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PREFACE

Many workers in the biological sciences—physiologists, psychologists, sociologists—are interested in cybernetics and would like to apply its methods and techniques to their own speciality. Many have, however, been prevented from taking up the subject by an impression that its use must be preceded by a long study of electronics and advanced pure mathematics; for they have formed the impression that cybernetics and these subjects are inseparable.

The author is convinced, however, that this impression is false. The basic ideas of cybernetics can be treated without reference to electronics, and they are fundamentally simple; so although advanced techniques may be necessary for advanced applications, a great deal can be done, especially in the biological sciences, by the use of quite simple techniques, provided they are used with a clear and deep understanding of the principles involved. It is the author's belief that if the subject is founded in the common-place and well understood, and is then built up carefully, step by step, there is no reason why the worker with only elementary mathematical knowledge should not achieve a complete understanding of its basic principles. With such an understanding he will then be able to see exactly what further techniques he will have to learn if he is to proceed further; and, what is particularly useful, he will be able to see what techniques he can safely ignore as being irrelevant to his purpose.

The book is intended to provide such an introduction. It starts from common-place and well-understood concepts, and proceeds, step by step, to show how these concepts can be made exact, and how they can be developed until they lead into such subjects as feedback, stability, regulation, ultrastability, information, coding, noise, and other cybernetic topics. Throughout the book no knowledge of mathematics is required beyond elementary algebra; in particular, the arguments nowhere depend on the calculus (the few references to it can be ignored without harm, for they are intended only to show how the calculus joins on to the subjects discussed, if it should be used). The illustrations and examples are mostly taken from the biological, rather than the physical, sciences. Its overlap with *Design for a Brain is* small, so that the two books are almost independent. They are, however, intimately related, and are best treated as complementary; each will help to illuminate the other.

It is divided into three parts.

Part I deals with the principles of Mechanism, treating such matters as its representation by a transformation, what is meant by "stability", what is meant by "feedback", the various forms of independence that can exist within a mechanism, and how mechanisms can be coupled. It introduces the principles that must be followed when the system is so large and complex (e.g. brain or society) that it can be treated only statistically. It introduces also the case when the system is such that not all of it is accessible to direct observation—the so-called Black Box theory.

Part II uses the methods developed in Part I to study what is meant by "information", and how it is coded when it passes through a mechanism. It applies these methods to various problems in biology and tries to show something of the wealth of possible applications. It leads into Shannon's theory; so after reading this Part the reader will be able to proceed without difficulty to the study of Shannon's own work.

Part III deals with mechanism and information as they are used in biological systems for regulation and control, both in the inborn systems studied in physiology and in the acquired systems studied in psychology. It shows how hierarchies of such regulators and controllers can be built, and how an amplification of regulation is thereby made possible. It gives a new and altogether simpler account of the principle of ultrastability. It lays the foundation for a general theory of complex regulating systems, developing further the ideas of *Design for a Brain.* Thus, on the one hand it provides an explanation of the outstanding powers of regulation possessed by the brain, and on the other hand it provides the principles by which a designer may build machines of like power.

Though the book is intended to be an easy introduction, it is not intended to be merely a chat about cybernetics—it is written for those who want to work themselves into it, for those who want to achieve an actual working mastery of the subject. It therefore contains abundant easy exercises, carefully graded, with hints and explanatory answers, so that the reader, as he progresses, can test his grasp of what he has read, and can exercise his new intellectual muscles. A few exercises that need a special technique have been marked thus: *Ex. Their omission will not affect the reader's progress.

For convenience of reference, the matter has been divided into sections; all references are to the section, and as these numbers are shown at the top of every page, finding a section is as simple and direct as finding a page. The section is shown thus: S.9/14—indicating the fourteenth section in Chapter 9. Figures, Tables, and

Exercises have been numbered within their own sections; thus Fig. 9/14/2 is the second figure in S.9/14. A simple reference, e.g. Ex. 4, is used for reference within the same section. Whenever a word is formally defined it is printed in **bold-faced** type.

I would like to express my indebtedness to Michael B. Sporn, who checked all the Answers. I would also like to take this opportunity to express my deep gratitude to the Governors of Barnwood House and to Dr. G. W. T. H. Fleming for the generous support that made these researches possible. Though the book covers many topics, these are but means; the end has been throughout to make clear what principles must be followed when one attempts to restore normal function to a sick organism that is, as a human patient, of fearful complexity. It is my faith that the new understanding may lead to new and effective treatments, for the need is great.

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CONTENTS

Chapter 1

WHAT IS NEW

1/1. Cybernetics was defined by Wiener as “the science of control and communication, in the animal and the machine”—in a word, as the art of *steermanship*, and it is to this aspect that the book will be addressed. Co-ordination, regulation and control will be its themes, for these are of the greatest biological and practical interest.

