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Henry Disney
Sally Corbett
Richard Hardwick
Sally Harley
It is perhaps interesting to consider a family of models taking the form of three-dimensional landscapes (mountains and valleys). As a fair number of such models have been used I thought it might be amusing and entertaining to present them as the subject of this talk. However, as it turned out, I became quite invloved in the matter and therefore this is rather a train of thought, associated with and leading from a consideration of these models, than any attempt at a comprehensive account.

I will start with a few examples. Most involve the travel of a ball under the influence of gravity down a slope or mountain. Gravity, like magnetism, is an obscure unseeable pull and hence serves as a useful representation of an "inherent tendency".

Some of the simplest things that can be represented by a mountain and a ball are the various types of equilibria. (Fig. 1). Thus we have unstable equilibrium (the ball wants to roll down), metastable equilibrium (the ball rests in a depression on the slope), and finally (when the ball can roll no further and has reached the valley) stable equilibrium. The tendency towards a stable equilibrium is represented by the tendency for the ball to roll down hill under the influence of gravity.

This system can, if rather facetiously, be used to represent living processes. Any physical system has a tendency to roll down-hill, to a lower energy content and/or to greater entropy or disorder. A living system counteracts this tendency to disorder and we can represent this thus: (Fig. 2). Life takes in energy in the form of sunlight so that the mountainside becomes a conveyor belt, a traveller, opposing the tendency of the ball to roll down hill.

One of the most celebrated landscapes in biology is the epigenetic one, first proposed and subsequently plugged by Waddington. He uses such a landscape to illustrate the property of development which brings about the development of organs and tissues that are usually distinct, clearly demarcated from their neighbours. Even when, for example, some intermediate types of tissue appear in development (e.g. neural crest cells) they nevertheless form distinct structures in later development (nerve chord ganglia). Developmental reactions follow definite paths, they are canalised toward producing a definite end result. This is also illustrated by study of the influences of genetic factors on development. A mutation in fruit flies is known which converts the antennae into legs—these are reasonably well formed and do not intergrade into antennae. Moreover if a mutation affecting leg structure is introduced into such a fly then the mutation affects antennal-leg as much as the normal legs. Here the development of the antennal region has been diverted into the path of development normally followed by the leg and once it is in this path it is subject to the same influences as any other leg. Waddington represents this by the following landscape. (Fig. 3). A ball rolling down an inclined surface represents the tendency for a developing tissue to move towards the adult state. Now this tendency is constrained along certain paths; the ball must roll down the valleys leading to a distinct organ or tissue. And any disturbance e.g. by mutation, will be equivalent to tilting the landscape so that the ball enters a wrong developmental path. Environmental changes, as in the Aphid where different temperatures at different developmental stages lead to several alternative end states of development (Fig. 4), may also be effective in tilting the landscape. In the Aphid diagram the developmental paths are represented two-dimensionally as a system of branching lines, but Waddington's is the more dynamic representation, representing paths as moving equilibrium states rather than unvarying entities or directions.

Another similar model has been used by Needham to illustrate the role of organisers
in restricting given embryonic regions in their ability to form various adult tissues and organs i.e. the role of organisers in determining parts to pursue fixed fates. This state of affairs can be represented as follows: (Fig.7).

At the top of the cone, the ball, its position representing the state of development of a region, is in extremely unstable equilibrium and under the influence of the primary organiser it is pushed off its equilibrium in a given direction to another position of unstable equilibrium, that is, to another apex of another cone. The tissue has now become determined with respect to the other tissues (or cones) not being any longer transformable into these other types. Nevertheless this determined tissue can be influenced by secondary organisers even though the primary organiser which acts at the top level of the 'cones' will not affect it. The prospective potencies of a tissue are represented by the cones immediately below the cone representing that tissue.

For example, the ectoderm of the embryo can form any tissue and which, is dependent on the relation of a region of this ectoderm to the dorsal lip, blastopore. Once, say, the neural tube has been determined, the dorsal lip of the blastopore will not affect it, but a secondary organiser, such as the eye-cup inducing a lens, will.

Many systems could be given such mountainous representation: sex-determinants, polymorphisms and switch mechanisms, and the process of speciation. Indeed, this led me to the idea that perhaps other models could represent the same thing which in essence is one path or line leading to one or more alternative paths. I even remembered a game in a side-show that I once saw at the fair. (Fig.6).

From this I noticed that the system seemed to be getting a little ridiculous, for other models, for example, a branching pipe with two taps, suggested themselves. So I started to inquire what models are for anyway and in what relation they stand to the thing they are trying to represent.

One obvious use is that they give people a picture of the phenomenon and therefore help them understand it. As Waddington says, "It is an amusing landscape to picture to oneself and I think it expresses some characteristics of development which are not easy to grasp in any other way."

