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Living Control Systems

The study of living control systems is the study of the behavior of living organisms. Organisms can be regarded as living control systems because their behavior is equivalent to that of nonliving control systems. The equivalence turns on the fact that both nonliving control systems and living organisms *control*, which means that they act to achieve *intended* or *goal results* in the face of unpredictable, and often undetectable, *disturbances* that would prevent these results from being achieved. For example, the thermostat – a nonliving control system – controls by acting to keep room temperature constant in the face of disturbances, such as variations in the number of people in the room, that would otherwise cause the temperature to vary considerably. Similarly, a person sipping tea controls by acting to get the cup consistently to their lips in the face of disturbances, such as the changing weight of the cup after each sip, that would otherwise cause "many a slip between cup and lip."[1]

The research methods described here are based on the fact that the behavior of organisms is a process of control. We know this because everything we see organisms doing – all of their behavior – is done in a world of continuously varying disturbances. These disturbances should make it impossible for organisms to produce the consistent results that we call their behaviors. Instead, we see organisms producing consistent results in the face of these disturbances. We see people consistently lifting cups to their lips without spilling a drop, a behavior called "sipping tea"; we see people consistently putting one foot in front of the other without falling, a behavior called "walking." The study of the behavior of living control systems is, therefore, the study of how organisms produce consistent results in the face of disturbance; that is, it is the study of how organisms control. But it could also be called the study of how organisms carry out their

[1] A video demonstration of the controlling involved in sipping tea is available at www.youtube.com/watch?v=88aXMEgvq68.

purposes because the controlling done by living organisms is equivalent to what is called *purposeful behavior*.

1.1 Purposeful Behavior

The behavior of control systems, like that of living organisms, is *goal-oriented*. This was enough to convince some scientists that the behavior of a control system is purposeful and, thus, could be used as a scientific basis for distinguishing purposeful from the nonpurposeful behavior (e.g., Rosenblueth, Wiener, & Bigelow, 1943). These scientists were right about the behavior of a control system being purposeful but wrong about goal-orientation being enough to distinguish purposeful from nonpurposeful behavior. The fact that goal-orientation alone is not enough to distinguish purposeful from nonpurposeful behavior was pointed out by the pioneering psychologist William James in his parable of Romeo and the iron filings (James, 1890). In that parable James notes that the behavior of iron filings moving to a magnet appears to be as goal-oriented as the behavior of Romeo moving to Juliet. Yet the iron filings have no purpose while Romeo certainly does. And the way to show this is by placing an obstacle in the paths to their goals; a card can be placed between the filings and the magnet and a wall between Romeo and Juliet. What we will see is that the filings are stopped by the card and never get to their "goal," while Romeo does whatever is necessary to get past the wall and close to Juliet. As James puts it, "With the filings the path is fixed; whether it reaches the end depends on accidents. With the lover it is the end which is fixed, the path may be modified indefinitely" (James, 1890, p. 7).

James correctly understood purposeful behavior to be a process of achieving goals ("ends") by varying actions as necessary ("modifying the path indefinitely") in order to compensate for disturbances ("obstacles") that would prevent goal-achievement. But he didn't understand how such behavior was possible since it seems to violate the law of cause and effect – that cause must precede (or, at least, be simultaneous with) effect. In purposeful behavior, this temporal relationship between cause and effect seems to be reversed: a future event – the goal – seems to be the cause of the present actions that are used to achieve it. After James described purposeful behavior, many efforts were made to explain it without violating the law of cause and effect. This was done by either ignoring the fact that organisms achieve their goals in the face of disturbances (e.g., Turvey, Shaw, & Mace, 1978) or by assuming that these disturbances had the remarkable ability to cause just the right actions that would get organisms past them and to their goals (Tolman, 1922).

