interactions which occur across that supposed boundary which are regarded as the stuff of life. There has to be action, movement, or behaviour of some kind, because we clearly regard life as a process, not as an object or a substance.

We may pause to wonder why a cell is so small - typically, a few micrometers in diameter (a line of 2000 red blood cells would fit across your thumbnail) - and one suggestion is that the molecular interaction across its boundary requires a very large surface area to volume ratio (the surface increases as the square, while volume increases as the cube, of the linear dimensions). There is an incredible variety of cell size and type, however, which has led biologists to focus on the function of particular structures and to attribute definitive and all-encompassing roles to certain components.

The most fundamental distinction which we make about the constituents of a cell (see Figure 1) is between its *cytoplasm* and its *nuclear* material. The latter is principally deoxyribonucleic acid, or DNA, whose base is a nucleotide molecule consisting of a (sugar) carbon ring (with a phosphate group attached) and a nitrogen-containing ring. Other nucleotide-based molecules such as RNA (ribonucleic acid) are intimately involved in the operations of the DNA. The importance of variation in structural patterns of nucleotides is considered elsewhere, but remarkably, there are only four kinds of DNA, which differ only in their nitrogen-containing base, and four corresponding kinds of RNA, in the whole realm of living things. Little wonder that this molecule has become a focus of attention in biology!

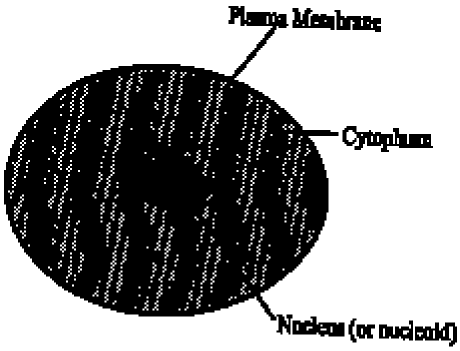

Figure 1. The basic structure of a living cell (of the eukaryotic type).

All bacteria and a few other simple organisms like blue-green algae - far and away the principal inhabitants of this earth in terms of evolutionary longevity - are called *prokaryotic* (pre-nucleated) because their nuclear material consists of a single, long, circular molecule of DNA which is free-floating in the cell interior. All other (more recent) forms of life are *eukaryotes* (true nucleus) in which the DNA is contained within its own membrane and tightly coiled with proteins in rod-like chromosomes within this entity called the nucleus. The significance of the double-stranded, helical shape of this molecule concerns the cell's ability to reproduce itself and will be considered later.

The nucleotide-based molecules contained within the nucleus, work closely with adenosine triphosphate (ATP) and other related molecules which are carriers and transducers of the energy required for the crucial steps in development of the cell. Textbooks are filled with detail about these processes which will not be described here and the mechanistic explanations are continually being revised in this current phase of biology. Very briefly, the assembly of proteins within the cell is currently explained in terms of the *transcription* of DNA patterns into a messenger RNA, which then binds into ribosomes, outside the nucleus in the cytoplasm, to form the structural templates on which the essential proteins can be built from their amino acids.

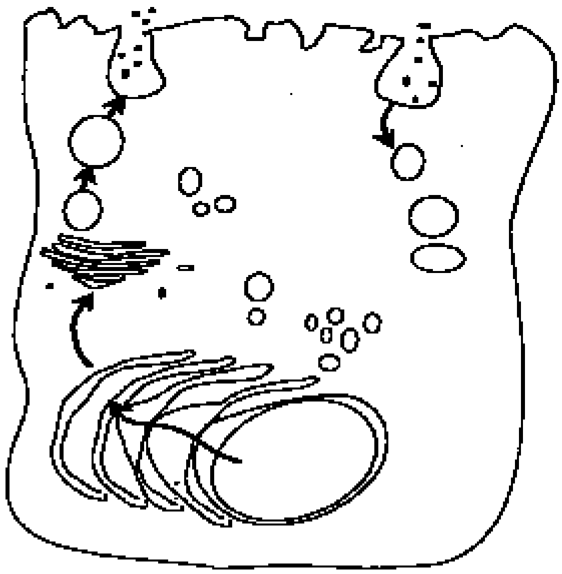

Figure 2. Molecular movement within the cell takes place across a system of membranes which distinguish various organelles. Some of these interchange with the plasma membrane of the cell.

Most of these proteins form into an endoplasmic reticulum which is a kind of workshop in which the molecular traffic within the cell moves back and forth to weave what is known as the *cytomembrane* system. Here various entities which are known as organelles (vesicles, Golgi bodies, lysozomes) are able to function in concert to maintain a constant and complex molecular flow. Each organelle appears to be discrete by virtue of its own surrounding membrane, but they fold and break off to create a flow across them which is a functional system in its own right. This is what enables the cell itself to secrete molecules into its surrounding medium and also to process incoming molecules. Not only protein, but lipid (*i.e.* fat) and other molecules are vitally involved in this continual modification and re-assembly of both organelle and cell membranes; the integrity and permeability of these membranes must be maintained. A representation of this process is given in Figure 2. The mechanism which guides this is not clear from current biochemical knowledge. We have only a description of the sequence of events.