We must, therefore, make a study of mechanism; but some introduction is advisable, for cybernetics treats the subject from a new, and therefore unusual, angle. Without introduction, Chapter 2 might well seem to be seriously at fault. The new point of view should be clearly understood, for any unconscious vacillation between the old and the new is apt to lead to confusion.

1/2. *The peculiarities of cybernetics.* Many a book has borne the title “Theory of Machines”, but it usually contains information about *mechanical* things, about levers and cogs. Cybernetics, too, is a “theory of machines”, but it treats, not things but *ways of behaving.* It does not ask “what *is* this thing?” but “*what does it do?”* Thus it is very interested in such a statement as “this variable is undergoing a simple harmonic oscillation”, and is much less concerned with whether the variable is the position of a point on a wheel, or a potential in an electric circuit. It is thus essentially functional and behaviouristic.

Cybernetics started by being closely associated in many ways with physics, but it depends in no essential way on the laws of physics or on the properties of matter. Cybernetics deals with all forms of behaviour in so far as they are regular, or determinate, or reproducible. The materiality is irrelevant, and so is the holding or not of the ordinary laws of physics. (The example given in S.4/15 will make this statement clear.) *The truths of cybernetics are not conditional on their being derived from some other branch of science.* Cybernetics has its own foundations. It is partly the aim of this book to display them clearly.

1/3. Cybernetics stands to the real machine—electronic, mechanical, neural, or economic—much as geometry stands to a real object in our terrestrial space. There was a time when "geometry" meant such relationships as could be demonstrated on three-dimensional objects or in two-dimensional diagrams. The forms provided by the earth—animal, vegetable, and mineral—were larger in number and richer in properties than could be provided by elementary geometry. In those days a form which was suggested by geometry but which could not be demonstrated in ordinary space was suspect or inacceptable. Ordinary space *dominated* geometry.

Today the position is quite different. Geometry exists in its own right, and by its own strength. It can now treat accurately and coherently a range of forms and spaces that far exceeds anything that terrestrial space can provide. Today it is geometry that contains the terrestrial forms, and not vice versa, for the terrestrial forms are merely special cases in an all-embracing geometry.

The gain achieved by geometry's development hardly needs to be pointed out. Geometry now acts as a framework on which all terrestrial forms can find their natural place, with the relations between the various forms readily appreciable. With this increased understanding goes a correspondingly increased power of control.

Cybernetics is similar in its relation to the actual machine. It takes as its subject-matter the domain of "all possible machines", and is only secondarily interested if informed that some of them have not yet been made, either by Man or by Nature. What cybernetics offers is the framework on which all individual machines may be ordered, related and understood.

1/4. Cybernetics, then, is indifferent to the criticism that some of the machines it considers are not represented among the machines found among us. In this it follows the path already followed with obvious success by mathematical physics. This science has long given prominence to the study of systems that are well known to be non-existent—springs without mass, particles that have mass but no volume, gases that behave perfectly, and so on. To say that these entities do not exist is true; but their non-existence does not mean that mathematical physics is mere fantasy; nor does it make the physicist throw away his treatise on the Theory of the Massless Spring, for this theory is invaluable to him in his practical work. The fact is that the massless spring, though it has no physical representation, has certain properties that make it of the highest importance to him if he is to understand a system even as simple as a watch.

The biologist knows and uses the same principle when he gives to *Amphioxus*, or to some extinct form, a detailed study quite out Of proportion to its present-day ecological or economic importance.

In the same way, cybernetics marks out certain types of mechanism (S.3/3) as being of particular importance in the general theory; and it does this with no regard for whether terrestrial machines happen to make this form common. Only after the study has surveyed adequately the *possible* relations between machine and machine does it turn to consider the forms actually found in some particular branch of science.

1/5. In keeping with this method, which works primarily with the comprehensive and general, cybernetics typically treats any given, particular**,** machine by asking not "what individual act will it produce here and now?" but "what are *all* the possible behaviours that it can produce?"

It is in this way that information theory comes to play an essential part in the subject; for information theory is characterised essentially by its dealing always with a *set* of possibilities; both its primary data and its final statements are almost always about the set as such, and not about some individual element in the set.

This new point of view leads to the consideration of new types of problem. The older point of view saw, say, an ovum grow into a rabbit and asked "why does it do this"—why does it not just stay an ovum?" The attempts to answer this question led to the study of energetics and to the discovery of many reasons why the ovum should change—it can oxidise its fat, and fat provides free energy; it has phosphorylating enzymes, and can pass its metabolises around a Krebs' cycle; and so on. In these studies the concept of energy was fundamental.