1.2 Control Theory

It is now possible to explain purposeful behavior without denying the reality of disturbances or attributing an unlikely level of intelligence to them. And it can be done in a way that is perfectly consistent with the law of cause and effect. It is done by recognizing that the purposeful behavior of organisms is equivalent to the controlling done by a control system. The way control systems do this controlling is explained by an engineering model called *control theory*.[2] The control theory model of a control system is shown in Figure 1.1. The first thing to notice about this model is that it distinguishes the system doing the controlling from the environment in which this controlling is done. The dashed line in the figure encloses the control system (the System), which can be thought of as being equivalent to the organism doing the controlling. Everything outside of the dashed line is the Environment in which the system does its controlling. If the System is thought of as an organism then the Environment is the world outside of the organism's nervous system, which includes its muscles and

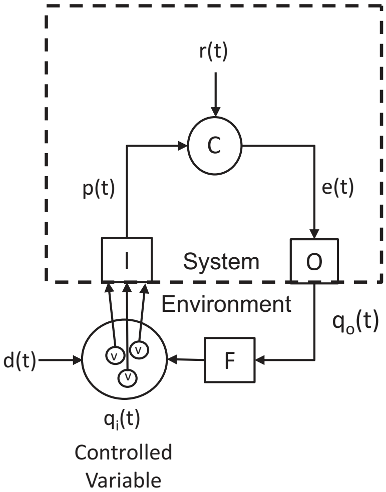

Figure 1.1 Control theory model of a control system (after Powers, 1973a, Figure 1).

[2] A very good nontechnical introduction to engineering control theory can be found in *A History of Control Theory* by Bennett (1993).

glands. The most important variable in the System's Environment is the *controlled variable*, symbolized $q_i(t)$, which is the variable that the system is controlling.[3] The controlled variable is typically a function of many physical variables, represented by the v's in the diagram. For example, Romeo is controlling his distance from Juliet. The distance from Romeo to Juliet is a controlled variable that is a function of two physical variables, which are the geographical locations of Romeo and Juliet.

A controlled variable is controlled in the sense that it is kept in a goal or *reference state*, protected from the effects of disturbances, $d(t)$. The reference state of the controlled variable is specified by a reference signal, $r(t)$, inside the control system. The reference state specified by $r(t)$ for the variable Romeo is controlling – the distance between him and Juliet – is "close to" or "near." A control system brings the controlled variable to the reference state and keeps it there – it achieves its purpose – by varying its actions, $q_o(t)$, in exactly the right way so as to oppose the effects of disturbances. Romeo controls for being close to Juliet by acting in just the right way, by scaling walls and dodging through forests, so as to oppose the disturbances created by walls and Capulets. The System side of the control theory model explains how this is done. That is it explains how the System is able to do exactly what is required in order to achieve the purpose of keeping the controlled variable in the reference state.

An important thing to notice about the System component of Figure 1.1 is that it is in a *closed-loop* relationship with respect to the controlled variable. This can be seen in the ring of arrows going into the System from the controlled variable, looping through the System, coming out and looping back through the Environment to where the loop started, at the controlled variable. A closed loop like this has no beginning or end. But when we describe the loop we have to start somewhere, and the typical place to start is with the input to the System – the controlled variable. The physical variables that are the basis of the controlled variable – the v's in Figure 1.1 – enter the System via an Input Function, I, that produces a perceptual signal, $p(t)$, that is an analog of the controlled variable. The perceptual signal then enters a comparator function, C, where it is continuously compared to a reference signal, $r(t)$, which specifies the desired state or value of $p(t)$. The result is an error signal, $e(t)$, which is proportional to the difference between the reference and perceptual signals. This error signal enters an output function, O, that produces an output, $q_o(t)$, which is an action that

[3] The "t" in parentheses next to the variable name (q_i in this case) simply means that the variable can vary over time.

is proportional to the size of the error signal. This output action completes the closed loop by "feeding back" through the environment, via a feedback function, *F*, to have an effect on the controlled variable, which was where we started.

A System that is in a closed-loop relationship with its Environment is a control system only if the feedback from its output to its input is negative. There is *negative feedback* in a closed loop when the error signal causes outputs that reduce – that is, have a negative effect on – the error signal itself. The error signal does this by continuously causing outputs that counter the causes of error. The causes of error are the effects of disturbances to the controlled variable as well as changes in the value of the reference signal, $r(t)$, that specifies the desired state of the perceptual signal. This negative feedback organization will keep the controlled variable in a reference state that corresponds to the state of the perceptual signal specified by the possibly varying reference signal.

