Ashby W.R. (1958) Requisite variety and its implications for the control of complex systems, *Cybernetica* 1:2, p. 83-99. (available at http://pcp.vub.ac.be/Books/AshbyReqVar.pdf, republished on the web by F. Heylighen—Principia Cybernetica Project)

# Requisite variety and its implications for the control of complex systems

by W. Ross ASHBY,

*Director of Research, Barnwood House (Gloucester)*

Recent work on the fundamental processes of regulation in biology (Ashby, 1956) has shown the importance of a certain quantitative relation called the law of requisite variety. After this relation had been found, we appreciated that it was related to a theorem in a world far removed from the biological—that of Shannon on the quantity of noise or error that could be removed through a correction-channel (Shannon and Weaver, 1949; theorem 10). In this paper I propose to show the relationship between the two theorems, and to indicate something of their implications for regulation, in the cybernetic sense, when the system to be regulated is extremely complex.

Since the law of requisite variety uses concepts more primitive than those used by entropy, I will start by giving an account of that law.

## I

### *Variety.*

Given a set of elements, its *variety* is the number of elements that can be distinguished. Thus the set

$$\{g\, b\, c\, g\, g\, c\}$$

has a variety of 3 letters. (If two observers differ in the distinctions they can make, then they will differ in their estimates of the variety. Thus if the set is

$$\{b\, c\, a\, a\, C\, a\, B\, a\}$$

its variety in shapes is 5, but its variety in letters is 3. We shall not, however, have to treat this complication).

For many purposes the variety may more conveniently be measured by the logarithm of this number. If the logarithm is taken to base 2, the unit is the bit. The context will make clear whether the number or its logarithm is being used as measure.

### *Regulation and the pay-off matrix.*

Regulation achieves a “goal” against a set of disturbances. The disturbances may be actively hostile, as are those coming from an enemy, or merely irregular, as are those coming from the weather. The relations may be shown in the most general way by the formalism that is already well known in the theory of games (Neumann and Morgenstern, 1947).

A set $D$ of disturbances $d_i$ can be met by a set $R$ of responses $r_j$.

The outcomes provide a table or matrix

| | | | $R$ | | |
|---|---|---|---|---|---|
| | | $r_1$ | $r_2$ | $r_3$ | … |
| | $d_1$ | $z_{11}$ | $z_{12}$ | $z_{13}$ | … |
| | $d_2$ | $z_{21}$ | $z_{22}$ | $z_{23}$ | … |
| $D$ | $d_3$ | $z_{31}$ | $z_{32}$ | $z_{33}$ | … |
| | $d_4$ | $z_{41}$ | $z_{42}$ | $z_{43}$ | … |
| | … | … | … | … | … |

in which each cell shows an element $z_{ij}$ from the set $Z$ of possible outcomes.

It is not implied that the elements must be numbers (though the possibility is not excluded). The form is thus general enough to include the case in which the events $d_i$ and $r_j$ are themselves vectors, and have a complex internal structure. Thus the disturbances $D$ might be all the attacks that can be made by a hostile army, and the responses $R$ all the counter-measures that might be taken. What is required at this stage is that the sets are sufficiently well defined so that the facts determine a single-valued mapping of the product set $D \times R$ into the set $Z$ of possible outcomes. (I use here the concepts as defined by Bourbaki, 1951).

The "outcomes" so far are simple events, without any implication of desirability. In any real regulation, for the benefit of some defined person or organism or organisation, the facts usually determine a further mapping of the set $Z$ of outcomes into a set $E$ of values. $E$ may be as simple as the 2-element set {good, bad}, and is commonly an ordered set, representing the preferences of the organism. Some subset of $E$ is then defined as the "goal". The set of values, with perhaps a scale of preference, is often obvious in human affairs; but in the biological world, and in the logic of the subject, it must have explicit mention. Thus if the outcome is "gets into deep water", the valuation is uncertain until we know whether the organism is a cat or a fish.

In the living organisms, the scale of values is usually related to their "essential variables"—those fundamental variables that must be kept within certain "physiological" limits if the organism is to survive. Other organisations also often have their essential variables: in an economic system, a firm's profits is of this nature, for only if this variable keeps positive can the firm survive.