Different cells have characteristic shapes, which may be associated with different ways of moving themselves, so it is believed that there is a *cytoskeleton* which is structured upon microtubules and microfilaments. These are most apparent in the flagellae and cilia, which are hair-like projections that single-celled animals wave about in order to move. When we come to the question of what organises the cytoskeleton, or what organises the microtubules, all that modern textbooks can say is that there is a network of microtubule organising centres! Here are shades of the "dormitive principle" invoked by the medical professor in Molière's satirical play in an unsuccessful attempt to explain to a layperson why opium put him to sleep.

Despite the gaping holes in our biochemical explanation of life processes, there is an implicit belief in biology today that the DNA, because of its apparent primacy in this sequence of events, has some sort of controlling influence over the whole affair. Detailed knowledge of certain aspects of these intracellular processes is what drives the vanguard of modern biology which is known as *molecular biology* - the science of structural manipulation of nuclear material to effect changes in the operation of organisms. So powerful is this tool in its manipulative capacity that "controlling life" has become a catch-cry - and a considerable bone of contention - in biology today.

But does this sensitivity to manipulation necessarily indicate life's constitutive process and can we reduce the constitutive explanation of life to the structure of a particular molecule - even one that is apparently universal? If we say that it was the appearance of DNA which marked the arrival of life, what was it that actually happened? To us, these purely reductionist explanations still lack that quality of satisfaction to which we alluded in the previous paper. However, it is necessary to explore the particular roles of molecular DNA in more detail to consider whether any characteristics of living things can be attributed to single components or whether they emerge from the component interactions.

Knowledge of the structural detail of cell constituents - the intricate diagrams of the process of living which science has provided - serve an important purpose, of course, but tend to convey a static image which draws attention away from the dynamics of the flow which occurs both within and across the boundary of the cell. Rather than a simple boundary, we are really talking about boundary conditions which are continually being established by the dynamics of the system as a whole. As well as being the line of demarcation between the cell and its surrounding medium, the cell membrane is operationally very much a part of the interior of the cell and of the constitutive explanation of that cell.

The need to speak of constitution, not appearance, was what drove Maturana to ask what was peculiar about living systems, other than appearance or function - which is only its meaning in terms of something other than itself. The crucial question is: what is it that would distinguish cellular dynamics from any other set of molecular interactions and transformations which occur in natural processes?

Autopoiesis

What particularly intrigued Maturana was the apparent circularity of the idea that DNA, through RNA *etc*, specified protein synthesis, while protein synthesis was essential to the synthesis of DNA itself. He saw in the closed dynamics of molecular production, where the molecules which are produced constitute the system which produced them, a distinctive property of life for which there seemed to be no proper terminology. He began to think of a cell as a network of molecular production in which the molecules produced constituted the network of molecular production. Of course, some molecules come in to the system (water, oxygen *etc*) and some go out (water, carbon dioxide *etc*), but the living system is the self-producing machinery of molecular production.

If one looks quickly at a modern biochemistry wall chart whose arrows seem to go from every point to every other point, this sounds quite reasonable - if a little strange - but it does not sound like the basis of a scientific revolution. However, Maturana's new term, *autopoiesis*, has opened a completely new space in the dialogue about the process of living. He and Varela called it "the realisation of the living" and the "organisation of living systems" in their seminal papers which described the idea [6].

The specific criteria for autopoiesis, which were originally listed by Varela, Maturana and Uribe in 1974 and amended by Fleischaker in 1988 [7] to strictly locate autopoiesis in the natural world and therefore within the constraints of the laws of thermodynamics, took the form of a key which is summarised below:

(1) Determine if the unity has an identifiable boundary.

(2) Determine if the unity has constitutive elements, *i.e.* discrete components.

(3) Determine if the unity is a mechanistic system, *i.e.* the component interactions and transformations are determined by component (physicochemical) properties.

(4) Determine if the boundary of the unity is constituted by relations among its components, *i.e.* the boundary is determined by component interaction, not imposed from outside.

(5) Determine if the boundary components are produced by component interactions and transformations (of matter).

(6) Determine if the system components are produced by component interactions and transformations which are generated by the transduction of energy.

Gail Raney Fleischaker made a study of the claims of Maturana and Varela that the autopoietic organisation which is described by these criteria is both necessary and sufficient to define a living system [8]. She did this in relation to the minimal cell model of Margulis [9] which is illustrated in Figure 3. She asked: does autopoiesis account for the characteristics which we recognise as living and is everything required for an entity to be regarded as being alive provided by it being autopoietic?

The cell membrane clearly provides the bio-logical equivalent of the system-logical requirement of an identifiable boundary. This plus the molecular and organellar constituents provide the system identity. She was satisfied as to the internal mechanistic operation, because the component properties (which are ionic, electrochemical, steric and hydrophobic) are what determines all component interactions. The cell membrane is constituted solely by these interactions, thus meeting the criterion of self-boundingness. The boundary and components result solely from internal metabolic processes, *i.e.* the system transformations. We can see now that other characteristics of cells such as whether they grow or use oxygen, *etc*., are not so useful because they do not apply to all cells.

