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# A Missing Link in Cybernetics

## Logic and Continuity

Springer

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# Contents

# Chapter 1
# Cybernetics: Origins and Aims

## Origins

The subject of cybernetics was announced by that name with the publication of Norbert Wiener's book (Wiener 1948). Of course, there were earlier stirrings including the influential paper of McCulloch and Pitts (1943) and other activity much earlier. A great deal stemmed from Warren McCulloch's lifelong quest that he epitomised (McCulloch 1960) as the attempt to answer the question: "What is a number, that a man may know it, and a man, that he may know a number?" Rather more concisely, his aim has been expressed as: "understanding man's understanding".

This can also be seen as the aim of much theorising that went before, under headings of philosophy and psychology, but McCulloch brought a fresh emphasis on experiment, particularly in neurophysiology. He also linked such studies to developments in technology, especially in automatic control and computing. The term "experimental epistemology" was coined, and it was recognised that an important aspect of the new approach was its interdisciplinary nature. This was sometimes illustrated by saying that the reflex arc of the neurophysiologist is essentially the same as the feedback loop of the control engineer, and this illustrates the general idea (even if closer examination shows the correspondence to be slightly tenuous). The interdisciplinary nature was acknowledged in the latter part of the title of Wiener's book where reference was made to "the animal and the machine".

It was also realised that the brain is a supreme example of a complex interconnected system that interacts with other complex systems, and consequently there has been much overlap between cybernetics and General Systems theory. The spanning of disciplines is now seen as not only linking neuroscience to physics and engineering but as also including such topics as sociology, management, and ecology.

Norbert Wiener was stimulated to consider these issues by his wartime work during the Second World War on predictors for antiaircraft gun control. Predictors that made a straight-line extrapolation of an aircraft's flight were standard, and Wiener's task was to examine the possibility of extrapolating a curved path as such. He then became impressed by the adaptability of pilots who could fly so as to avoid the presumed extrapolation. Wiener's findings were never in fact implemented in actual predictors, possibly because of the realisation that pilots would still outwit them.

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(Since then the problem has been solved in different ways, first by the use of shells that would explode at a required height without necessarily hitting their target, and later by the invention of homing missiles.) Nevertheless the mathematical treatment produced by Wiener is a major contribution to the theory of automatic control, and its elaboration in the context of human interaction makes it germane to cybernetics.

At a more general level, as elegantly reviewed by Seymour Papert (1965), it can be argued that a range of technical developments introduced considerations that were not readily treated within the existing scientific disciplines, and cybernetics emerged to fill the gap. These considerations were associated with the manipulation and transmission of information, which was shown to be, at least according to one interpretation, measurable in units like a physical quantity (Shannon and Weaver 1949). There was a connection with physical entropy, but not in a way that immediately made sense to engineers concerned with heat engines. Feedback control depends on information made to flow in a particular way and is fundamental to servomechanisms and homing missiles and to a vast range of biological processes. Warren McCulloch's lifelong quest integrated nicely with the new discipline that these considerations prompted.

I am aware that I have given greater attention to the contribution of Warren McCulloch than to that of Norbert Wiener. It happens that I am more familiar with McCulloch's views and can comment on how they bear on what I now want to convey. For many years anyone wishing to discuss the topics at their source had unfortunately to join the camp of one or the other but not both of these founding fathers because there was a rift between them. The cause of the rift was not any disagreement over their scientific views, and at the time of launching of cybernetics they were firm friends and collaborators, as confirmed in the definitive biography of Wiener (Masani 1990). Masani acknowledges that the collaboration with McCulloch and Pitts was entirely positive for Wiener. The bias toward McCulloch here is not intended to be partisan, except insofar as it may compensate for the opposite bias in many other publications. There are of course many other people who contributed, as acknowledged by Wiener and McCulloch in their publications.

Early interest in cybernetics, and my own introduction, were with a strong emphasis on neurophysiology. The wartime requirements of radar were met by development of circuits to deal with pulses and other special waveforms, paving the way for electronic digital computers and also for recording equipment and stimulators applicable in neurophysiological research. Many bright young people had become acquainted with electronics, some of them after direction into this field when their first choice under normal circumstances would have been a biological subject. When the Second World War was over, the prospect of applying the new knowledge in the constructive and arguably humanitarian field of neurophysiology was extremely attractive. Means of recording from single nerve units, and of stimulating them, were developed, and it looked as though the nervous system could be analysed as though it was a computer or other electronic device, essentially as visualised by McCulloch. Since that time enormous advances have been made, but nevertheless much about the working of the brain and nervous system remains mysterious.

