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A cognitive view of biological process

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From the study of biological pattern formation, formal rules have begun to emerge which allow one to generate structures representing characteristic biological forms such as limbs, eyes, and plant leaves. These rules are phenomenological, providing a structuralist, non-reductionist approach to the problem of biological form. This approach is developed in relation to a cognitive view of biological process which sees organisms as systems which operate on the basis of knowledge. This knowledge is expressed in the form of rules or constraints which generate behaviour useful to the organism or the species for survival, reproduction and evolution.

Organisms, defined as cognitive (knowledge using) systems, are characterised by generative processes which involve both constraint and innovation, properties which are taken to define creative behaviour. Both development and evolution are then seen to be aspects of a creative process. Such a concept of creative becoming is basic to a philosophy of organism such as Whitehead's, but is problematic to a philosophy of substance such as Descartes'. It is argued that the dualistic and positivistic aspects of contemporary science, deriving from philosophies of substance, are detrimental to an understanding of biological process, and that a cognitive view is helpful in conceptualizing biological problems in terms of creative process.

Introduction

My intention in this essay is to describe the emergence of a new view of biological pattern formation which links this area of study very much more closely to human pattern-forming activities than has been the case in the past. During most of this century, biologists have tended to make the assumption that, somehow or other, detailed studies in genetics, biochemistry and biophysics would eventually provide explanations of the processes which generate limbs in insects, feathers on birds, spiral patterns in the arrangement of leaves on plants, and spots on ladybirds' backs. This expresses a reductionist belief which is now foundering badly and is being replaced by a view of biological process which seeks to understand pattern formation in terms of rules or laws operating at levels above the molecular and the genetic (in the sense of products of the primary genetic material, DNA). Furthermore, these rules are biological, not physical, although they in no sense violate the laws of physics and chemistry. It is here that this new approach to morphogenesis differs quite sharply from the view of the most outstanding student of biological form in this century, D'Arcy Wentworth Thompson. His study *On Growth and Form*, published in 1917, sets forth the thesis that form can only be understood through mathematics and that the forces which operate in the genesis of biological structure are essentially physical. That mathematics and form or order belong together few

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would dispute, but D'Arcy Thompson's view tends to eliminate the biological as a distinct and autonomous realm of nature; i.e. his reduction of biological structure to the operation of mathematical and physical laws fails to recognise the biological origins of the constraints which generate this structure. It is biological process which 'discovers' rules, expressible in mathematical form, these rules giving rise to order and pattern. This process is both orderly and creative. Furthermore, I will argue that it may also be seen to be cognitive. Thus biological pattern formation assumes characteristics which link it closely with the processes which generate pattern and order in human society. However, this similarity is not an identity: I do not wish to imply any reduction of the social order to biological order, which would simply commit again the reductionist fallacy at another level. The creativity of Nature is not the same as the creativity of Mind. But I will argue that they are much more akin than current thinking allows.

The failure of the reductionist view of pattern formation

One of the most distinctive characteristics of biological process is its capacity to generate a great diversity of structures, forms and patterns. The evolutionary process produces species of distinct morphology and behaviour, the developmental process generates individuals of characteristic form from eggs or buds, the process of living manifests itself in behaviour patterns such as hunting, feeding, talking, building, etc., typical of the individual and its species. In recent decades, the dramatic success of such subjects as genetics, molecular biology and neurophysiology in analysing biological activities in terms of units such as genes, molecules and neurons encouraged the view that a satisfactory understanding of biological pattern formation would arise from the detailed study of the properties and behaviour of these units, order and complexity arising from their interaction. However, this analytical programme of reduction and resynthesis works satisfactorily only when there is an extremely simple and direct relationship between the units of a system and its higher level behaviour, as in a gas where the momentum or the kinetic energy of the molecules can be averaged to determine the pressure or the temperature of the gas. Of course there must always be *some* relationship between the properties of the units which are construed to exist within a complex system and the behaviour of the system itself. The problem is that if the units themselves are complex, in the sense that macromolecules or neurons are complex, then there are very many different ways in which higher order behaviour can arise. The reductionist programme is then faced with the virtually impossible task of exploring all the possible interaction patterns available and selecting those which conform to observed higher order behaviour. Given that one never has complete knowledge of the properties of the units, so that the relevant behaviour may well be missing from the computation to begin with, it is clear that this is not a very reliable strategy to pursue in the study of biological pattern formation at the macroscopic level, that of the species, the individual and its behaviour.