Given the goal—the "good" or "acceptable" elements in $E$—the inverse mapping of this subset will define, over $Z$, the subset of "acceptable outcomes". Their occurrence in the body of the table or matrix will thus mark a subset of the product set $D \times R$. Thus is defined a binary relation $S$ between $D$ and $R$ in which "the elements $d_i$ and $r_j$ have the relation $S$" is equivalent to "$r_i$, as response to $d_i$, gives an acceptable outcome".

*Control.*

In this formulation we have considered the case in which the regulator acts so as to limit the outcome to a particular subset, or to keep some variables within certain limits, or even to hold some variables constant. This reduction to constancy must be understood to include all those cases, much more numerous, that can be reduced to this form. Thus if a gun is to follow a moving target, the regulation implied by accuracy of aim may be represented by a keeping at zero of the difference between the gun's aim and the target's position. The same remark is clearly applicable to all cases where an unchanging (constant) relation is to be maintained between one variable that is independent and another variable that is controlled by the regulator.

Thus, as a special instance, if a variable *y* (which may be a vector) is to be controlled by a variable *a*, and if disturbance *D* has access to the system so that *y* is a function of both the control *a* and the value of disturbance *D*, then a suitable regulator that has access to the disturbance may be able to counter its effects, remove its effect from *y*, and thus leave *y* wholly under the control of *a*. In this case, successful regulation by *R* is the necessary and sufficient condition for successful control by *a*.

*Requisite variety.*

Consider now the case in which, given the table of outcomes (the pay-off matrix), the regulator *R* has the best opportunities for success. (The other cases occur as degenerate forms of this case, and need not be considered now in detail).

Given the table, *R*'s opportunity is best if *R* can respond knowing *D*'s value. Thus, suppose that *D* must first declare his (or its) selection $d_i$; a particular row in the table is thereby selected. When this has been done, and knowing *D*'s selection, *R* selects a value $r_j$, and thus selects a particular column. The outcome is the value of *Z* at the intersection. Such a table might be:

| | | *R* | | |
|---|---|---|---|---|
| | | $r_1$ | $r_2$ | $r_3$ |
| | $d_1$ | *c* | *a* | *d* |
| | $d_2$ | *b* | *d* | *a* |
| *D* | $d_3$ | *c* | *d* | *c* |
| | $d_4$ | *a* | *a* | *b* |
| | $d_5$ | *d* | *b* | *b* |

If outcomes *a*, *b* count as Good, and *c*, *d* as Bad, then if *D* selects $d_1$, *R* must select $r_2$; for only thus can *R* score Good. If *D* selects $d_2$, *R* may choose $r_1$ or $r_3$. If *D* selects $d_3$, then *R* cannot avoid a Bad outcome; and so on.

Nature, and other sources of such tables, provides them in many forms, ranging from the extreme at which everyone of *R*'s responses results in Good (these are distinctly rare!), to those hopeless situations in which every one of *R*'s responses leads to Bad. Let us set aside these less interesting cases, and consider the case, of central importance, in which each column has all its elements different. (Nothing is assumed here about the relation between the contents of one column and those of another). What this implies is that if the set *D* had a certain variety, the outcomes in any one column will have the same variety. In this case, if *R* is inactive in responding to *D* (i. e. if *R* adheres to one value $r_j$ for all values of *D*), then the variety in the outcomes will be as large as that in *D*. Thus in this case, and if *R* stays constant, *D* can be said to be exerting full control over the outcomes.

*R,* however, aims at confining the actual outcomes to some subset of the possible outcomes *Z*. It is necessary, therefore, that *R* acts so as to lessen the variety in the outcomes. If *R* does so act, then there is a quantitative relation between the variety in *D*, the variety in *R*, and the smallest variety that can be achieved in the set of actual outcomes; namely, *the latter cannot be less than the quotient of the number of rows divided by the number of columns* (Ashby, 1956; S.11/5).

If the varieties are measured logarithmically, this means that if the varieties of *D*, *R*, and actual outcomes are respectively $V_d$, $V_r$, and $V_o$ then the minimal value of $V_o$ is $V_d - V_r$. If now $V_d$ is given, $V_o$'s minimum can be lessened *only by a corresponding increase in* $V_r$. This is the law of requisite variety. What it means is that restriction of the outcomes to the subset that is valued as Good demands a certain variety in *R*.

We can see the relation from another point of view. *R*, by depending on *D* for its value, can be regarded as a channel of communication between *D* and the outcomes (though *R*, by acting as a regulator, is using its variety subtractively from that of *D*). The law of requisite variety says that *R's capacity as a regulator cannot exceed its capacity as a channel for variety.*

The functional dependencies can be represented as in Fig. 1. (This diagram is necessary for comparison with Figs. 2 and 3).