It should be mentioned that the word "cybernetics" (as "cybernetique") was used much earlier by Ampère and even earlier by Plato and Aristotle. Wiener claimed that he was not initially aware of the earlier use and my inclination is to accept this, but alternative views are reviewed in an appendix to this chapter.

## Understanding

Warren McCulloch's aim has been denoted as "understanding man's understanding", and the term "understanding" needs clarification. The word has slightly different connotations in its two appearances: the first suggests a state of finality equivalent to "explanation" whereas the second suggests mental activity more generally, perhaps with a qualification that it should be to some extent rational. In either sense the term implies construction or acceptance of theories, whether recognised as such or referred to by some term such as "worldview".

As argued by Popper (1972) and more recently by others under the heading of "constructivism", a theory or worldview is necessarily an invention. In the context of the so-called exact sciences it is generally assumed that the current theory is the choice, of those devised to date, that best fits observations, perhaps fitting exactly within the precision of measurement. There is of course no guarantee that the theory will fit all future observations, and in any case there are other considerations that bear on the acceptability of a theory.

To say that something is understood or has been explained can only mean that a theory has been devised that seems, to a particular observer or group of observers (possibly including everyone who has given attention to the matter), to be highly satisfactory. Confidence is increased if the theory allows accurate predictions and if it provides a basis for successful manipulations that might include therapy in the case of brain theory.

However, in the case of Warren McCulloch's quest to understand man's understanding, no definite end point can be specified. The difficulty is increased by the recursive nature of the goal, epitomised by saying that a theory of the working of the brain would have the unique feature of being written by itself. This recursion must be a feature of neuroscience and Artificial Intelligence. (The use of capitals in referring to Artificial Intelligence, or AI, is to denote the subject area as now understood rather then the direct implication of the words.)

Although an end point to McCulloch's quest has to remain vague, there can probably be general agreement about progress towards it, and a great deal has been achieved. I am hoping, in this book, to show how some of the effort has been misdirected and so possibly to help set a course for the future.

## Theories

The meaning of "understanding" depends strongly on the view taken of scientific theories, and it is worthwhile to make a digression to consider this in some detail, if only to clarify my own underlying assumptions.

As pointed out by Popper (1972), a theory can never be proved correct. If a perfect theory were to be formed, there would be no way of recognising it as such.

Popper goes further and denies that there is a formalisable deductive method by which theories can be derived from observations. He accepts that although a theory can never be verified it may be falsified, and a theory is only accepted as scientific or empirical if it is in principle falsifiable. He also shows, however, that falsification is not so simple as it appears at first sight, since an aberrant theory can be modified or supplemented so as to remain acceptable. An early example would be the survival of Newton's theories of gravitation and of motion following the observation that a feather falls more slowly than does a brick, where the theories were saved by bringing in the additional consideration of air resistance.

Especially when investigating an existing complex system such as the nervous system, there is no feasible alternative to forming, and then testing, quite bold theories. It is easy to have misgivings about such a method, and some wild flights of fancy have rightly been criticised as producing "theories looking for facts to fit them". However, Popper's claim that there is no formalisable method of inductive inference supports the view that progress has to depend on exercise of imagination.

A further fundamental uncertainty, referred to by Masani (1992) and others, stems from the fact that all science depends on the unprovable assumption that the future will have characteristics in common with the past. All forms of adaptation and learning can be regarded as implicitly embodying this assumption. Masani (2001) also claims that scientific thought has more in common with religious faith than is generally supposed. Though this view is unlikely to appeal to scientists, it is undeniable that the "experimental epistemology" approach depends on acceptance that the working of the brain can be explained in mechanistic terms without participation of some "vital force" unique to living systems. My own inclination is to go along with this, but with admission that it has the character of an act of faith.

Another criterion by which theories are judged is conciseness, where the choice of a short formulation is sometimes referred to as application of Occam's razor, the reference being to the philosopher William of Ockham who was born in Ockham in Surrey, England, and lived from c. 1280 to c. 1348. A theory is necessarily a succinct representation of a mass of sensory data, and it is reasonable to regard brevity as a virtue. A succinct theory is more likely to allow extrapolation to situations not previously encountered and thus predictions that inspire confidence if they turn out to be correct. Sometimes the razor principle is advanced as an assertion that nature is basically parsimonious and that a short theory is intrinsically preferable to a longer one, but this cannot be more than speculation. The matter of conciseness is discussed by Gaines (1977), with a review of relevant philosophical viewpoints. Gaines refers to an argument between advocates of respective models, of whom one may claim "My model is a better approximation", but the other could counter with the claim that his is simpler, and thereby further from being essentially just a record of the observed behaviour.