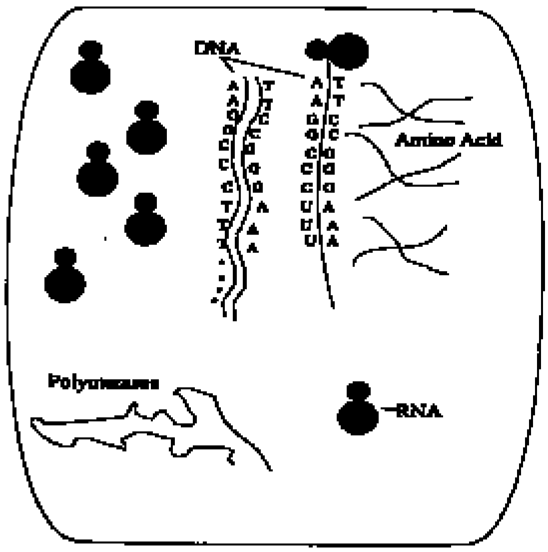

Figure 3. The components of the minimum contemporary cell - as described by Margulos - are DNA (for replication), RNA (for protein synthesis), enzymes (as catalysts), membranes (for maintaining structure) and cytoplasm (as a solvent and for food).

Fleischaker went on to agree that autopoietic organisation was also a sufficient criterion, *i.e.* nothing else was required, provided that it was restricted to the physical domain and thereby satisfied the thermodynamic laws. She used the model of the minimum contemporary cell (Figure 3) and a minimal universal cell to examine the question of the origins of life. This led her to conclude that the earliest life would have been the first autopoietic system, *i.e.* a cell capable of energy capture and material transformation in its own component production. This is consistent with earlier work by Varela and others showing that the minimum structure which is capable of regeneration of cell-like units is one with organisational closure. In other words, what happened at the very beginning of life was a form of *closure* of organisation which enabled self-replacement of components to begin.

Autonomy and Operational Closure

Whereas allopoietic systems have as their product something different from themselves, autopoietic systems actually produce themselves. Their operation is not considered in terms of inputs and outputs. However, they can be perturbed by independent events and they can compensate for this perturbation. An autopoietic system can also be visualised as an allopoietic system - as is commonly done - but not without overlooking some of its special properties. These two types of behaviour form a complementary pair, in the sense that we will need to apprehend them as observers.

Autonomous systems are, by definition, operationally closed - or closed by virtue of their organisation. We are saying that this is what constitutes the system as a recognisable unity. The formal mathematical expression of the stability of what are called dynamical systems is a specific case of this. Instead of the classical notion of simple feedback, stability here depends on the system's coherence or viability - understood as the capacity to be distinguished in some domain.

This dynamical stability, coherence or viability has been expressed in various mathematical forms including the closure thesis of Church and related proofs of Tarski and Turing. The notion of eigenbehaviour (*eigen* meaning proper or self), which is an algebraic foundation for self-referential system processes, is central to the explanation of autonomy. [10] Varela provides many explanations of this showing how the recursivity of a natural network is only seen through the *invariant* aspect of its behaviour which is proper to the processes by which it is interconnected. Eigenbehaviours are the fixed points of certain transformations; they are invariant by virtue of being recursive and self-referential.

Von Foerster has a flair for putting such concepts into everyday living images, some of which will be elaborated further in a moment when we deal with cognition. He asks: why don't we notice our blind spot? We know we have a blind spot - we can find it - but we never notice it in what we do. This recognition of a *second-order* blindness is a crucial element in the meaning which our story is intending to unfold. The reader may like to re-investigate his or her own blind spot using different objects such as a line running through a circle. We will continue to talk about the concept of operational closure in different ways.

The idea that the stability of any system depends on closure of its organisation arose in early cybernetics. The notion of feedback was originally self-referential although its use in engineering has directed attention away from this aspect. Biological stability was brought into focus by Claude Bernard in the middle of last century with his idea of the constancy of the *milieur interieur*, but it is best understood today in terms of Walter Cannon's principle of homeostasis which originated around 1914. Every biologist regards it as axiomatic that the level of activity of physiological processes must be regulated within certain limits (or in certain correspondence with the surrounding medium) if the organism is to survive. To now embrace what we are saying about the autopoiesis of autonomous unities we must expand this way of thinking.

We have said that a living system generates and specifies its own organisation through its production of its own components. It does this in a continuous turnover of components while it is subject to continuous perturbations and is compensating for those perturbations. It is therefore a particular kind of homeostatic (or relations-static) system that has its own organisation as the fundamental invariant. Having now found its way into at least one dictionary of modern thought [11], autopoiesis is defined as "(in cybernetics) a special case of homeostasis in which the critical variable of the system that is held constant is that system's own organisation."

The idea of autopoiesis extends the principle of homeostasis in two ways: (1) by making every homeostatic reference internal to the system itself through the mutual interconnectedness of processes, (2) by proposing this interdependence as the very source of the system's identity as a unity we can distinguish. In other words, living systems produce their own identity (*i.e*. they distinguish themselves from their background).

In biology, we generally think of separate processes of *specification* - effected by the nucleic acids, *constitution* - determined by proteins and *order* (or regulation) - controlled by metabolites. Here we are taking a quite different approach. The autopoietic process is considered to be closed in the sense that it is entirely specified by itself. The process is working to keep the organisation constant, not the structure. It is a process which is complementary to the repertoire of biochemical interaction, but is also quite different in that it has its own properties.

The linearity of conventional explanation produces what is commonly known as the "chicken and egg" problem (which came first), particularly when considering the origins of life. What Fleischaker is saying is that the first life was a cell in which structure and organisation had simultaneous origin; at that point the closure of organisation (and energy capture) became the method of replacement of system parts. However, as we steer away from the obvious hard places of linearity, we find that we run dangerously close to the quicksands of solipsism. The difficulties of circularity will be confronted again later.