An alternative approach, which has always been an important strategy in science, is to observe the behaviour of the system of interest, to record its regularities and then to see if it is possible to devise simple formal rules which act as axioms from which the behaviour of the system may be deduced. These formal rules then represent the constraints within the system which underly its orderly behaviour. It may happen that they can never be reduced to certain categories of behaviour of simpler units, as the inverse square rule or law of gravitational attraction could never be reduced to the mechanical properties of matter, much to the discomfiture of seventeenth-century mechanical philosophers. However, scientists rapidly accommodate themselves to such eventualities and quite soon even go so far as to believe that a phenomenon such as gravitational attraction is in some sense explained by the law, whereas it is only described. What is explained by the use of the rule is, for example, planetary motion. Newtonian mechanics is a generative theory in the sense that it allows one to generate patterns (trajectories which are conic sections, e.g. ellipses, parabolae or hyperbolae) by means of formal operations constrained by rules (the calculus, with the inverse square law of attraction) and these patterns fit the observed behaviour of the planets. This is not a reductionist theory, since the phenomena can be explained in terms of units and rules which correspond to the level of the observables themselves. Reductionism entered science largely with the adoption of the atomic hypothesis in the seventeenth century. It is an extremely useful hypothesis for the explanation of certain microscopic phenomena in physics, chemistry and biology; but not, I submit, for the understanding of biological pattern formation.

Cognitive biology

In facing the problem of pattern and order in biological process, I believe that biologists will be induced to adopt a very different view of organisms and their evolution from the reductionist and materialist one which has prevailed throughout this century. This will bring biology much closer to the ideas expressed by Whitehead in his philosophy of organism and the idealist approach to the understanding of form which originated in the West with Pythagoras. Developmental biologists are now beginning to describe the appearance of characteristic structures such as limbs and eyes in terms of systems obeying formal rules whose molecular interpretation is left undescribed and is irrelevant for the explanation of the phenomena of interest (French, Bryant & Bryant, 1976; MacDonald, 1977). These rules are not in the category of natural law, as the physicist tends to regard the law of gravitational attraction. They are rules which have been arrived at by the evolutionary process as a solution to the problem of reliably and repeatedly generating particular types of form. And they are of course inherited, passed on from generation to generation.

What sort of system is this which employs rules to generate useful structures and behaviour patterns and which can transmit the rules to its progeny? I have argued that such rules constitute knowledge and that a system which uses knowledge is a cognitive system (Goodwin, 1976*a*, 1977). This comes from an extension of an argument presented by Chomsky (1972) in a linguistic context. In his analysis of linguistic competence, Chomsky presents evidence for an instinctive, unlearned capacity for generating correct sentence structure or syntax, a capacity which emerges in the course of the human developmental process. The rules or constraints which constitute linguistic competence define the processes which generate the correct surface structure of sentences from their deep structure, such as structure-dependent operations in sentence transformation. Possession of these rules, i.e. possession of the structural (anatomical) and functional (physiological) constraints which are the embodiments of the rules, is equivalent to having the knowledge required for speaking correct sentences. This knowledge is not learned, but is innate, inherited as part of the human phenotype. Chomsky's (1972) contention is that: 'knowledge of language results from the interplay of initially given structures of mind, maturational processes, and interaction with the environment.' Innate structures are thus seen to constitute elements of knowledge. I have simply used this proposition in a more extended form to suggest that the basic attribute of living organisms is their possession of knowledge about aspects of the world, knowledge which renders them competent to survive and to reproduce in the environment to which they are adapted or which they know.