FIG. 1

The value at *D* threatens to transmit, via the table *T* to the outcomes *Z*, the full variety that occurs at *D*. For regulation, another channel goes through *R*, which takes a value so paired to that of *D* that *T* gives values at *Z* with reduced variety.

*Nature of the limitation.*

The statement that some limit cannot be exceeded may seem rash, for Nature is full of surprises. What, then, would we say if a case were demonstrated in which objective measurements shows that the limit was being exceeded? Here we would be facing the case in which appropriate effects were occurring without the occurrence of the corresponding causes. We would face the case of the examination candidate who gives the appropriate answers before he has been given the corresponding questions! When such things have happened in the past we have always looked for, and found, a channel of communication which has accounted for the phenomenon, and which has shown that the normal laws of cause and effect do apply. We may leave the future to deal similarly with such cases if they arise. Meanwhile, few doubt that we may proceed on the assumption that genuine overstepping of the limitation does not occur.

*Examples in biology.*

In the biological world, examples that approximate to this form are innumerable, though few correspond with mathematical precision. This inexactness of correspondence does not matter in our present context, for we shall not be concerned with questions involving high accuracy, but only with the existence of this particular limitation.

An approximate example occurs when a organism is subject to attacks by bacteria (of species $d_i$) so that, if the organism is to survive, it must produce the appropriate anti-toxin $r_j$ . If the bacterial species are all different, and if each species demands a different anti-toxin, then clearly the organism, for survival, must have at least as many anti-toxins in its repertoire of responses as there are bacterial species.

Again, if a fencer faces an opponent who has various modes of attack available, the fencer must be provided with at least an equal number of modes of defence if the outcome is to have the single value: attack parried.

*Analysis of Sommerhoff.*

Sommerhoff (1950) has conducted an analysis in these matters that bears closely on the present topic. He did not develop the quantitative relation between the varieties, but he described the basic phenomenon of regulation in biological systems with a penetrating insight and with a wealth of examples.

He recognises that the concept of "regulation" demands variety in the disturbances *D*. His "coenetic variable" is whatever is responsible for the values of *D*. He also considers the environmental conditions that the organism must take into account (but as, in his words, these are "epistemically dependent" on the values of the coenetic variable, our symbol *D* can represent both, since his two do not vary independently.) His work shows, irrefutably in my opinion, how the concepts of co-ordination, integration, and regulation are properly represented in abstract form by a relation between the coenetic variable and the response, such that the outcome of the two is the achievement of some "focal condition" (referred to as "goal" here). From our point of view, what is important is the recognition that without the regulatory response the values at the focal condition would be more widely scattered.

Sommerhoff's diagram (Fig. 2) is clearly similar. (I have modified it slightly, so as to make it uniform with Figs. 1 and 3).

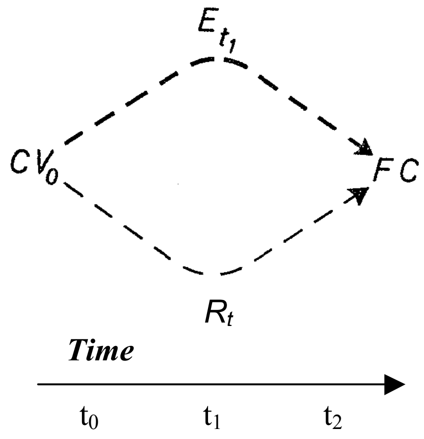


FIG. 2

His analysis is valuable as he takes a great many biological examples and shows how, in each case, his abstract formulation exactly catches what is essential while omitting the irrelevant and merely special. Unfortunately, in stating the thesis, he did what I did in 1952—used the mathematical language of analysis and continuous functions. This language now seems unnecessarily clumsy and artificial; for it has been found (Ashby, 1956) that the concepts of set theory, especially as expounded by Bourbaki (1951), are incomparably clearer and simpler, while losing nothing in rigour. By the change to set theory, nothing in fact is lost, for nothing prevents the elements in a set from being numbers, or the functions from being continuous, and the gain in generality is tremendous. The gain is specially marked with biological material, in which non-numerical states and discontinuous functions are ubiquitous.

