INTRODUCTION TO CONTROL THEORY

William T. Powers
November 1990

Control theory, as we use the term, means engineering control theory adapted for use as a model of the behavior of living systems. Those who already understand engineering control theory therefore already know part of the story. The rest of the story lies in the way we organize a model of control to explain organismic behavior. Sensors, comparators, and effectors appear in this model just as in ordinary models of nonliving control systems. Where we understand enough of real behavior, the models are set up much like models that others use and for the same purpose: to analyze behavior through simulations. But there are some critical differences.

In a living control system, the reference input is not accessible from outside the system. Engineering diagrams commonly show the reference signal as an input from the outside world, which it is in artificial systems: it's the means by which the human user tells the control system the level at which to keep its controlled variable. In a living control system, the "user" is the whole organism. Reference signals are set by higher systems that are also control systems (the higher systems act by adjusting reference signals for lower systems). In some cases the reference signals are derived from genetically-specified information (for example, the reference signal for body temperature). In the majority of the control systems that exist in the brain, however, the organization is learned within a general matrix of preorganization, and reference signals derive from the operation of a multi-leveled, "massively parallel" system.

One of the basic insights behind our uses of control theory is that all control systems control their own inputs, not their outputs. In engineering, this fact is obscured because the inputs are arranged so as to represent an external variable of interest to the user of the system, generally a variable directly affected by the actions of the system: position, temperature, acceleration, pressure, and so on. But a little thought will show that such variables can be known to the system only as signals generated by sensors; in every case it is the signal, not the external variable, that is under control (just picture what happens when the sensor drifts out of calibration). Our model must be understood from the viewpoint of the system itself, not that of an external user.

The human system knows the external world through millions of sensors. It affects the external world, and thus its inner world of sensory signals, by its actions. The sensory signals also play a part in the production of action: we propose, specifically, that it is the same role played by the sensory signals in control systems. This leads to a new understanding of behavior, in which action and perception are part of a closed control loop, the action serving to maintain the perception at whatever level is currently specified by an inner reference signal. External disturbances tending to alter the signals, the perceptions, result in actions that oppose those effects, thus leading to the spurious appearance that the

system senses the disturbances and simple reacts to them.

This picture is very different from a stimulus-response model, and it is also very different from a cognitive or command-driven model. One level in the model does not tell a lower level what act to perform: it provides an example (in the form of a signal) of the state to which the lower system is to bring its own sensory signal. The lower system itself provides the action needed to match perception to the reference. A sensory signal entering a control system does not cause any particular action to occur; the action is based not on the perception but on the DIFFERENCE between the perception's state and state currently being specified by the reference signal.

This model is very tightly interconnected. A perceptual signal in a given control system is derived from the perceptual signals in a set of lower- level systems. The derived signal is of a new type; it is a function of the set of lower perceptual signals. This higher-level perception is compared with a reference signal, and the difference is converted to a set of output signals. These output signals enter THE SAME SYSTEMS FROM WHICH THE LOWER- LEVEL PERCEPTIONS CAME, serving as reference signals that specify the states of the lower-level perceptions. All loops are closed: all behavior at all levels is purposive. Every effect generated by any system is controlled in terms of the perception that represents it: nothing organized ever happens open-loop.

The evidence in support of this model ranges from excellent at the lowest levels to sketchy at the highest. Where we know how to do experiments, we construct quantitative working models and match them to behavior by adjusting their parameters. We're trying to expand the scope of these experiments to higher levels, but the going is slow. One factor that encourages us is that all control loops, in this model, can be detected and tested from outside the system, because all loops are closed, ultimately, through the environment. Where the model is wrong we can find out that it is wrong.

The model is also approached in another way, as an organizing principle for reinterpreting phenomena of behavior. Given the basic organization of control as we see it at the lower levels, the question is whether higher levels of organized behavior also make sense in these same terms -- more sense than when interpreted in conventional ways. So far the answer seems to be a unanimous yes. We are trying, however, to extend the method of modeling so it can be useful in areas where quantitative experiments are difficult. In this way we hope to test and buttress the insights of our clinician-members and real-life investigators by linking their work to that of our computer modelers. Both contingents will learn from this interaction. But all have a long way to go. There are more than enough research problems awaiting us at all levels of analysis.

While our uses of control theory have many roots in the past and many resemblances to the work of others, our approach is basically not connected to any mainstream line of development. It is a new departure, almost a reconstruction of behavioral theory from scratch. Some of us are convinced that it amounts to a revolution in the life sciences.

Bill Powers