The behavior of the control system model of purposeful behavior shown in Figure 1.1 can be described by the following two equations:

$$q_o(t) = O \cdot [r(t) - p(t)], \tag{1.1}$$

$$p(t) = q_i(t) = I \cdot [F \cdot q_o(t) + d(t)]. \tag{1.2}$$

In order to simplify the mathematics, the functions in these equations – the output function, *O*, and the input function, *I* ,– are shown as constant multipliers. Equation (1.1) is called the *system equation* because it describes the input–output characteristics of the control system: the output of the system, $q_o(t)$, is proportional to the error signal, $e(t)$, which is the difference between the perceptual signal, $p(t)$, and the reference signal, $r(t)$; $r(t)$ - $p(t)$. Equation (1.2) is called the *environment equation* because it describes how variables in the environment part of the loop, including the output of the control system itself, affect the perceptual input to the system, $p(t)$. Since $p(t)$ is an analog of the controlled variable, $q_i(t)$, its value is ultimately determined by the combined effects of system output, $q_o(t)$, and disturbances, $d(t)$.

1.3 Perceptual Control Theory (PCT)

Equations (1.1) and (1.2) describe the causal relationships between variables that exist in a closed negative feedback loop. This shows up in the fact that system output, $q_o(t)$, is a function of system input, $p(t)$, per Eq. (1.1), while system input is a function of system output, per Eq. (1.2). Moreover, the relationships between system input and output described by Eqs. (1.1) and (1.2) are happening at the same time; input is causing output, while output is causing input. Therefore, in order to understand what this control system is doing in terms of the behavior of its output and input, Eqs. (1.1) and (1.2) must be solved simultaneously. When we do this, making the appropriate assumptions about the values of *I*, *O,* and *F*, we get:

$$q_o(t) \approx r(t) - 1 / F \cdot d(t), \tag{1.3}$$

$$p(t) \approx r(t). \tag{1.4}$$

These equations describe the two main characteristics of the behavior of a properly functioning control system: *disturbance resistance* and *perceptual control*. Equation (1.3) describes the disturbance resistance characteristic of control system behavior. This can be seen most clearly if we make $r(t)$ a constant equal to 0. In that case, Eq. (1.3) becomes $q_o(t) \approx -1/F \cdot d(t)$, which says that variations in the output of the control system are negatively related to variations in disturbances to the controlled variable. This means that system outputs compensate for or "resist" the effects that disturbances would otherwise have on the controlled variable.

Equation (1.4) describes the perceptual control characteristic of control. It says that the control system keeps its perceptual signal, $p(t)$, approximately equal to the reference signal, $r(t)$. The reference signal functions as a specification for the "goal" state of the perceptual signal. The perceptual signal is controlled in the sense that it is brought to this goal state and maintained there in the face of disturbances. Since the perceptual signal is an analog of the controlled variable, Eq. (1.4) means that a control system will keep the controlled variable, $q_i(t)$, in a reference state, $q_i(t)^*$, which corresponds to the value specified by the reference signal. More succinctly, Eq. (1.4) says that the behavior of a control system is the *control of perception* in the sense that the system acts to keep a perceptual analog of the controlled variable in a reference or goal state (Powers, 1973b, 2005b). This fact about control system operation is particularly important when control theory is applied to the behavior of living organisms. This is because understanding the behavior of living organisms in terms of control theory is largely a matter of trying to figure out what perceptual variables they control (Marken, 2020). So when control theory is applied to the behavior of living organisms we give it a special name: *Perceptual Control Theory* or PCT.