Multicellular Dynamics

This form of explanation can then be extrapolated easily enough from the single cell to the multicellular organisms with which we are most concerned. We simply move to a higher-order autopoietic system whose components are themselves autopoietic, but whose domain of operations is different from the domain of its components. This could even be extended to include a hive of honey bees, for example. It seems that Maturana has never put restrictions on the space in which an autopoietic system may exist, thus leaving open the possibility of defining even large social systems as operational systems in their own right. However, Varela and Fleischaker, appear to have chosen to restrict the use of the term to systems which are clearly physical, *i.e.* subject to what we know as the laws of thermodynamics.

The essential point is that a close aggregation of cells which has descended from a single cell to produce a metacellular unity is a condition which is totally consistent with the continuous autopoiesis of those cells. This can be considered as a special case of Maturana and Varela's structural coupling. One version of this which is believed by Lynn Margulis to have been crucial in the evolution of cells is symbiosis, in which the boundaries of one cell become enclosed within the boundaries of another. In this way, the organelles of eukaryotic cells would seem to have all derived from prokaryotic ancestors, *e.g.* the mitochondria of our own cells were once free-living bacteria.[12]

We could argue that multicellular organisms should be regarded as first-order unities, but to do this successfully we would have to know as much about whole organism dynamics as we do about intracellular dynamics. This is simply not the case in biology today. How little we do know about organismic processes will become apparent as we proceed further. At this point we are saying, for the sake of our story, that multicellular organisms have operational closure in exactly the same way as a unicellular organism. Thus, when we speak of cognition, autonomy and structural coupling in animals such as ourselves, we speak of fundamental processes of which both the unity and its individual cells are capable.

Cognition

Maturana has said that, in order to avoid the confusion which arises from considering cognition to be a special property of higher nervous systems, we should take note of the organic roots of any multicellular system, organ or organism *i.e.* millions of cells, reciprocally coupled, making up a second-order unity. By his definition, cognition occurs regardless of whether there is a nervous system or not. It is the sum of all interactions of the living organism in its operational domain. "Living systems are cognitive systems and living as a process is a process of cognition." A system whose "organisation defines a domain of interactions in which it can act with relevance to the maintenance of itself" is a cognitive system.

There is much more to say about cognition, particularly the way in which the nervous system allows its scope to be expanded, but for the time being we might consider a simple example - one which Maturana used - of a single-celled organism such as an amoeba which is in the process of engulfing a protozoan. Molecules released from the protozoan trigger membrane changes in the amoeba which enable its further exposure to the molecules and so on until the amoeba has eventually been able to form a pseudopod which entirely surrounds the protozoan. We can explain this process as being achieved by the amoeba *maintaining an internal correlation between its sensory and motor surfaces*. This correlation is maintained through processes inside the cell which are proper to that particular unity.

In more complex organisms the process is essentially the same. The sensory surface may be connected to the motor apparatus by a neuronal network, but it is still a sensorimotor coordination - this receiving-acting combination - which is occurring. We are not saying that this is an instructive signal, or message, which is being received and acted upon. We are saying that it is the maintenance of the internal correlation which is crucial. Through operational closure and autopoiesis, the organism is able to operate with relevance to the maintenance of itself in any particular situation. Cognition is not merely sensorimotor coordination, but that is an essential aspect of it.

The notion of cognition, in popular usage, is most commonly associated with information processing, as in a computer model, but we are regarding it here as, first of all, fundamentally linked to the concept of autonomy. Biological autonomy means that the way an organism specifies itself through its interaction is not separable from the way its cognitive performance is understood. The notion of information becomes one dealing with construction rather than instruction - with internal coherence rather than representation.

In the computer model, information is that which is represented - or a certain correspondence between symbols in one structure and symbols in another. In our biology, information is co-dependent, or constructive, and we recognise a correspondence only in terms of the structural pattern by which the two are connected. We do not say that the nervous system "maps" its surroundings, but that its form must be able to shape (and fit) its domain of interactions. The information is only specified in its operation; it is not "out there." It is formed within (*in formare*). We could say, with Varela, that it exists nowhere except in the interlock between the observer, the unity, and its interactions.

Von Foerster's interesting examples [13] will illustrate this. The first concerns the medical treatment of a soldier who was shot through the head in the first world war. There was an occipital brain lesion, but such a clean (easily healed) bullet wound that the soldier recovered quickly. Later, he began to stumble and drop things and suffered a complete breakdown of physical coordination despite the fact that his motor systems tested as perfectly normal. It took some detective work to discover that the problem was due to his severely restricted visual field. He had a greatly enlarged blind spot without realising it. His sensorimotor coordination gradually broke down because he was relying on visual clues which were no longer there. When he realised his blindness he could retrain his proprioceptive system accordingly.

There is a parallel here with any form of psychotherapy which consists of uncoupling people from relying on clues which are no longer there. Victor Frankl [14] treated a man with severe depression after his wife died by conversing about a new, identical, wife until the man realised he was living through an imaginary relationship, now that she was no longer there. In von Foerster's inimitable words: "when he could see that he was blind, then he could see!"