I have defined knowledge as a useful description of some aspect of the world, giving the possessor the competence to behave in a manner which contributes to its survival and reproduction (Goodwin, 1976*a*). The fact that we are dealing with descriptions means that there are codes or sets of codes which relate them to that which is described. The unravelling of such codes, which is the equivalent of learning to read an unknown language, together with the solution of the problem how the knowledge is transmitted reliably from generation to generation, has been a major preoccupation of contemporary biology: coded knowledge is located largely in the DNA, which acts as a primary memory store for the organism, this knowledge being in the form of hypotheses which need to be translated into active form for testing. However, there is a great deal of 'tacit' knowledge in other structures. The elucidation of the translation and assembly process from the coded linear sequences in the DNA to active three-dimensional proteins, which function as tests of genetic hypotheses by revealing their meaning, constitutes one of the triumphs of twentieth-century biology.

I used the term 'meaning' above in relation to the translation and testing of genetic hypotheses and it needs some clarification in this context. In coded form as it occurs in the DNA, the information for a particular protein such as the enzyme β-galactosidase (required for the catabolism of the nutrient lactose in micro-organisms) or a crystallin (a protein which forms the transparent lens of the eye) cannot be tested because it exerts no action upon the organism or its environment. Before it can be tested, the information in the DNA must be translated into a form in which it exerts a particular type of force and acts within a particular context. Thus the β-galactosidase converts lactose into glucose and galactose when it operates within the context of the bacterial cell (which defines particular conditions of pH, osmotic concentration, substrate level, etc.); while a crystallin transmits light rays in a particular way within the context of the eye. These activities may be said to constitute tests of meaning of the coded hypotheses in the hereditary material, involving the interpretation of the information. This interpretation takes place within a particular context, which in part determines the pattern of forces which operate during the testing operation. We then arrive at a distinction between information and knowledge. The technical definition of information involves only selection (e.g. specifying one out of a set of possibilities), but says nothing about meaning, which I take always to involve activity in real space–time. Thus knowledge differs from information in that it not only involves selection of alternative possibilities, but also includes instruction for action which, operating in a particular context, conveys meaning.

Generative processes

In the rather detailed discussion given above, it is clear that every aspect of the behaviour of what I have called a cognitive system is compatible with physical and chemical laws. However, such a system transcends the rules of physics and chemistry in that, besides obeying these, its behaviour is constrained by other rules which are the embodiment of particular types of knowledge of which it makes use. This allows such systems to operate in domains which, while available to systems obeying the laws of physics and chemistry, are relatively improbable; i.e. cognitive systems can stabilize behaviour in physically and chemically improbable states by means of particular rules of action which they have embodied in parts of their own structure, such as catalysis of chemical reactions by enzymes so that relatively high rates of metabolic transformation can occur at low temperatures. By thus regulating their own activities through the imposition upon themselves of specific rules or constraints, biological systems have managed to discover and exploit an immense range of behavioural and morphological patterns. To give an architectural example, although rectangular stones occur in nature they are very rare; and structures in which they are piled on top of one another are much rarer still. However, the art of the stone-mason and the builder consists in following some very simple rules about shaping stone and assembling it and these rules then permit the construction of an immense variety of highly improbable structures, from Stonehenge to Chartres Cathedral.

