HIERARCHIES OF CONTROL PROCESSES AND THE EVOLUTION OF CONSCIOUSNESS

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1. Introduction

The purpose of this paper is to sketch an application of some ideas in the mathematical theory of control processes to biological phenomena such as instinct, learning, curiosity, adaptation, and, finally, consciousness. We shall employ the language and methodology of the theory of dynamic programming. Detailed accounts of the mathematical ideas will be found in [1], [2], [3]. For a quite different approach to consciousness, see [6].

2. Control processes

We begin with the idea of a process. Consider a system described by a point p in a space S. Let $T(p)$ be a transformation with the property that $p_1 = T(p)$ belongs to S whenever p is in S. We call the pair $[p, T(p)]$ a process. More precisely, this is a particular description of a process.

When the transformation is repeated, yielding a sequence of states, $p_1, p_2, \cdots$, where $p_1 = T(p)$, $p_2 = T(p_1)$, $\cdots$, we call it a multistage process. This is an abstract version of a dynamic process.

Assume next that $T(p)$ is replaced by a transformation of the form $T(p, q)$ having the property that for any p in S and any q in a decision space D, the point $p_1 = T(p, q)$ is in S. A choice of vectors (decisions) $q_1, q_2, \cdots$, then yields a sequence of states $p_1 = T(p, q_1)$, $p_2 = T(p_1, q_2)$, $\cdots$. We call this a multistage decision process. It is also an abstract version of a control process. From the mathematical point of view, control and decision processes are equivalent; see [2], [3].

A determination of the q_i may be effected by maximizing a criterion function which depends on the history of the process $K = K(p, p_1, \cdots; q_1, q_2, \cdots)$. In many important cases this has a separable structure $K = k_1(p, q_1) + k_2(p_1, q_2) + \cdots$, in other words an accumulation of single stage effects. A criterion function is a measure of the effectiveness of a control process.

The maximizing q_i will be functions of the states $p_1, p_1, \cdots$. In the most important cases the q_i which maximizes depends only upon the present and past history of the process $q_i = q_i(p, p_1, \cdots, p_{i-1})$, and frequently only upon the current state, $q_i = q_i(p_{i-1})$.

Let us call any function of this type a policy, reserving the term optimal policy for a policy which maximizes K. The study of control and decision processes may then be considered to be the study and effective determination of optimal policies. Unfortunately, in many of the control processes of greatest significance either no criterion function exists or there are too many of them. (The criterion function is a measure of the sequence of decisions.) This makes the application of mathematical theories such as the calculus of variations and dynamic programming quite difficult; see, however, [5].

Nevertheless, the concept of policy remains meaningful. Furthermore, the powerful and flexible theory of simulation can be used to study the complex processes associated with animate and human systems; see [3].

3. Instinct

Let us now identify instinct as a policy, a policy which controls the behavior of an organism in a particular situation. We consider instinctive behavior a precise automatic response to a signal or stimulus acting on an organism. The evolutionary value of instinct is clear since in critical circumstances there may not be time for conscious behavior. The response must be preprogrammed to ensure survival.

The point we wish to emphasize, however, is that instinct is not solely a low level intellectual activity. What seems to be the case is that there are levels of instinctive behavior, intermingled with conscious behavior. We shall return to this point below.

4. Levels of control processes

When the original system does not cope in a satisfactory style, survival of the species depends upon the development over time of control mechanisms to improve the performance. At the lowest level these are feedback control devices. These control systems, however, themselves require supervision and modification. Gradually, then, we see the development of control systems for control systems, and so on. The operation of any complex system requires a hierarchy of control systems.

We can identify this hierarchy of control systems with levels of consciousness. Indeed, if we wish to discuss consciousness in a meaningful fashion, we must utilize the concept of levels of consciousness. Similarly, to study thinking, we must consider levels and kinds of thinking. A confusion of levels leads to paradoxes and other difficulties; see [4], [7].

5. Instructions

Let us pursue this subject of hierarchies in another direction. Suppose that an organism contains certain types of mechanisms for conveying instructions. Some of these instructions may well be instructions for issuing instructions, and so on, again a hierarchal concept.

An error in one kind of instruction is thus seen to be far more critical than an error in another type of instruction. An error in the instructions for issuing instructions will lead to an infinitely greater number of errors than an inaccurate instruction which leads to the development of one faulty organ, for example. We see then that numerical probabilities of mutation are not inherently meaningful. We must take the structure of the organism into account and examine the responsiveness of the structure to a change in one component. These are questions of mathematical stability and sensitivity.

6. Uncertainty

So far we have considered only deterministic processes, processes where cause and effect is assumed to hold. Let us now consider processes where uncertainty plays a major role.

One way to construct mathematical models of uncertainty is to introduce random variables. This leads to the concept of a stochastic transformation $T(p, q, r)$. The point $p_1 = T(p, q, r)$ belongs to S whenever p is in S, q is in D and r is a random variable in R; see [2].

A choice of a sequence $q_1, q_2, \cdots$, and a selection of random variables $r_1, r_2, \cdots$, leads as before to a sequence of states $p_1, p_2, \cdots$. An optimal policy may be determined in a process of this nature by maximizing the expected value of a criterion function.

This, however, takes care of only first level processes. There are far more complex levels of uncertainty. In the foregoing we assumed that the probability distributions for the random variables were known. Frequently, this is not the case. Instead, we may possess some initial clues as to the nature of the uncertainty and then proceed to discover more of the structure of the process using observation of the events that occur. We call this an adaptive control process, and equate this operation with learning. One instinct associated with learning is curiosity. There are, however, levels of learning. We learn, we learn how to learn, and so on; see [5].

7. Higher level instinct

A mathematical technique for studying adaptive control processes is the theory of dynamic programming. In animals, however, it seems that adaptive control involves higher level instincts. If so, this plausibly explains why it is so difficult to carry out mathematical studies of pattern recognition, language translation, and human communication. If these are instinctive, they are not based upon the mathematical principles of the last 5000 years, but instead upon techniques developed by evolutionary selection over hundreds of millions of years.

In other words, we possess in our brain very complex, genetically determined, internal mechanisms specifically designed for particular tasks. Existing mathematical methods and computers cannot yet compete with these consequences of selective breeding.

8. Theory of types

It is apparent that what has proceeded has been considerably influenced by the Russell theory of types and the Liouville-Ritt theory of elementary functions. See the expository discussion in [7], as well as [4] for an analysis of one type of humor in terms of paradoxes.

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