A second example which von Foerster relates is the work of Hudson Hawkland using microprobes placed in the auditory neural pathways of a cat, *i.e.* "listening in" to its hearing. The cat had a lever-operated box containing food (fish), but the lever only worked when a tone was sounded. On first hearing, the tone produced no responses whatsoever in the auditory pathways, but as the cat learned the significance of the tones, the physiological hearing response became clearly evident. Without sensorimotor closure or correlation there was no interpretation of sound - the cat could not "hear." The same presumably applies to sight because Maturana and Frenk found recursive nerve fibres running from the brain to the retina as well as to the cochlea. People are inclined to say that "seeing is believing," but this shows that it would be more realistic to say that believing is seeing. It makes us feel a little more tolerant of our young children's behaviour when they are in a learning situation and claim not to have heard what they were told!

What these examples have in common is a property of operational closure which is achieved by the maintenance of *internal* correlations, but which, paradoxically, exists only through the connection which the autonomous unity has with something else, *i.e.* its surrounding medium or other autonomous unities. Cognition does not primarily mean knowing something about the rest of the world; rather it means knowing one's self through one's interaction with the rest of the world in order to maintain one's integrity *viz-à-viz* everything else.

Our Knowledge as Observers

This brings us back to some alarming questions about our own cognitive process - the very process from which our so-called knowledge of cognition must be derived. We are always observers and we have chosen here to take full responsibility for explaining what we observe in personal, not objective, terms. Our challenge is to see how we can make best use of this knowledge in our living together. Therefore we should examine more closely what it is that we call our knowledge in this particular story which we are telling.

The identity of a system, its interactions, and our view of those two domains may be visualised as three interwoven strands. In order to unravel them, we have to move towards acceptance of the idea that our description of anything reveals more about the observer than about the subject. Thus we come to acknowledge our own cognitive mechanism as having the same nature as that which we observe; so we see our own biological integrity in that which we observe in nature.

The first explicit proposal (by Maturana, researching in neurophysiology, in 1969) that the nervous system operated as a closed autonomous system seems to us to be a fundamental insight indeed. The prevailing dogma of neuroscience was (and is) that (1) the nervous system picks up "information" from the environment and "processes" it and (2) this "processing" is adequate because it provides a "representation" of the outside world in our minds. In 1979, Varela succinctly stated the converse of this: that the nervous system is a closed network without inputs or outputs, "that its cognitive operation reflects only its organisation and that information is imposed on the environment, not picked up from it." This links in a completely new way our understanding of the operation of the nervous system with our understanding of epistemology, *i.e.* the way in which our knowledge arises in our living.

The idea of *perception* takes on a different meaning. It is inseparable from action because perception is an expression of the nervous system closure. We can say (with Varela) that perception is equivalent to the construction of invariances through sensorimotor coupling. In the process of remaining viable in our environment we experience the phenomenon whereby environmental noise becomes the objects of our perception through the closure of the nervous system. Von Foerster was a pioneer in explaining the way in which an object arises in our perception as an invariant constructed within an autonomous system.

Our awareness of this and our ability to discuss it here resides in the operation of distinctions which we mentioned in the previous paper. It was Spencer-Brown [15] who first articulated this. "A universe comes into being when a space is severed or taken apart . . . By tracing the way we represent such a severance we can begin to reconstruct, with an accuracy and coverage that appears almost uncanny, the basic forms underlying linguistic, mathematical, physical and biological science, and can begin to see how the familiar laws of our own experience follow inexorably from the original act of severance." What Spencer-Brown called the *Laws of Form* are the basis of Varela's more advanced "calculus of indications" and theory of cognition in *observing systems,* rather than observed systems - which had been the focus of all earlier work in cybernetics.

Hence we can say (with Maturana) that, when language arises, objects arise. These objects are relations of action (or coordinations of coordinations of behaviour - see the previous paper on the notion of language), but they have the effect of obscuring the actions by whose coordination they arose. In living with objects we simply don't realise that they were constituted in this way. It requires this epistemological leap into a second-order operation if we are to speak about our knowledge as observing systems.

The idea of a true perception (certain knowledge) compared with an illusion is a misleading idea which tends to be widely abused in human interaction. Maturana defines illusion as a statement in one domain which is being listened to in another domain and he points to the desirability of treating it respectfully and kindly. From a consideration of visual illusions (of which there are many famous examples including the widely-publicised Ames experiments) we can see that distance, or perceptual space, is not essentially a feature of our environment, but is an internal neural correlation. We do not extract information on distance, we generate it in a way that enables us to get around.

Memory and learning are concepts we associate with our knowledge, but we now see these not as storage or record-keeping functions, but simply standing for a history of structural coupling. Nothing is actually acquired, but there is a continual change in the domain of possible states of the nervous system (and the immune system, *etc*). That this is a cognitive bootstrap process of development (the only foundation is self-foundation) is what makes our ontogenic drift (and particularly our co-drifting) so fascinating to us - and also so difficult to explain using the classical ontological approach. Becoming more aware of the groundless nature of our existence is what spurs us on to grapple with the connection between cognitive science and human experience - to paraphrase the subject of Varela's most recent book[16] (with Thomson and Rosch).

So our knowledge as observers, which arises in the realisation of our living, is a profound and wonderful phenomenon, but we cannot argue scientifically for its reliability or validity when it is being considered independently of our individual lives. So what can we say about the validity or truth of our explanation? Does the explanation of organisational closure bring us any closer to knowing what actually did happen at the very beginning of life? Is this attribute - giving us a distinction between the living and the non-living - to be regarded as an absolute? We think not; nor do we think it is necessary to have such absolutes in our knowledge.