However, not only can such a model be an illustration, but can act as a scientific hypothesis, from which predictions and generalisations can be made. Such a model has in fact all what one may crudely call the characteristics of a scientific hypothesis.

This is well illustrated by the use of mountains when considering evolution and adaptation. Wright in 1931 realized that the number of possible gene combinations in any population was normally very large and that under certain environmental conditions this number was effectively more than under other conditions. Moreover certain given combinations were better, with respect to adaptive value, than others. One combination under certain conditions, at say a certain position, will give a peak adaptability. At different positions, this adaptability will fall off. Similarly a population with a certain combination of genes that are realised in different ways in different individuals making them on the whole fitter than other populations under given conditions. The situation can be represented by a contour map: (Fig.7b). Using this model we can now make certain predictions. For example, should there be two conditions under which a certain gene combination is adaptive, then there will be two peaks. And the raising of two peaks will automatically result in a valley. This gives rise to a so-called 'evolutionary landscape' with peaks separated by valleys and which itself changes as the environment changes. Then, as Wright says, "the problem of evolution is that of a mechanism by which a species may continually find its way from lower to higher peaks."
Thus we see that a considerable amount can be inferred by the use of this model. We can use the model to predict what would happen if the situation becomes more complex. And explanation and prediction are two characteristics of a scientific hypothesis. Indeed (I quote Hesse), "a hypothesis is not produced by a deductive machine by feeding experimental observations into it: it is produced by a creative imagination of a mind which absorbs the experimental data until it sees them fall into a pattern." Such a pattern can be a model - one of the types we have outlined above or simply a theoretical explanation which we can understand in the same way as we can understand the model.

Such thoughts led me to inquire into the nature of the relation between the model and what it represents: for, predictions about what the model itself represents can be made using the model itself, despite its being divorced from reality. One way of putting it, is that there is an analogy between the two. For further light on the problem I again quote Hesse: "When we say there is an analogy between a model and certain phenomena of nature, we are in some way asserting an identity of mathematical structure between the model and nature." This identity through mathematical structure can be seen in the similarity between the systems of selection derived from Wright's mountains, the mathematical equations of population theory, and the actualities of nature. Also it can be seen in the two figures given by Lotka (Ref. pp.149,150) where we have mathematical equations and models of equilibrium states in malarial epidemics.

Thus these models can be said to serve instead of mathematical representations. (cf. Waddington's recent accounts of the mathematical theory of epigenesis). By being pictorial and therefore nearer to our experience, we can naturally understand models better and they do mean something if only in a rather crude sort of way. They are valid hypotheses and not crude substitutes for the real process.

To conclude, we may consider the situation in reverse where we see that abstract mathematical formulae can also be called "models". And again, just as we use ridges and valleys to represent epigenesis because the mathematical theory has not been fully worked out, so conversely we may have difficulty in constructing a model of a mathematical representation.

Here we must invoke physics to see the relevance that this has for biology. During the development of physics there has been a transition from mechanical to purely mathematical explanations of the observed phenomena and nowadays mathematical formulations function as models of a mechanical kind did in the old days, yet do not have in themselves any mechanical or other physical interpretation.

To be more specific, the model of the atom as electron spinning round nucleus has been replaced by a probability function which is more accurate but harder to visualise. And if we try to visualise the speed of light - c - as something going very fast i.e. as a mechanical model, then the mathematical systems do not make sense. No-one can visualise the curvature of space (although the words seem to make sense!). The mathematical theories to which such descriptions refer are almost solely of pragmatic value.

Thus physics has reached an unimaginable (literally), transcendental level! And as biologists looking at the present day scene we must marvel at the words of a physicist writing about the physics of former times. "Their so-called mechanistic outlook arose, not from a false metaphysics, but from the fact that they were not yet familiar with mathematical languages other than those of classical mechanics ...... and that they therefore tended to express their hypotheses in terms of those languages."

Today, in that we can provide many mechanical models as explanations to biological
phenomena, we feel that life and its complications will be mechanically explained in understandable terms. Surely this is analogous to the mechanical attitude of the 14th Century physicists, and that once we start applying more mathematical knowledge to biological phenomena, the situation will not become explained but 'unexplained' in the sense that we will not be able to see how it happens! My original lack of faith in such models as illustrated above, is not because they are unscientific but because they are a simplification of processes which can only be described in terms of, not more complex models, but by intangible, unrepresentable mathematics.

I certainly felt highly cynical about the pictures I was going to show today, but with the train of thought that followed, I regard them with reverence, as the last strongholds of comprehension in biology.
AN APHID

NORMAL

PARTHOGENETIC

STAGE IN DEVELOPMENT

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