Equations (1.3) and (1.4) describe the behavior of a properly functioning control system. The main factor that affects how well a control system controls is the relationship between its *loop gain* and *speed of response*. Loop gain is a measure of the "strength" of the control system; it is mainly determined by the degree to which the output function, *O*, amplifies the effect of error on the controlled variable. Speed of response depends on how quickly error is turned into the output that affects the controlled variable. A control system will function properly only if loop gain and speed of response are inversely related; the greater the system's loop gain, the slower must be the system's speed of response. This relationship between loop gain and speed of response exists in any properly functioning living control system. Since our main concern in this chapter will be the behavior of living control systems that are functioning properly – that are "in control" – we can assume that there is the correct inverse relationship between loop gain and speed of response in these systems. This means that, when studying the behavior of living control systems, the requirement that there be an inverse relationship between loop gain and speed of response can be safely ignored. However, when we build models of the controlling done by living systems, we will have to take this relationship into consideration in order to make the models "work."

1.4 Perceptual versus Manual Control Theory

PCT is not the only application of control theory to understanding the behavior of organisms. Another approach, which started just after World War II, was also aimed at evaluating human performance in manual control tasks, such as flying airplanes (Craik, 1947, 1948). Because of the emphasis on the study of manual control, this approach to the application of control theory can be called *Manual Control Theory* or MCT. Both PCT and MCT use the same control theory to model behavior. The difference is in the way control theory is *mapped* to the behaving system, which results from a difference in the way behavior is viewed. MCT views behavior as output caused by stimulus input, whereas PCT views behavior as the control of input. The PCT view of behavior results in the mapping shown in Figure 1.1; the MCT view of behavior results in the mapping shown in Figure 1.2.

Figure 1.2 is the typical control system diagram that is found in texts on the MCT approach to understanding human behavior. The names of the variables and functions in Figure 1.2 have been selected so that they correspond to those in Figure 1.1. The System in Figure 1.2 represents an organism as an input–output device. Input is converted into output by a

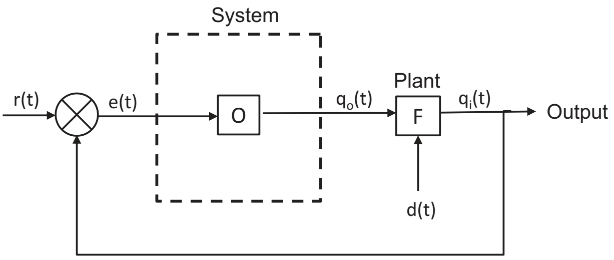

Figure 1.2 Manual Control Theory (MCT) mapping of control theory to behavior.

transfer function, *O*, which corresponds to the output function in Figure 1.1. As in Figure 1.1, the output function converts the error signal, $e(t)$, into the output variable, $q_o(t)$. But in this case, the error signal is *outside* the boundary of the System (the dashed lines), in the environment. The error signal is produced by a comparator (the circle around an "X") that subtracts the fed-back "Output" of the System – the variable called $q_i(t)$ in Figure 1.1 – from a reference signal, $r(t)$. System output, $q_o(t)$, is converted into the fed-back Output, $q_i(t)$, by the feedback function, *F*, as it is in Figure 1.1.

The MCT mapping of control theory to behavior is designed to be consistent with an input–output or stimulus-response view of behavior. The behaving System is viewed as a transfer function (the function *O*) that converts stimulus input, $e(t)$, into behavioral output , $q_o(t)$. MCT uses control theory to evaluate characteristics of this transfer function, such as the speed of response to stimulus input or the effect of the spectral composition of disturbances on the conversion of input into output (Sheridan & Ferrell, 1974; Jagacinski & Flach, 2002; Wickens et al., 2012).

The most obvious difference between the MCT and PCT mappings of control theory onto behavior is in the location of the reference signal, $r(t)$. In control theory, $r(t)$ specifies the result to be produced by the control system. According to MCT, organisms produce *behavioral results* that are "specified" by events in the environment, so $r(t)$ is placed in the System's environment. According to PCT, organisms produce *perceptual results* that are specified by events *inside* the organism itself, so $r(t)$ is placed inside the System. This apparently small difference in the way control theory is mapped to behavior leads to a significant difference in the goals of research aimed at understanding the behavior of organisms. Research based on MCT is aimed at understanding characteristics of the organism's output (or transfer) function, *O*. PCT research, on the other hand, is aimed at understanding characteristics of the organism's perceptual (or input) function, *I*. This difference in research objectives is highlighted by the fact that the input function, *I*, is a prominent feature of the PCT diagram in Figure 1.1, but is not to be found in the MCT diagram in Figure 1.2.