We maintain that it is no more absolutely true than the Book of Genesis, the Australian Aboriginal stories of how Baiame brought the animals into being or any of the other creation myths which every different culture treasures. We are referring now to the inherent limitations of our knowledge; to the fact that languaging itself - whether it is scientific or not - does not only operate with closure of organisation - producing invariants; it has another quality which is a kind of creative instability.

The logic with which we conduct our affairs in language is not only groundless; it is also a "logic of mirrors." [17] Consider the value of money. If I believe that you think "X" is valuable, I will act as if it is valuable, and you will believe that I believe that it is, which confirms your belief and leads to further action - and so on. After a time we tend to think this value is a transcendent quality, but it has arisen as an emergent property from our interaction in language. The idea of speculation comes from the Latin word for mirror, which is *speculum*. The bootstrap process of mirroring each other is not in this sense closed, but open, and this quality is creative.

Without a closer consideration of histories of structural coupling, we cannot pursue this much further. We have reached the point where we can value our knowledge, while at the same time recognising its limitations. That it is inherently incomplete - in a fundamental way - is elegantly shown by the mathematical theorems of Gödel and, more recently, Bell, Turing and others, which broadly state that any logical system which is capable of explaining anything must, logically, be incomplete. To put it crudely: an explanation could never explain itself. This has a connection with David Bohm's idea of the *unlimited* and his explanation of the relationship between explicit meaning and a universal meaning.

What we call our knowledge about autopoiesis and organisational closure - as the definitive characteristic of life - may not be any absolute truth. However, the point is that such knowledge can serve us very well if it means that respecting and preserving life will consist of respecting and preserving wholeness of organisation - respecting the other autonomous unity as a legitimate other, whose knowledge is also legitimate - and trusting in the validity of our own explanations in the context of our own lives. The kind of operational closure in language which leads to agreements and commitments for action (see Winograd and Flores [18]) is just as important as the openness mentioned above.

This way of thinking opens a space for ethical considerations; how might we be able to determine, individually and collectively, what is right from what is wrong? We believe this to be one of the most profound aspects of a new biology of cognition - the possibility that it can suggest a practical biological basis for ethical decision-making and for responsibility in our living together; the kind of issues which may be absolutely vital for our survival as a species on this earth. We are not sure if it can or not, but we want to raise this possibility.

One common and powerful way of reacting to the "problem" of not having a proper foundation for our knowledge is to posit a universal mind - an omniscient being - to whom all things are known and who will take care of everything. For some in science this has taken the form of saying that the so-called laws of physics are thoughts in the mind of God. For others, no recourse to scientific logic, or any form of reason, is required; to hold a belief (in a God) is complete and valid in itself. The satisfaction achieved by this process is evident in a great many people in different religions throughout the world. Of course, we have no argument with that. We are also looking only to our satisfaction. We regard all opinions as equally valid.

The way in which opinions are used seems to vary, however, from life-promoting, positive and unconditional, on the one hand, to self-destructive, manipulative and negative on the other. This is not a trivial issue. Different forms of explanation have very different consequences in the way they are acted out in our living. We spoke of this in a previous paper. We referred to our preference for scientific expanation because it is empowering and liberating, promoting mutual respect in our co-drifting. It is now time to consider how the scientific explanation works - what it is that scientists actually do in playing their part in our vital global conversation.

Scientific Explanation

In view of the limitation to our knowledge which the biological explanation of cognition reveals, we might ask: is there any value in our elaborate scientific explanation? Much has been written in answer to this question by notable philosophers of science (such as Karl Popper), but we do not wish to explore the nature of the scientific method in such depth in our particular story. We are simply considering in a very rudimentary way what it is that makes some particular explanations scientific whereas others are not and whether this can help us in our living together.

We often hear that science is reductionist in nature which suggests that it is more concerned with analysis into parts than with synthesis or creation. Maturana has highlighted our ability in science to propose generative mechanisms, or operational links, which explain (rather than describe) the relationships between parts by which something new is constituted. He and Varela proposed the following four operations as the criteria of validation for an explanation to be scientific:

(1) *describing* a phenomenon that has been experienced in a way that allows others to agree or disagree as to its existence;

(2) *proposing* an explanation for the existence of this phenomenon. This explanation is a generative mechanism in the sense that, when the mechanism operates, the phenomenon will appear;

(3) *deducing* (from the first experience) other experiences that coherently would also be expected to result from the operation of this mechanism (if it is genuine - in these terms);

(4) *experiencing* the other phenomena that were deduced in (3).

The desired validity of the scientific explanation lies in the idea that it is repeatable (not exactly, but within reasonable limits) and therefore the proposed mechanism is more-or-less refutable or confirmable, *i.e.* others can deal with it, too, using an agreed common currency. This is only an agreement, of course; it has no universal validity as the "proper" path to the "truth" - although scientists sometimes fall into the trap of saying that it has. Feyerabend [19] has argued persuasively from his study of the history of science that there can be no such thing as a certain scientific method (for producing "facts"). The practice of science shows obvious cultural variations around the world. The so-called "Big Science" in the United States differs markedly from European science; French science differs from German; New Zealand and Australian science has a distinctive style - and so on.