The essence of order and pattern is adherence to laws or rules; and the characteristic of cognitive systems is that they operate in terms of rules which stabilize useful temporal and spatial patterns. The process whereby such rules and the variety of their applications is discovered is described as creative in a human context and I would suggest that the evolutionary process shares this property. We do not yet know how to describe this creative potential of evolution, which generates organisms of greater and greater complexity constrained by the necessity that this be relevant, meaningful in its context; i.e. that it be biologically successful. (But see Saunders & Ho, 1976, for a very thoughtful and interesting paper on this subject.) Such generative processes appear to have the property of proceeding from symmetry to asymmetry, which involves an increase in complexity; but then a new symmetry is generated which resolves the complexity into higher order simplicity without, however, losing the lower-level complexity. Thus in the evolution of the human hand, the development of the opposable thumb involved the breaking of a structural and dynamic symmetry in the organization and behaviour of primate digits. The grasping action of the primate hand wherein all the digits act in unison, so well adapted to swinging in trees and grasping certain types of object, is transformed into a much more complex structure with great independence of action of the thumb. However, the human uses a series of co-ordinating activities for the hand which involve higher order symmetries such as the coming together of the first finger and thumb in the typical action of picking up a small object, or the opposed wrapping of thumb and fingers around a stick. These symmetries have a bilateral element rather than the simpler unilateral action of the primate, giving a unity of movement and action to the more complex structure.

Alternatively, asymmetry can arise as a functional adaptation within a system with higher order symmetry as in the breaking of symmetry of the aortic arches in the evolution of the circulatory system in vertebrates, which retain a bilaterally symmetric overall body plan. Thus the hierarchical organisation of biological systems, both structural and functional, allows for the appearance of asymmetry at one level and symmetry at another. However, the general tendency is for symmetry to evolve into asymmetry, as in the phenomenon of cerebral dominance and handedness in human beings, which breaks the bilateral body symmetry of the vertebrate line; and then for a higher level symmetry to appear. In relation to human evolution, the higher level symmetry which transcends the asymmetry of cerebral dominance is not yet evident. It is, however, clear that the biosphere needs a more balanced dominant being than the one currently with us, and we may look forward hopefully to its emergence.

It is of some interest to pursue this line of thinking in a little more detail, and to see if there is an analytical foundation for the ideas presented above, since in certain respects they appear to be at variance with some basic generalisations about 'natural' process as described by physics and chemistry. What I am suggesting is that there is a natural tendency for systems to break their symmetries and become asymmetric, thus becoming more complex. On the other hand, physics says that, for a system with given constraints, there is a natural tendency for asymmetry to disappear and for entropy (disorder) to increase. Thus if a thermally isolated gas or liquid starts with a temperature gradient, then the natural tendency is for this to disappear and for the initial heterogeneity of state (asymmetry) to decay into homogeneity (symmetry), with a uniform temperature throughout the system. This is a fundamental property of thermodynamically isolated systems, and is expressed in the second law of thermodynamics. However, observe that the statement of the law depends upon the assumption of fixed constraints: entropy increases to the maximum, subject to given constraints, in a thermodynamically closed system. If we are concerned with systems whose constraints can change, then the law no longer applies, and this is the situation for developing or evolving organisms. The problem then is to formulate a 'law' which describes the general tendency for complexity to increase in systems which can undergo this more general change, and which suggests why such a process is 'natural'. By 'natural' one usually means that increased complexity is, on the whole, more stable than decreased complexity. One way of looking at this problem is in terms of structural stability, a concept used to describe the properties of dynamical systems whose parameters ('constraints') are subject to change. In this context, it is the case that asymmetry is more stable than symmetry; i.e. systems with symmetry transform into asymmetric systems under a perturbation (variation) of parameters. Particular examples are the transformations of periodic systems undergoing simple harmonic motion, such as an ideal pendulum, into either a damped oscillation (a real pendulum with friction which eventually comes to rest) or into a limit cycle (a child on a swing); the emergence of spiral motion in water running down a plug-hole, from an initially symmetric flow; or the appearance of coherent light emission from a laser when the external 'pump' exceeds a particular energy level. All these asymmetrics arise spontaneously in systems which are displaced from thermodynamic equilibrium and are subject to parametric perturbations. Thus the transition from symmetry to asymmetry, i.e. the breaking of symmetry, is a natural process in systems whose constraints are subject to change, and this provides a description of the general tendency of such systems to increase this complexity (asymmetry is more complex than symmetry; it requires more terms to describe it). However, this is a long way from giving us a theory of the evolution of living systems. These are not simply complex; they show ordered complexity or organisation. The way one represents this central property of organisms is crucial to any attempt at a formal analysis of generative processes, ones which operate on the basis of knowledge or useful descriptions, seen as ordering or organising constraints. I do not wish to pursue these technical problems here, but rather to take up the more general discussion of the implications of such a view regarding the creativity of the biological process.