The MCT mapping of control theory onto behavior makes the mistake of placing the reference signal and, thus, the error signal, in the environment. The error signal, which drives the output of a control system, represents a discrepancy between what an organism wants, $r(t)$, and what it is getting, $q_i(t)$. A control theory model of organisms should place $r(t)$ – and $e(t)$ – inside the System. Placing $r(t)$ in the System's environment is an example of what Powers (1978) called the *man-machine blunder*. The effect of this blunder on behavioral research was described by Powers as follows:

> If one's primary purpose is to keep pilots from flying airplanes into the ground or to make sure that a gunner hits a target with the shell, that is, if one's purposes concern objectivized side effects of control behavior, the man-machine blunder amounts to nothing worse than a few mislabelings having no practical consequences. If one's interest is in the properties of persons, however, the man-machine blunder pulls a red herring across the path of progress. (Powers, 1978, p. 419)

An *objectivized side effect of control* is what happens in the environment while a person (or other organism) is controlling its own perceptions. Clearly, there are many practical situations where knowing about these side effects is extremely important. For example, it's important to know what is happening to the actual attitude of an airplane while the pilot is controlling her perceptions of the displayed values of pitch, roll, and yaw in the cockpit. It is possible to learn how to prevent unwanted side effects of control – especially poor control – without learning too much about how a person does this controlling. But if you want to understand how organisms "work" – how their internal properties function to make it possible for the organism to control various aspects of the environment – you have to do research aimed at determining the perceptual variables being controlled when they are carrying out various behaviors. When you do this kind of research – research on purpose – you will learn not only how organisms control but also what the objectivized side effects of this controlling will be when they don't control well.

1.5 Controlled and Perceptual Variables

According to PCT the variables organisms control are *perceptual variables* constructed from the sensory effects of environment variables. These environmental variables are the v's inside the circle representing the controlled variable, $q_i(t)$, in Figure 1.1. The "construction" is done by the input function, I, of the control system. The result of this "construction" is presumed to be an afferent neural signal that fires at a rate proportional to the value of the controlled variable – the variable constructed by the input function. The variables constructed by input functions do not necessarily correspond to a "real" entity in the environment. This means that controlled variables are perceptions themselves in the sense that they are *aspects of the environment* – functions of the v's in Figure 1.1 – that can be perceived by an observer of the behaving system. For example, the taste of lemonade is the state of a perceptual variable, $p(t)$, that is constructed from the sensory effects of sugar (v_1), acid (v_2), and oils (v_3) mixed with water (v_4).[4] A simplified version of the input function that constructs this taste variable might look like this:

$$p(t) = k_0 + k_1 * v_1(t) + k_2 * v_2(t) + k_3 * v_3(t) + k_4 * v_4(t), \tag{1.5}$$

where $p(t)$ is a taste perception created by the input function that is a linear combination of the environmental variables, $v_i(t)$. The k_i are the coefficients that define how these variables combine to produce the taste perception. When the appropriate amounts of sugar (v_1), acid (v_2), oils (v_3), and water (v_4) are mixed together, the taste perception is that of lemonade. As Powers notes, however, no matter how real this perception seems, "there is no physical entity that corresponds to it" (Powers, 2005b, p. 112).

Since perceptual variables are assumed to be analogs of controlled variables, the same function that defines the perceptual variable, $p(t)$, also defines the controlled variable, $q_i(t)$. It is in this sense that both $q_i(t)$ and $p(t)$ are perceptual variables. Both are functions of the sensory effects of physical variables. While the functions that produce $p(t)$ are the input functions, I, in the organism under study, the functions that produce $q_i(t)$ are the input functions of the human who is observing the organism's behavior. The input functions of the observer can be the person's perceptual functions, but more often these functions are carried out by human-made devices that allow the observer to perceive aspects of the environment that could not be perceived without them, such as the otherwise undetectable acoustical echoes controlled by bats.

[4] This example is based on one described by Powers (2005b, p. 112).