Quite different, though equally valid, is the point of view of cybernetics. It takes for granted that the ovum has abundant free energy, and that it is so delicately poised metabolically as to be, in a sense, explosive. Growth of some form there will be; cybernetics asks "why should the changes be to the rabbit-form, and not to a dog-form, a fish-form, or even to a teratoma-form?" Cybernetics envisages a set of possibilities much wider than the actual, and then asks why the particular case should conform to its usual particular restriction. In this discussion, questions of energy play almost no part—the energy is simply taken for granted. Even whether the system is closed to energy or open is often irrelevant; what *is* important is the extent to which the system is subject to determining and controlling factors. So no information or signal or determining factor may pass from part to part without its being recorded as a significant event. Cybernetics might, in fact, be defined as *the study of systems that are open to energy but closed to information and control*—systems that are "information-tight" (S.9/19.).

1/6. *The uses of cybernetics.* After this bird's-eye view of cybernetics we can turn to consider some of the ways in which it promises to be of assistance. I shall confine my attention to the applications that promise most in the biological sciences. The review can only be brief and very general. Many applications have already been made and are too well known to need description here; more will doubtless be developed in the future. There are, however, two peculiar scientific virtues of cybernetics that are worth explicit mention.

One is that it offers a single vocabulary and a single set of concepts suitable for representing the most diverse types of system. Until recently, any attempt to relate the many facts known about, say, servo-mechanisms to what was known about the cerebellum was made unnecessarily difficult by the fact that the properties of servo-mechanisms were described in words redolent of the automatic pilot, or the radio set, or the hydraulic brake, while those of the cerebellum were described in words redolent of the dissecting room and the bedside—aspects that are irrelevant to the *similarities* between a servo-mechanism and a cerebellar reflex. Cybernetics offers one set of concepts that, by having exact correspondences with each branch of science, can thereby bring them into exact relation with one other.

It has been found repeatedly in science that the discovery that two branches are related leads to each branch helping in the development of the other. (Compare S.6/8.) The result is often a markedly accelerated growth of both. The infinitesimal calculus and astronomy, the virus and the protein molecule, the chromosomes and heredity are examples that come to mind. Neither, of course, can give *proofs* about the laws of the other, but each can give suggestions that may be of the greatest assistance and fruitfulness. The subject is returned to in S.6/8. Here I need only mention the fact that cybernetics is likely to reveal a great number of interesting and suggestive parallelisms between machine and brain and society. And it can provide the common language by which discoveries in one branch can readily be made use of in the others.

1/7. *The complex system.* The second peculiar virtue of cybernetics is that it offers a method for the scientific treatment of the sys-

tem in which complexity is outstanding and too important to be ignored Such systems are, as we well know, only too common in the biological world!

In the simpler systems, the methods of cybernetics sometimes show no obvious advantage over those that have long been known. It is chiefly when the systems become complex that the new methods reveal their power.

Science stands today on something of a divide. For two centuries it has been exploring systems that are either intrinsically simple or that are capable of being analysed into simple components. The fact that such a dogma as "vary the factors one at a time" could be accepted for a century, shows that scientists were largely concerned in investigating such systems as *allowed* this method; for this method is often fundamentally impossible in the complex systems. Not until Sir Donald Fisher's work in the '20s, with experiments conducted on agricultural soils, did it become clearly recognised that there are complex systems that just do not allow the varying of only one factor at a time—they are so dynamic and interconnected that the alteration of one factor immediately acts as cause to evoke alterations in others, perhaps in a great many others. Until recently, science tended to evade the study of such systems, focusing its attention on those that were simple and, especially, reducible (S.4/14).

In the study of some systems, however, the complexity could not be wholly evaded. The cerebral cortex of the free-living organism, the ant-hill as a functioning society, and the human economic system were outstanding both in their practical importance and in their intractability by the older methods. So today we see psychoses untreated, societies declining, and economic systems faltering, the scientist being able to do little more than to appreciate the full complexity of the subject he is studying. But science today is also taking the first steps towards studying "complexity" as a subject in its own right.

Prominent among the methods for dealing with complexity is cybernetics. It rejects the vaguely intuitive ideas that we pick up from handling such simple machines as the alarm clock and the bicycle, and sets to work to build up a rigorous discipline of the subject. For a time (as the first few chapters of this book will show) it seems rather to deal with truisms and platitudes, but this is merely because the foundations are built to be broad and strong. They are built so that cybernetics can be developed vigorously, without t e primary vagueness that has infected most past attempts to grapple with, in particular, the complexities of the brain in action.

Cybernetics offers the hope of providing effective methods for the study, and control, of systems that are intrinsically extremely complex. It will do this by first marking out what is achievable (for probably many of the investigations of the past attempted the impossible), and then providing generalised strategies, of demonstrable value, that can be used uniformly in a variety of special cases. In this way it offers the hope of providing the essential methods by which to attack the ills—psychological, social, economic—which at present are defeating us by their intrinsic complexity. Part III of this book does not pretend to offer such methods perfected, but it attempts to offer a foundation on which such methods can be constructed, and a start in the right direction.

PART ONE

MECHANISM

The properties commonly ascribed to any object are, in last analysis, names for its behavior.

(Herrick)