Rosenbrock (1990) has referred to the fact that many physical laws have alternative versions of which one is essentially causal and the other variational, and he extends the idea to biological and social systems. Well-known variational principles in physics are those of Hamilton, usually applied in dynamics, and of Huygens in optics. There can be no fundamental superiority of a variational principle over the causal alternative typified by Newton's laws, because the two versions are equivalent in the sense that each can be derived mathematically from the other. For a particular purpose one version may be more convenient than the other, but there is also something in human nature or culture that encourages preference for the causal alternative. This is a further way in which acceptance of a particular formulation is somewhat arbitrary.

In recent years, the realisation that a theory or worldview is essentially an invention of the observer has been discussed under the related headings of second-order cybernetics of and constructivism, the former being defined as "cybernetics that includes the observer" and the latter as the view that an observer's worldview is his or her own construction. Second-order cybernetics and its special flavour of constructivism originated with Heinz von Foerster (von Foerster and Poerksen 2002; Poerksen 2004), although he deprecated the "-ism" description. Von Foerster saw attention to the observer as closing a loop that had previously been ignored.

Some discussions from a constructivist viewpoint actually seem to deny, or at least to de-emphasise, any contribution from anything external to the observer, a view vigorously contested by Masani (1992, 2001). It is impossible to see such "radical constructivism" providing a basis for everyday functioning and indeed survival, and a more reasonable view is that each construction is formed subject to constraints imposed by the environment. This is consistent with Popper's assertion that a theory (or a worldview) can never be verified but should be in principle falsifiable.

One implication of these observations on theories is that there is no way of getting at anything that can be called absolute truth. On the other hand, access to absolute truth is not necessary in order to operate effectively and to feel satisfaction with explanations. We do have some knowledge of the external reality that must be assumed to exist, expressed as its conformity to a particular theory over the set of observations to date, even if the criterion of this varies from person to person. The access to reality is indirect and the tentative nature of theories must be kept in mind, but the achievements of science are undeniable and really do tell us something about the universe (Andrew 1993, 1994a, 1994b).

## Neuroscience

Warren McCulloch considered "man's understanding" from many points of view. He was well acquainted with relevant philosophical works and at one stage began to train as a minister of religion. Later, as a psychiatrist he analysed individual behaviour. However, his emphasis on "experimental epistemology" found expression mainly in examination of the working of the brain and the rest of the nervous system at the level of individual neurons and neural connections. This can be seen from preparations he made in what he intended to become an international research centre in Orange, New Jersey (see later), as well as from his important contributions to neuroanatomy using the technique of strychnine neuronography, and from projects in the group around him, first in Chicago and then at the Massachusetts Institute of Technology.

There is a fundamental assumption that the brain is the seat of intellect. A great deal of evidence supports the view, including the effects of injury to the brain and recent observations using scanning techniques, though it is possible that other parts of the body are also involved. Reference is often made to a “gut feeling” and there is certainly some intimate connection between mental processes and the viscera, as well as to the endocrine system, but the brain seems to be the main seat of processing. Attention has been drawn to an important part played by the reticular formation of the brain stem (Kilmer, McCulloch, and Blum 1968, 1969), which suggests that this structure should be included, and the convenient term “brain” should, strictly, be replaced by “central nervous system”.

Strychnine neuronography is a technique that allows mapping of pathways within the nervous system. An application of strychnine at a particular point evokes propagated “strychnine spikes” that reveal connecting paths. The spikes are conveyed antidromically, or in the opposite direction to that of normal transmission, and so do not usually cross synapses from one neuron to another. This is advantageous in allowing stage-by-stage mapping. The importance of McCulloch’s early contributions is confirmed by an acknowledgement in the preface to the third edition of a classic text on neurophysiology (Fulton 1949) in its review of significant advances since the previous edition.

Many other techniques have been brought to bear on examination of the nervous system, many of them depending on electrical recording of neural activity, either noninvasively by surface electrodes (electroencephalography) or by electrodes placed close to a neural structure or even penetrating an active neuron. The necessary microelectrodes are made according to a variety of methods, the smallest being micropipettes of glass drawn to less than a micrometre diameter and filled with a conducting solution. Others to record from single units without penetration can be relatively crude, with metal cores. They can also be used for localised excitation by a pulse of current, and micropipettes have been used both for this and to inject minute amounts of transmitter substances that play a part in transmission across synapses. The importance of chemical specificity of synapses is an aspect that was not recognised in early work.