Biological process as creative becoming

To obtain some initial focus on the concept of creativity, let us start with Descartes' description of speech and language as creative expression, as discussed by Chomsky (1968). There are three essential ideas here: unlimited variety, freedom from stimulus control and relevance or appropriateness. A competent language user can generate an unlimited variety of sentences, each of which is relevant or appropriate to some situation; and the particular one selected is not dictated by any obvious controlling stimulus. Grammatical and syntactical rules determine sentence structure, these constraints arising from the demands of communication: the hearer must be able to recover the meaning of the sentence. These rules and constraints constitute part of the knowledge required for linguistic competence as described by Chomsky (1968). It is this view of knowledge, extended to the basic organisation of living systems, which provides the basis for the cognitive biology which I have described in previous sections. The question we now face is whether biological processes at levels below that of the human mind, with linguistic behaviour as one example, can be said to reveal creative expression in the terms defined above.

An example of behaviour conforming to these general criteria is embryonic development. The developing embryo certainly defines its own goals, so that its behaviour is free from a wide range of stimulus control. Furthermore, it is capable of making an unlimited variety of appropriate responses to situations which demand an altered strategy of development from the normal one. Thus, for example, damage to an amphibian embryo, such as removal of part of the tissue which would normally form the tail, results in a compensatory response in which other tissue which would have become part of the mid-back musculature, say, becomes tail. And such a regulatory response occurs irrespective of the nature of the damaging stimulus, whether surgery, cauterization, focussed ultrasound or any other method of removing tissue. Within certain defined tolerance limits, the response is always appropriate to the goal, which is the formation of a complete organism and is independent of the type of stimulus acting on the system. It is the property of appropriateness relative to an internally defined goal which I take to be the essence of creative response, together with the other features of unlimited variety and independence of stimuli which do not constitute part of the internal goal-seeking process. Embryos have this capacity and so do organisms in their behaviour.

Animal behaviour was, in fact, something which Cartesians assumed could be explained in strictly mechanical terms, which for them meant the absence of creative expression. Therefore in using Cartesian criteria for creativity and concluding that organismic behaviour reveals this property, I am contradicting their conclusions. It will become evident that I also reject the basic metaphysical dualism of the Cartesians regarding mind and body and it is precisely this dualism which underlies their sharp division between creative human expression as revealed in language, and organismic behaviour below the human level. My extension of cognitive process to the lower levels is consistent with a parallel extension of the concept of creative expression; and this requires a concept of perception which is similarly extended over the Cartesian one which associates it with thinking, hence with human consciousness. The abandonment of the Cartesian criteria for identifying the distinctive features of human cognition in terms of creative self-expression does not eliminate the problem of accounting for the discontinuity of creative level between the human and the biological spheres; it means only that I choose to characterize this discontinuity in other terms. This involves primarily an analysis of symbol use and function, of imagination and morality, but I am unable to undertake this here.