Let me summarise what has been said about "regulation". The concept of regulation is applicable when there is a set $D$ of disturbances, to which the organism has a set $R$ of responses, of which on any occasion it produces some one, $r_j$ say. The physico-chemical or other nature of the whole system then determines the outcome. This will have some value for the organism, either Good or Bad say. If the organism is well adapted, or has the know-how, its response $r_j$, as a variable, will be such a function of the disturbance $d_i$ that the outcome will always lie in the subset marked as Good. The law of requisite variety then says that such regulation cannot be achieved unless the regulator $R$, as a channel of communication, has more than a certain capacity. Thus, if $D$ threatens to introduce a variety of 10 bits into the outcomes, and if survival demands that the outcomes be restricted to 2 bits, then at each action $R$ must provide variety of at least 8 bits.

*Ergodicity*

Before these ideas can be related to those of the communication theory of Shannon, we must notice that the concepts used so far have not assumed ergodicity, and have not even used the concept of probability.

The fact that communication theory, during the past decade, has tended to specialise in the ergodic case is not surprising when we consider that its application has been chiefly to telephonic and other communications in which the processes go on incessantly and are usually stationary statistically. This fact should not, however, blind us to the fact that many important communications are non-ergodic, their occurrence being especially frequent in the biological world. Thus we frequently study a complex biological system by isolating it, giving it a stimulus, and then observing the complex trajectory that results. Thus the entomologist takes an ant-colony, places a piece of meat nearby, and then observes what happens over the next twenty-four hours, without disturbing it further. Or the social psychologist observes how a gang of juvenile criminals forms, becomes active, and then breaks up. In such cases even a single trajectory can provide abundant information by the comparison of part with part, but the only ergodic portion of the trajectory is that which occurs ultimately, when the whole has arrived at some equilibrium, in which nothing further of interest is happening. Thus the ergodic part is degenerate. It is to be hoped that the extension of the basic concepts of Shannon and Wiener to the non-ergodic case will be as fruitful in biology as the ergodic case has been in commercial communication. It seems likely that the more primitive concept of "variety" will have to be used, instead of probability; for in the biological cases, systems are seldom isolated long enough, or completely enough, for the relative frequencies to have a stationary limit.

Among the ergodic cases there is one, however, that is obviously related to the law of requisite variety. It is as follows.

Let $D$, $R$, and $E$ be three variables, such that we may properly observe or calculate certain entropies over them. Our first assumption is that if $R$ is constant, all the entropy at $D$ will be transmitted to, and appear at, $E$. This is equivalent to

$$H_r(E) = H_r(D) \qquad (1)$$

By writing $H(D, R)$ in two forms we have

$$H(D) + H_d(R) = H(R) + H_r(D)$$

Use of (1) gives

$$H(D) + H_d(R) = H(R) + H_r(E) = H(R,E)$$

$$\leq H(R) + H(E)$$

i.e.

$$H(E) \geq H(D) + H_d(R) - H(R) \qquad (2)$$

The entropy of $E$ thus has a certain minimum—the expression on the right of (2). If $H(E)$ is the entropy of the actual outcomes, then, for regulation, it may have to be reduced to a certain value. Equation (2) shows what can reduce it; it can be reduced:

(i) by making $H_d(R) = 0$, i.e. by making $R$ a determinate function of $D$,

(ii) by making $H(R)$ larger.

If $H_d(R) = 0$, and $H(R)$ the only variable on the right of (2), then a decrease in $H(E)$ demands at least an equal increase in $H(R)$. This conclusion is clearly similar to that of the law of requisite variety.

A simple generalisation has been given (Ashby, 1956) in which, when *R* remains constant, only a certain fraction of *D*'s variety or entropy shows in the outcomes or in *H*(*E*). The result is still that each decrease in *H*(*E*) demands at least an equal increase in *H(R).*

With this purely algebraic result we can now see exactly how these ideas join on to Shannon's. His theorem 10 uses a diagram which can be modified to Figure 3 (to match the two preceding Figures).

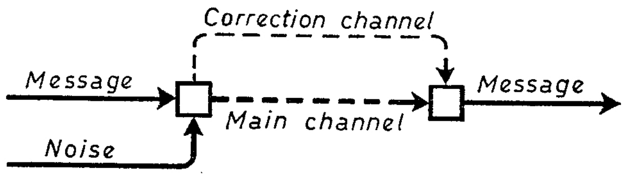


FIG. 3

Our "disturbance *D*", which threatens to get through to the outcome, clearly corresponds to the noise; and his theorem says that the amount of noise that can be prevented from appearing in the outcomes is limited to the entropy that can be transmitted through the correction channel.