Some of the early work tends to be overshadowed by findings from tomographic scanning of the brain, of which positron emission tomography (PET) and nuclear magnetic resonance (NMR) scanning are the best known methods. These allow fairly precise location of neural activity in the brain and have the great advantage of being noninvasive (except for an initial injection in the case of PET) so that observations can be made on conscious subjects exposed to stimuli and performing mental tasks. A great deal of valuable and surprising data has come from such experiments, though as the methods operate by detecting metabolic changes associated with nervous activity, they cannot be expected to reveal the full picture at the single-neuron

# Chapter 7
# Fractal Intelligence

## Is Intelligence Fractal

In the Past chapter, it was suggested that there is a connection between the detection of cyclic activity at the conscious level, perhaps arising from paradox or dilemma, and the detection of incipient instability at the continuous-control level. In each case, detection is normally followed by action that suppresses the cyclic activity. It is further suggested that in biological systems, the continuous-control action should be seen as the more primitive, with conceptual-level behaviour evolved from it but not displacing it.

The acquisition of skill in tasks like riding a bicycle, or acting as a self-stabilising servo in various situations, is readily termed "learning", but there is a tendency to think of it as distinct from learning at the intellectual or discrete-logic level. This may be partly because, if all the physical aspects (masses, elasticities, viscosities, and physical arrangement) are known, mathematical analysis of a continuous task may be possible. However, people and animals excel at learning continuous tasks without formal analysis and where essential parameters are not known. This implies learning how the environment behaves, equivalent to forming a model of it. Learning may be wholly or partly by imitation, corresponding to rote-learning in linguistic contexts.

## Elementary Exemplification

A number of important ideas connected with AI have an "elementary exemplification" (Andrew 1989, 1992) in terms of continuous variables. For example, Minsky's "heuristic connection", introduced by him with reference to complex problem-solving, has an elementary exemplification in the exploitation of environment continuity by process controllers and by people and animals performing acts of skill. The similarity of the problem of what to do when a bicycle has tilted to 3 degrees and what to do for 4 degrees is an elementary exemplification of heuristic connection between problems.

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problem solving (MacKay 1959) seems remarkably natural, even when no means of computing a numerical criterion has been devised.

It is also easy to believe that the principle of elementary exemplification has a bearing on the backpropagation of errors, alternatively termed "significance feedback" with an odd objective function (Andrew 1993), as applied in practical applications of artificial neural nets. Current applications operate in terms of simple numerical error, but introspection suggests that an analogous process is a part of higher-level learning and conscious thought, where "errors" are likely to be expressed in terms of structured variables, as when a person says "I should have been more forceful" or "more tactful", and so forth, and the adaptation that will affect future behaviour is correspondingly structured. Backpropagation as currently implemented could be seen as an elementary exemplification of the structured version. Just how the structured version might be realised in neural nets is difficult to say, but seems a fruitful area for speculation.

## Fractal Intelligence

The ideas in this chapter suggest a possible reason for the failure of known evolutionary or self-organising principles, embodied for example in artificial neural nets, to achieve the required transition from continuous to concept-based processing. It may be necessary for the elementary (pretransition) organisation to play dual roles. One is to provide the initial state, or substrate, from which the new one develops, but it must also provide a kind of blueprint of which the pretransition version might be seen as an elementary exemplification. It is certainly not easy to see how the "blueprint" function could be implemented, but the reappearance of elementary principles in the higher-level context suggests it plays a part and that the want of such a function may be a reason for the failure of self-organising networks to achieve the transition.

The dual role of the pretransition organisation in providing both substrate and exemplar invites comparison with the emergence of recursive or fractal structures in the physical form of organisms. As is clear from illustrations in Peitgen *et al.* (1992), fractal growth produces lifelike forms, suggesting a correspondence to natural development. It is reasonable to suppose that intelligence may have analogous characteristics.

## Summary of Chapter 7

It is shown that a number of principles associated with mainstream AI, and expressed in terms of discrete concepts, have "elementary exemplification" in terms of continuous variables. It is suggested that this observation may hold the key to a means of usefully extending the field of application of backpropagation of error in neural nets.

It is also suggested that the "elementary exemplification" principle may indicate an important characteristic of the evolution of intelligence, namely that the more primitive state from which evolution stems must serve two functions, denoted by substrate and blueprint. That intelligence should have the fractal character that this— and the general idea of elementary exemplification—implies is in keeping with other evidence that fractal growth simulates living development.

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