This is not a philosophical, but a practical issue for us. This procedure for a scientific explanation begins and ends with an experience. It is not a theory, but a creation in language which works in practice, *i.e.* it can be used in our daily living. What we may refer to as the new knowledge which has arisen is only to be understood in terms of effective action. That is the kind of knowledge which we now recognise as an integral part of our living through our explanation of the process of cognition. The whole story could be a fabrication, of course, but we are saying that it has an internal consistency from which we derive satisfaction, that we find it works for us, and also that it is an aid to our conversation to have some degree of agreement with other scientists - as long as we don't take it too seriously.

It follows from this that we can use such explanations in our co-drifting in a liberating and empowering way rather than impose them on the world - as scientists have sometimes attempted to do. It is the creative nature of scientific explanation, existing together with its complementary aspect - its reasonably formal (and therefore somewhat refutable/repeatable) syntax - which appeals to us as its greatest strength. What we call the generative mechanism has much in common with what in language is called metaphor. There is an interplay between what might be called a metaphorical logic and an exclusive logic in this kind of work. We explore this in the final paper in this volume, speaking of similarity between the poet and the scientist in their ways of expressing the coherence of our living process.

Experimental Manipulation

Most of our "facts" about biology have been derived from an experimental approach in which individual variables (or components of the system) are cleverly controlled or manipulated so that the experimenter may hope to discern their effects one at a time. What does this really tell us? It is meant to reveal the part each component has to play in the mosaic picture of the whole living organism. What is overlooked in this approach is that every change in a component also means a change in system organisation and the change in organisation may not be related in any obvious (*e.g.* linear) way to the change in the component. There are many examples in the physical sciences where behaviours emerge at the system level which are not explicable in terms of the molecular properties of the components. This is the essence of a systems-theoretic point of view.

So it follows that one component may not be responsible for anything in particular - even if its behaviour can be correlated by an observer with some other behaviour. The suggestion of a controlling role for molecular DNA is a case in point. Certainly morphological changes can be correlated with genetic changes, showing that these affect the operation of the total system, but this doesn't prove that an individual gene is instructive in the constitution of the system. It is equally possible that some pattern of interaction between them - rather than individual genes - is what determines the form of the system. Population genetics implies acceptance of this, for most cases, but the thrust of molecular biology is nevertheless to control life through genetic manipulation.

We must acknowledge, however, that enormous benefits have accrued from biological knowledge acquired in this rather dubious way. We are certainly not arguing against experimental manipulation as a useful tool for developing some of our explanations about life processes. What we are concerned about is recognising the limitations (and probably the dangers) of relying solely on this linear and reductionist way of thinking. We seek biological explanations which will be capable of enriching our living experience and providing a kind of knowledge which perhaps we can use even more effectively in our daily work of living together.

Organismic and Mechanistic

There is a tendency to refer to the linear, reductionist kinds of explanation as mechanistic and to refer to holistic, systems-theoretic explanations as somehow illustrating the properties of organism - as distinct from those of a machine. Although we have emphasised organisational properties in this paper we are working on the assumption that there is no need to throw away any mechanistic notions of the living process. On the contrary, our explanation of living systems as structure-determined (see the previous paper) is entirely mechanistic in the sense that it is totally deterministic. All interactions between components in a living organism are determined by their molecular properties. However, we find that an organismic notion prevails simultaneously, in that the system organisation is also something quite different from its structure. It is an additional property from which we hope to learn more about how living things work.

To speak of mechanistic processes may imply that the traditional cybernetical model (of machines) is identical with the living process, *i.e.* of autopoiesis, but there is an interesting distinction between them which Fleischaker (acknowledging von Foerster) has brought out. The two have different conceptual frameworks which are evident in their use of the term, homeostasis. In engineering, homeostasis is the ability to maintain (*to be maintained at*) a stable state, whereas in biology it is the ability to maintain (*by self-maintenance*) this stable state. Other language also shows the difference, *e.g.* machine systems are operationally open (heteronomous), and are said to have linear causality - be teleological - whereas living systems are described as autonomous and operating according to the logic of a recursive network which is non-teleological (by that definition). Of course, language changes and distinctions such as these will come and go, but we make this point here to steer a subtle course between the two extremes of equating organismic and mechanismic or taking the distinction too seriously.

Earlier we mentioned the tricky navigation needed between absolute linearity and absolute circularity - both of which land us in dissatisfaction. Let us compare the epistemological niche we are striving to establish with its alternatives. The solipsistic position is an idealism, holding that individual minds *create* reality, that everything "out there" is a projection of what is "in here." The representationist position is a realism which is basically the opposite view. Our "in here" mirrors what is "out there" - in evolution, for example, we are said to undergo *adaptation* to our (passive) environment. There is also an anthropic (or anthropocentric) view that the universe is only here because we are here. We take the idea of autopoiesis to be philosophically unique. It says that we (living organisms) arise from within the universe, retain our coherence by our interchange with the universe, and - in the course of these interactions - inevitably change ourselves and the universe together (the "knowable" part of it, anyway).

It is our hope that what we call our knowledge of living organisms as being autonomous unities is more than just an exercise in biology. Our attempt to extend the science of biology towards the newer science of social ecology implies that we want our language to invite conversation from people generally - and to apply to our actual living together. In doing this we don't wish to sell out any aspect of biology, nor to depart completely from a biological explanation - nor take ourselves too seriously, either!