*The message of zero entropy.*

What of the "message"? In regulation, the "message" to be transmitted is a constant, i.e. has zero entropy. Since this matter is fundamental, let us consider some examples. The ordinary thermostat is set at, say, 70º F. "Noise", in the form of various disturbances, providing heat or cold, threatens to drive the output from this value. If the thermostat is completely efficient, this variation will be completely removed, and an observer who watches the temperature will see continuously only the value that the initial controller has set. The "message" is here the constant value 70.

Similarly, the homeostatic mechanism that keeps our bodies, in health, about 98º F is set at birth to maintain this value. The control comes from the gene-pattern and has zero entropy, for the selected value is unchanging.

The same argument applies similarly to all the regulations that occur in other systems, such as the sociological and economic. Thus an attempt to stabilise the selling price of wheat is an attempt to transmit, to the farmers, a "message" of zero entropy; for this is what the farmer would receive if he were to ask daily "what is the price of wheat today"? The stabilisation, so far as it is successful, frees the message from the effects of those factors that might drive the price from the selected value.

Thus, all acts of regulation can be related to the concepts of communication theory by our noticing that the "goal" is a message of zero entropy, and that the "disturbances" correspond to noise.

*The error-controlled regulator.*

A case in which this limitation acts with peculiar force is the very common one in which the regulator is "error-controlled". In this case the regulator's channel for information about the disturbances has to pass through a variable (the "error") which is kept as constant as possible (at zero) by the regulator *R* itself. Because of this route for the information, the more successful the regulator, the less will be the range of the error, and therefore the less will be the capacity of the channel from *D* to *R*. To go to the extreme: if the regulator is totally successful, the error will be zero unvaryingly, and the regulator will thus be cut off totally from the information (about *D*'s value) that alone can make it successful—which is absurd. The error-controlled regulator is thus fundamentally incapable of being 100 percent efficient.

Living organisms encountered this fact long ago, and natural selection and evolution have since forced the development of channels of information, through eyes and ears for instance, that supply them with information about *D* before the chain of cause and effect goes so far as to cause actual error. At the present time, control by error is widely used in industry, in servomechanisms and elsewhere, as a means to regulation. Some of these regulations by error control are quite difficult to achieve. Immersed in the intricacies of Nyquist's theorem, transfer functions, and other technical details, the design engineer may sometimes forget that there is another way to regulation. May I suggest that he would do well to bear in mind what has been found so advantageous in the biological world, and to consider whether a regulation which is excessively difficult to design when it is controlled by error may not be easier to design if it is controlled not by the error but by what gives rise to the error.

This is a first application to cybernetics of the law of requisite variety and Shannon's theorem 10.

It is not my purpose in this paper, however, to explore in detail how the limitation affects simple regulators. Rather I want to consider its effect in matters that have so far, I think, received insufficient attention. I want to indicate, at least in outline, how this limitation also implies a fundamental limitation on the human intellect, especially as that intellect is used in scientific work. And I want to indicate, in the briefest way, how we scientists will sometimes have to readjust our ways because of it.

## II

*The limitations of the scientist.*

In saying that the human intellect is limited, I am not referring to those of its activities for which there is no generally agreed valuation—I am not referring for instance, to the production of pictures that please some and displease others—for without an agreed valuation the concept of regulation does not exist. I refer rather to those activities in which the valuation is generally agreed on, and in which the person shows his capacity by whether he succeeds or fails in getting an acceptable outcome. Such is the surgeon, whose patient lives or dies; such is the mathematician, given a problem, which he does or does not solve; such is the manager whose business prospers or fails; such is the economist who can or cannot control an inflationary spiral.

Not only are these practical activities covered by the theorem and so subject to limitation, but also subject to it are those activities by which Man shows his "intelligence". "Intelligence" today is defined by the method used for its measurement; if the tests used are examined they will be found to be all of the type: from a set of possibilities, indicate one of the appropriate few. Thus all measure intelligence by the *power of appropriate selection* (of the right answers from the wrong). The tests thus use the same operation as is used in the theorem on requisite variety, and must therefore be subject to the same limitation. (*D*, of course, is here the set of possible questions, and *R* is the set of all possible answers). Thus what we understand as a man's "intelligence" is subject to the fundamental limitation: it cannot exceed his capacity as a transducer. (To be exact, "capacity" must here be defined on a per-second or a per-question basis, according to the type of test.)