If the above propositions regarding the creative behaviour of organisms are accepted, then the evolutionary process itself, involving the discovery of rules or constraints which generate new and successful organisms, is also seen to be creative. This involves the process described above, the transformation of symmetry to asymmetry by parametric perturbation, subject to the constraint of survival or relevance which tends to require the emergence of a higher order symmetry. Expressed less technically, this is the process of generating new organisms as a creative response to new opportunities which emerge from the on-going nexus of organic evolution. In order to make a full transition to the description of biology as a creative process, one needs a philosophy which takes the essence of being to be creative becoming and which is free of the positivistic and dualistic elements which permeate contemporary science. There can be no atoms of substance or meaning in a creative process where every element of structure or function is sensitive to its context, a property which I have elsewhere argued is characteristic of biological systems (Goodwin, 1976*a*, *b*); and a cognitive biology which assumes that organisms have real knowledge of the world requires that the 'subject' possessing this knowledge and the 'object' whose properties the knowledge expresses be essentially similar in nature, not distinct. It is here that one needs definitions of perception and experience which describe a continuity of relationship between subject and object. A philosophy which satisfies these requirements is that of A. N. Whitehead. What I shall do finally in this essay is to explore what I regard as some of the implications of an organic philosophy of Whitehead's type, particularly those relating to his manner of resolving the body–mind or substance–quality dualism which is a prominent feature of contemporary scientific thought, and is a severe hindrance to the development of an adequate theory of organism.

Cognition and creative process

My own definition of knowledge as a useful description of an aspect of the world has itself dualistic overtones, since it can be taken to mean that the description need not reproduce the essence of that described, but only represent it in some formal sense. My meaning is that knowledge is manifest when there is a re-enactment of the process which is described, as the biological clock re-enacts the cyclic process of the night–day–night transition. The evolutionary history of the organism, which includes the experience of these day–night cycles, is embodied in the organism's activity. Therefore its knowledge is in its process; it is not something static, set aside from this process. Thus instead of a description of the organism's world emerging from the organism as subject, which is the Cartesian or the Kantian way of looking at knowledge, we have the organism emerging from the world as an organised, coherent whole in which knowledge is a constituent of activity: a constraining, ordering constituent, as described above. As Whitehead (1929) has put it: 'Descartes in his philosophy conceives the thinker as creating the occasional thought. The philosophy of organism inverts the order, and conceives the thought as a constituent operation in the creation of the occasional thinker. . . . In this inversion we have the final contrast between a philosophy of substance and a philosophy of organism.' The creative process thus realises itself through the organised activities of beings. For Whitehead this description applies not only to organisms, but to Nature in general, thus avoiding a physical–biological dualism. But we then find ourselves in the position of asking what is the nature of these beings if they are other than biological organisms; i.e. how are we to recognise other 'actual entities' apart from ourselves and other organisms? We are faced with some kind of distinction between the organic and the inorganic, between animate and inanimate. Whitehead regards this distinction as fictitious, arising from an abstraction. He also appears to deny that there is any significant distinction between organic order and mind. This denial results in the important assertion of continuity, of a basic unity in the world; but it fails to recognise different levels of creative organisation, and to distinguish between them. I have suggested a distinction between biological and physical process in terms of the concept of a cognitive system (Goodwin, 1976*a*); but a distinction between organisms and minds requires, I believe, a theory of symbolic and moral processes which characterises human intelligence and contrasts it sharply with the constrained knowledge which operates in organisms. Symbolic thought has degrees of freedom not available to processes which employ fixed relationships of interpretation and meaning between structures and their descriptions (reproductions or re-enactments). A brilliant beginning for such a theory of symbolism is provided by Sperber (1975).

However, despite the necessity for clear distinctions between levels of organisational complexity in Nature, I believe that a major consequence of Whitehead's philosophy of organism is the resolution of the Cartesian duality in his vision of the world as creative process. The fundamental category of being is activity, creative activity. In relation to organismic process, knowledge is an essential ordering ingredient. Man as an actual entity interacts with every other actual entity, i.e. the rest of the universe, and this is how the world can be known, why it is intelligible. Knowledge cannot be obtained without this union and the way of science is the way of experience. Knowledge comes through the resolution of complication into greater and greater simplicity and the art of resolution is the art of life. A cognitive biology seeks to bring this vision into clearer perspective. The way is made infinitely easier by the extraordinarily penetrating insights of Whitehead.

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