So what is life? We like to say that we are free to choose our own explanation; we can call it whatever we like. Thus Lloyd will say that, for his knowledge about life to have the quality of satisfaction which he desires, he needs to sense (see, hear, imagine) how it arises from his particular form of interaction. The best example which Lloyd can give of this is in his experience of music. Varela cites the musical metaphor as having a particular place for him in preference to the common topological, (*i.e.* spatio-temporal) metaphors such as "reaching out," or "bringing back" reality, because music is not located anywhere in particular - it just is. (Differences between the visual and the auditory kinds of experience are interesting in themselves.) So the songs which Lloyd has written for this book are various expressions of his definition of life which are intended to complement the scientific explanation.

David's definition of life leads him to indulge at times in a poetic metaphor such as the famous Blake quatrain: "To see a world in a grain of sand; And a heaven in a wild flower; Hold infinity in the palm of your hand; And eternity in an hour." And Homer's *Odyssey,* the story of Ulysses, holds a special place for David as a vivid explanatory model of the living process. The terrible battle which Ulysses has with the Cyclops carries an echo of Blake's line about one-eyed vision being contrary to life. The incredibly difficult passage between Scylla and Charybdis is a favourite metaphor of our co-drifting explanation. Ulysses loses all his companions - six taken by Scylla's six heads - and ships and belongings - and changes a great deal, together with his changing world, throughout his long journey, but he maintains his integrity and manifests the living process as he goes.

In summing up, what would we like to say is common to all living systems that could characterise them as living? Is it a vital force, or an organising principle, or what? Notwithstanding their diversity, living systems can be recognised as having a common organisation - which is what we have been principally concerned with here. Modern molecular biology has focussed attention on isolated components as if they somehow provide the organisational as well as the structural properties and this has led us to ignore whatever it is that makes the living system a whole, autonomous unity. We feel that this powerful branch of science which is molecular biology needs the company of its complementary science which is biological autonomy and autopoiesis - as they can be explained within our self-referential cognitive domain.

This is needed to enrich the science of biology - to help equip it for grappling with ecological questions which presently baffle us completely. The mystery of how biological form arises from, but is not reducible to, molecular interactions; the complex patterns of animal behaviour which seem inexplicable in mechanistic terms; the examples of mutualism and symbiosis (rather than competition) in ecological interaction; and unaccountable taxonomic anomalies are all aspects of biology which we cannot seem to reach without an organismic, or system-organisational, perspective.

We may not need to go outside biology to add or impose something different in order to construct our richer vision of life. The richness could be in the biological explanation itself. Brian Goodwin has argued strongly against the idea that organisms require some special principle such as a mind which can direct and shape organic forms on the grounds that this perpetuates the mind/body split which caused the problem in the first place. Instead he seeks a fundamental *unity* "in which becoming and knowing are inseparable; subject and object exist in mutual transformation which is what generates our knowledge in its creative interplay." Perhaps this is also what Goethe described in his vision of organisms as dynamic forms, forever changing in order to be themselves.

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1. James Lovelock is an independent scientist and originator, with Lynn Margulis, of the Gaia Hypothesis. He is the author of Gaia: A New Look at Life on Earth and The Ages of Gaia.

2. See The New Biology: Discovering the Wisdom in Nature (1987) by Robert Augros and George Stanciu pp18-20

3. S.L. Miller (1953) Science 117:528

4. See for example Biology: The Unity and Diversity of Life (5th Edition) edited by Starr and Taggart.

5. See Oken's Principles of Physio-Philosophy and biographical works such as Lorenz Oken: A Biographical Sketch by Alexander Ecker..

6. See the list of Maturana and Varela's papers which is given in the References.

7. See Autopoiesis: System Logic and Origins of Life a Boston University Dissertation presented in 1988.

8. See Autopoiesis: System Logic and Origins of Life as above.

9. In her book Symbiosis in Cell Evolution (1980).

10. See Varela's book Principles of Biological Autonomy for discussion and further references.

11. The Fontana Dictionary of Modern Thought, 2nd Edition, which appeared in 1988.

12. See the writings of Lyn Margulis including Symbiosis in Cell Evolution (1980)

13. These examples are taken from a videotape of a lecture by Heinz von Foerster in the USA in 1980.

14. Victor Frankl was Professor of Neurology and Psychiatry at the University of Vienna and the leading figure in the "will to meaning" school of Psychotherapy. Author of many books, he is probably most widely known for Man's Search for Meaning (1959).

15. G. Spencer Brown discovered his non-numerical arithmetic in the course of investigating switching circuits in electronic engineering and described this in his book Laws of Form (1969). - more needed.

16. The Embodied Mind (1991) by Francisco Varela, Evan Thomson (son of William Irwin Thomson) and Eleanor Rosch (from the University of California).

17. From a Conversation Between Francisco Varela and Allyn B. Brodsky published in the IS (International Synergy) Journal in 1987.

18. See Understanding Computers and Cognition (1987) by Terry Winograd (Palo Alto California) and Fernando Flores (formerly from Chile).

19. Paul Feyerabend is Professor of Philosophy at the University of California and Professor of the Philosophy of Science at the Federal Institute of Technology in Zurich. His books and papers such as Against Method (1988) challenge much conventional thinking about scientific method.