*The team as regulator.*

It should be noticed that the limitation on "the capacity of Man" is grossly ambiguous, according to whether we refer to a single person, to a team, or to the whole of organised society. Obviously, that one man has a limited capacity does not impose a limitation on a team of $n$ men, if $n$ may be increased without limit. Thus the limitation that holds over a team of $n$ men may be much higher, possibly $n$ times as high, as that holding over the individual man.

To make use of the higher limitation, however, the team must be efficiently organised; and until recently our understanding of organisation has been pitifully small. Consider, for instance, the repeated attempts that used to be made (especially in the last century) in which some large Chess Club played the World Champion. Usually the Club had no better way of using its combined intellectual resources than either to take a simple majority vote on what move to make next (which gave a game both planless and mediocre), or to follow the recommendation of the Club's best player (which left all members but one practically useless). Both these methods are grossly inefficient. Today we know a good deal more about organisation, and the higher degrees of efficiency should soon become readily accessible. But I do not want to consider this question now. I want to emphasise the limitation. Let us therefore consider the would-be regulator, of some capacity that cannot be increased, facing a system of great complexity. Such is the psychologist, facing a mentally sick person who is a complexly interacting mass of hopes, fears, memories, loves, hates, endocrines, and so on. Such is the sociologist, facing a society of mixed races, religions, trades, traditions, and so on. I want to ask: given his limitation, and the complexity of the system to be regulated, what scientific strategies should he use?

In such a case, the scientist should beware of accepting the classical methods without scrutiny. The classical methods have come to us chiefly from physics and chemistry, and these branches of science, far from being all-embracing, are actually much specialised and by no means typical. They have two peculiarities. The first is that their systems are composed of parts that show an extreme degree of homogeneity: contrast the similarity between atoms of carbon with the dissimilarity between persons. The second is that the systems studied by the physicist and chemist have nothing like the richness of internal interaction that have the systems studied by the sociologist and psychologist.

Or take the case of the scientist who would study the brain. Here again is a system of high complexity, with much heterogeneity in the parts, and great richness of connexion and internal interaction. Here too the quantities of information involved may well go beyond the capacity of the scientist as a transducer.

Both of these qualities of the complex system—heterogeneity in the parts, and richness of interaction between them—have the same implication: the quantities of information that flow, either from system to observer or from part to part, are much larger than those that flow when the scientist is physicist or chemist. And it is because the quantities are large that the limitation is likely to become dominant in the selection of the appropriate scientific strategy.

As I have said, we must beware of taking our strategies slavishly from physics and chemistry. They gained their triumphs chiefly against systems whose parts are homogeneous and interacting only slightly. Because their systems were so specialised, they have developed specialised strategies. We who face the complex system must beware of accepting their strategies as universally valid. It is instructive to notice that their strategies have already broken down in one case, which is worth a moment's attention. Until about 1925, the rule "vary only one factor at a time" was regarded as the very touchstone of the scientific method. Then R. A. Fisher, experimenting with the yields of crops from agricultural soils, realised that the system he faced was so dynamic, so alive, that any alteration of one variable would lead to changes in an uncountable number of other variables long before the crop was harvested and the experiment finished. So he proposed formally to vary whole sets of variables simultaneously—not without peril to his scientific reputation. At first his method was ridiculed, but he insisted that his method was the truly scientific and appropriate one. Today we realise that the rule "vary only one factor at a time" is appropriate only to certain special types of system, not valid universally. Thus we have already taken one step in breaking away from the classical methods.

Another strategy that deserves scrutiny is that of collecting facts "in case they should come in useful some time"—the collecting of truth "for truth's sake". This method may be efficient in the systems of physics and chemistry, in which the truth is often invariant with time; but it may be quite inappropriate in the systems of sociology and economics, whose surrounding conditions are usually undergoing secular changes, so that the parameters to the system are undergoing changes—which is equivalent to saying that the systems are undergoing secular changes. Thus, it may be worthwhile finding the density of pure hafnium, for if the value is wanted years later it will not be changed. But of what use today, to a sociologist studying juvenile delinquency, would a survey be that was conducted, however carefully, a century ago? It might be relevant and helpful; but we could know whether it was relevant or not only after a comparison of it with the facts of today; and when we know these, there would be no need for the old knowledge. Thus the rule "collect truth for truth's sake" may be justified when the truth is unchanging; but when the system is not completely isolated from its surroundings, and is undergoing secular changes, the collection of truth is futile, for it will not keep.

There is little doubt, then, that when the system is complex, the scientist should beware of taking, without question, the time-honored strategies that have come to him from physics and chemistry, for the systems commonly treated there are specialised, not typical of those that face him when they are complex.

Another common aim that will have to be given up is that of attempting to "understand" the complex system; for if "understanding" a system means having available a model that is isomorphic with it, perhaps in one's head, then when the complexity of the system exceeds the finite capacity of the scientist, the scientist can no longer understand the system—not in the sense in which he understands, say, the plumbing of his house, or some of the simple models that used to be described in elementary economics.

*Operational research.*

It will now be obvious that the strategies appropriate to the complex system are those already getting well known under the title of "operational research". Scientists, guided doubtless by an intuitive sense of what is reasonable, are already breaking away from the classical methods, and are developing methods specially suitable for the complex system. Let me review briefly the chief characteristics of "operational" research.

Its first characteristic is that its ultimate aim is not understanding but the purely practical one of control. If a system is too complex to be understood, it may nevertheless still be controllable. For to achieve this, all that the controller wants to find is some action that gives an acceptable result; he is concerned only with what happens, not with why it happens. Often, no matter how complex the system, what the controller wants is comparatively simple: has the patient recovered?—have the profits gone up or down ?—has the number of strikes gone up or down ?

A second characteristic of operational research is that it does not collect more information than is necessary for the job. It does not attempt to trace the whole chain of causes and effects in all its richness, but attempts only to relate controllable causes with ultimate effects.

A third characteristic is that it does not assume the system to be absolutely unchanging. The research solves the problems of today, and does not assume that its solutions are valid for all time. It accepts frankly that its solutions are valid merely until such time as they become obsolete.

The philosopher of science is apt to look somewhat askance at such methods, but the practical scientist knows that they often achieve success when the classical methods bog down in complexities. How to make edible bread, for instance, was not found by the methods of classical science—had we waited for that we still would not have an edible loaf—but by methods analogous to those of operational research: if a variation works, exploit it further; ask not why it works, only it it works. We must be careful, in fact, not to exaggerate the part played by classical science in present-day civilisation and technology. Consider, for instance, how much empirical and purely practical knowledge plays a part in our knowledge of metallurgy, of lubricants, of house-building, of pottery, and so on.

What I suggest is that measurement of the quantity of information, even if it can be done only approximately, will tell the investigator where a complex system falls in relation to his limitation. If it is well below the limit, the classic methods may be appropriate; but should it be above the limit, then if his work is to be realistic and successful, he must alter his strategy to one more like that of operational research.

My emphasis on the investigator's limitation may seem merely depressing. That is not at all my intention. The law of requisite variety, and Shannon's theorem 10, in setting a limit to what can be done, may mark this era as the law of conservation of energy marked its era a century ago. When the law of conservation of energy was first pronounced, it seemed at first to be merely negative, merely an obstruction; it seemed to say only that certain things, such as getting perpetual motion, could not be done. Nevertheless, the recognition of that limitation was of the greatest value to engineers and physicists, and it has not yet exhausted its usefulness. I suggest that recognition of the limitation implied by the law of requisite variety may, in time, also prove useful, by ensuring that our scientific strategies for the complex system shall be, not slavish and inappropriate copies of the strategies used in physics and chemistry, but new strategies, genuinely adapted to the special peculiarities of the complex system.

**REFERENCES**.

ASHBY, W. Ross, Design for a brain. 2nd. imp. Chapman & Hall, London, 1954.

ASHBY, W. Ross, An introduction to cybernetics. Chapman & Hall, London, 1956.

BOURBAKI, N., Théorie des ensembles. Fascicule de resultats. A.S.E.I. N°1141. Hermann et Cie, Paris, 1951.

NEUMANN, J. (von) and MORGENSTERN, O., Theory of games and economic behaviour. Princeton, 1947.

SHANNON, C. E. and WEAVER, W., The mathematical theory of communication. University of Illinois Press, Urbana, 1949,

SOMMERHOFF, G., Analytical biology. Oxford, University Press, London, 1950.

CYBERNETICA (Namur) Vol I — N° 2 — 1958.